DRH 0661-1

ANL-9006375
(DE89006375)

Energy

CONSERVATION

ELECTROMAGNETIC CONTINUOUS CASTING PROJECT

Final Report

By

J. E. Battles

D. M. Rote

B. Misra

W. F. Praeg

J. R. Hull

L. R. Turner

V. L. Shah

R. J. Lari

N. Gopalsami

T. Wiencek

October 1988

Work Performed Under Contract No. W-31109-ENG-38

For

U. S. Department of Energy

EG&G Idaho, Inc.

Idaho Falls, Idaho

By

Argonne National Laboratory

Argonne, Illinois

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Price: Printed Copy A08
Microfiche A01

Prepared by

ARGONNE NATIONAL LABORATORY
Chemical Technology Division
9700 South Cass Avenue
Argonne, Illinois 60439

**ELECTROMAGNETIC CONTINUOUS CASTING PROJECT
FINAL REPORT**

by

J. E. Battles	Chemical Technology Division
D. M. Rote	Energy and Environmental Systems Division
B. Misra	Chemical Technology Division
W. F. Praeg	Electromagnetic Technology Program
J. R. Hull	Materials and Components Technology
L. R. Turner	Electromagnetic Technology Program
V. L. Shah	Materials and Components Technology
R. J. Lari	Electromagnetic Technology Program
N. Gopalsami	Materials and Components Technology
T. Wiencek	Materials and Components Technology

October 1988

This work was conducted under the auspices of the U.S. Department of Energy under Contract W-31-109-Eng-38.

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ELECTROMAGNETIC CONTINUOUS CASTING PROJECT FINAL REPORT

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J. E. Battles, D. M. Rote, B. Misra,
W. F. Praeg, J. R. Hull, L. R. Turner,
V. L. Shah, R. J. Lari, N. Gopalsami, and T. Wiencek

ABSTRACT

This report describes the work on development of an electromagnetic casting process for steel, which was carried out at Argonne National Laboratory between January 1985 and December 1987. This effort was concerned principally with analysis and design work on magnet technology, liquid metal feed system, coolant system, and sensors and process controllers. Experimentation primarily involved (1) electromagnetic studies to determine the conditions and controlling parameters for stable levitation and (2) feed-system studies to establish important parameters that control and influence fluid flow from the liquid metal source to the caster.

SUMMARY

Electromagnetic Technology

The development of an electromagnetic process for continuous casting (EMCC) of steel in large-aspect-ratio shapes was pursued with two basic concepts. The first levitates a sheet of molten metal horizontally by the interaction of a horizontal high-frequency (HF) magnetic field and longitudinal eddy currents induced in the sheet by the HF magnetic field. In the second concept, a vertical molten sheet is confined by a vertical HF magnetic field produced by a large-aspect-ratio solenoid. The sheet is shaped by the interaction of a vertical HF magnetic field and peripheral horizontal eddy currents induced in the sheet by the vertical solenoid field. During FY 1987, experimental effort was limited to tests of the horizontal concept. Theoretical analyses were done on both the horizontal and the vertical concepts.

During FY 1987, a test magnet was designed and built for performing levitation experiments with liquid tin. Experiments were conducted by energizing the magnet from an existing motor-generator set (frequency, 10 kHz; power, 30 kW). Results indicated that a higher power and frequency source may be needed to achieve stable levitation of the liquid metal. Experiments were planned with a 300 kW power supply that can operate at frequencies of 25-200 kHz, but were never carried out because of project termination.

Feed System Design and Fluid Flow Analysis

The casting process requires a system that will provide a suitable feed stream from the liquid metal source to the caster. The requirements for a

liquid metal feed system for various scales of electromagnetic continuous casters were identified, and conceptual system designs were developed. Since relatively little information was available on flows through large-aspect-ratio nozzles, both analytical computer models and physical models were used to develop information and data needed for conceptual and engineering system designs.

Experimental equipment consisting of a tundish, catch basin, recirculation pump, and nozzle was designed and fabricated for feed-system tests with a model fluid (water). Water was used because its kinematic viscosity is close to that of liquid steel. The experiments established the important geometrical and hydrodynamic parameters that control and influence fluid flow patterns in the tundish, nozzle, and stream entering the EM casters.

A closed-loop experimental facility was designed and fabricated for carrying out experiments with liquid tin. This facility was to be used for several purposes: (1) to verify the applicability of the water modeling results to the case of tin flow, (2) to study the flow of tin through nozzles of various shapes and sizes, and (3) to investigate the feasibility of controlling and shaping liquid metal streams using various electromagnetic flow control devices. Initial tests of this facility indicated that some design refinements were required.

Based on the work performed on this effort, a set of guidelines for the design of feed systems suitable for EM casters was developed.

Heat Transfer and Coolant System

Removal of heat from an electromagnetically levitated sheet of liquid steel leading to solidification within the EM confinement presents unique design problems. Because of the reactive nature of the liquid steel and the susceptibility of EM levitation to disturbances at the coolant/liquid interface, several restrictions have been imposed on the coolant system. As a consequence, the coolant selection must be confined to nonoxidizing gases at low mass flow rates, which result in poor heat transfer coefficients. Extensive theoretical and numerical analyses have been conducted to define the coolant requirement and identify possible solutions to the design problems. Based on an initial evaluation of the coolant system requirements, reference operating conditions have been selected. These conditions include a casting speed of 30 cm/s, magnet length of 4-10 m, coolant pressure of 140-210 kPa, steel emissivity of 0.4-0.6, and coolant velocity of 30-40 m/s. Consistent with these operating conditions, work has been directed toward (1) parametric investigations for establishing the cooling requirements in terms of casting speed, magnet length, coolant mass flow rate, and degree of heat transfer augmentation, (2) experiments to obtain supporting data for heat transfer augmentation, and (3) development of nomograms for studying the interaction of various operating parameters in the EMCC process.

The results of the parametric studies showed that a coolant system based on gaseous nitrogen or carbon dioxide can be designed for the EMCC process. However, to limit the length of the electromagnet to less than 10 m, augmentation of heat transfer by a factor of two to three is required. The

literature data indicate that such a modest heat transfer enhancement can be easily obtained by a variety of techniques. Additional studies showed that the magnet length can be significantly reduced by providing mechanical support to a partially solidified strip and by introducing mist coolants (a mixture of fine droplets of water with a carrier gas) within the EM confinement after a solidified layer is formed. An experimental program was initiated to evaluate the effectiveness of mist coolants, especially at elevated temperatures. Extensive nomograms have been developed for the EMCC process covering a broad range of operating parameters. These nomograms can be used to develop design charts that will aid in the optimum design of the coolant system.

Sensors and Process Control

An assessment of the sensor and control requirements for a horizontal EMCC process is presented. This is based upon our present understanding of the process, as well as knowledge gained through our experiments. A review of the sensor requirements and available sensor technology pointed to sensor deficiencies for determining on-the-fly flow profile, on-the-fly shape fluctuations, positions of the onset of solidification, and thickness of solidified skin. The feed system flow and shaping control and the dynamic matching of the inlet and outlet velocities of the caster were identified as key control problems.

A capacitance-type wave detector was developed for quantifying the surface-wave formation in the preliminary experiments on liquid metal stability. In addition, a spectrophotometer-based fiber optic measurement system was assembled and tested for on-line determination of a tracer concentration. The purpose was to estimate the residence time of a tundish with water as the working fluid. A simplified mathematical model of the EMCC system was derived for process control analysis. Analysis with this model showed that the caster must provide a restraining force for bulk stability of the liquid/solid strip. Recommendations to further work and future directions are outlined.

1.0 INTRODUCTION

This research and development program resulted from the Steel Industry/Federal Laboratories Research Initiative to identify innovative technologies that would significantly benefit the U.S. steel industry. The primary objective was to develop an electromagnetic process for the continuous casting of various grades of steel in large-aspect-ratio shapes such as steel strip. This includes the development of the electromagnetic technology for the caster, the required liquid metal feed system, the coolant system, and sensors for on-line process monitoring and control of the casting process. Expected benefits to the steel industry include a superior sheet product with significantly reduced capital and operating costs. The three major phases of this project are development of a proof-of-concept bench-top caster, development of a laboratory-scale caster, and demonstration of a pilot-scale caster. This program was initiated in FY 1985 on a limited basis with support obtained from the Office of Basic Energy Sciences of the Department of Energy (DOE), and continued in FY 1986 at a low level on Laboratory discretionary funds and limited funding from the Office of Industrial Programs of the DOE. Major funding (~\$2.3 M) was allotted to this project by the DOE Office of Industrial Programs in FY 1987.

Extensive workshops were conducted in 1987 by ANL and industry scientists to assess the technical feasibility of the electromagnetic continuous casting (EMCC) concept. Subsequent to these workshops, the American Iron and Steel Institute (AISI) "... concluded that the probability of success is insufficient to justify pursuing this objective as part of the Steel Initiative." This action necessitated that the program be discontinued. Hence, the purpose of this final report is to provide documentation on various EMCC concepts; analysis of EMCC designs (both horizontal and vertical orientations); and experimentation in the areas of metal levitation and stability with various magnet designs, feed system and fluid flow, heat transfer and cooling, and sensors and process control. It is hoped that this documentation will provide a substantial starting base should the program be revived some time in the future.

1.1 Purpose

The ultimate purpose of this ambitious research and development project was to develop an electromagnetic (EM) levitation-based process for the continuous casting of various grades of steel in large-aspect-ratio shapes such as steel strip. The EMCC concept should also be applicable to the casting of other shapes such as tubes, squares, slabs, and "dogbones"; however, the primary focus of the program was on a process for the casting of thin strip/sheet.

The program was structured in a way that addressed the critical phenomena and technical issues crucial to the development of an EMCC process. As such, the program consists of three major phases. The purpose of Phase I was to demonstrate the feasibility of stable levitation and confinement of a flowing liquid steel sheet under laboratory conditions. The electromagnetic technology for stable liquid metal containment and control was supported by R&D efforts in five areas: (1) levitated strip/sheet stability, (2) fluid flow

from liquid metal feed system, including EM stream shaping and flow rate control, (3) heat transfer and strip/sheet cooling, (4) influence of varying coolant velocities and pressures, and (5) requirements for sensors and process control. Phase II was to address process development issues and to include the design, construction, and operation of a laboratory-scale EM caster based on the process concept selected from Phase I. It was envisioned that the laboratory-scale caster would be capable of casting steel sheets in widths up to about 60 cm, and would provide the engineering details needed in Phase III for the design, construction, and operation of a pilot-plant EM caster of moderate size.

1.2 Background

This R&D program resulted from the Steel Industry/Federal Laboratories Research Initiative to identify innovative technologies that would significantly benefit the domestic steel industry. The origin of the Steel Initiative started when the May 1983 report of the White House Science Council's Federal Laboratory Review Panel, known as the "Packard Report," strongly recommended increasing the collaboration of the federal laboratories* with universities and industry.

As members of the presidential Committee on Industrial Competitiveness (PCIC), Dr. G. A. Keyworth, Science Advisor to the President, and Howard M. Love, Chairman of National Intergroup, identified the possibility that this recommendation could be related to the long-range problems of the domestic steel industry.

In a February 3, 1984, presentation to the PCIC, Mr. Love made the following suggestion:

What I am proposing, then, is that steel firms come together to identify an agenda for R&D on leapfrog technologies, and then join with the National Labs to realize that agenda. Let me stress that this must be R&D on leapfrog technologies. If we fall into the rut of "business-as-usual," and merely agree on a modest agenda on R&D for incremental improvements, we will have failed. Let's envision a steel industry where we throw away the blast furnaces, throw away coke ovens, and develop entirely new ways of making a higher quality, higher yield product, at smaller scales, with greater flexibility and more automation.

Let me also stress that by seeking a technological solution, we are building upon our national strengths. We can't compete with the third world on the cost of labor or capital. The one thing we have in our favor is the best science and technology base in the world. Let's take advantage of the base; let's utilize it for the benefit of our basic industries.

*There are 750 federal laboratories, all owned by the Federal Government. In FY 1985, they had a budget of \$18 billion.

On February 8, 1984, members of the Committee on General Research joined Mr. Love and Dr. Keyworth for a meeting in the White House; and, shortly thereafter, joint exploratory studies between certain national laboratories and steel industry scientists were underway. The nature of this joint effort was reviewed by Dr. Keyworth in his speech at the AISI General Meeting on May 24, 1984.

During the period May to September 1984, four task groups under the direction of a Joint Steering Committee comprised of steel industry, national laboratory, and government representatives made an intensive search for highly innovative approaches to iron- and steelmaking which, if developed, would give domestic steel firms a competitive advantage in the 1990s and beyond. The focus was on four broad technological areas: (1) the reduction of domestic raw materials to liquid steel, (2) the production of near-net-shape solids from liquid steel, (3) the development of universal grades of steel, and (4) the application of automatic processing technology to steel production. Opportunities for novel-technology development were identified in two areas: (1) direct production of liquid steel from iron ore and (2) continuous electromagnetic casting of liquid steel to near-net-shape solids. After four meetings of the Steering Committee, some 15 meetings of individual task groups, and a number of visits by national laboratory representatives to steel firms, work plans were developed for R&D in these two areas. After review of the work plans, the steering committee approved the EMCC project, and recommended proceeding with the project. They also recommended further studies to identify an appropriate program in the area of reduction of domestic raw materials to liquid steel. These actions were approved by the General Research Committee of the AISI. Funds for the initial feasibility and caster design analyses were provided from discretionary funds of Argonne National Laboratory. A brief chronological history of the major events in the Steel Initiative and the EMCC project is listed in Table 1-1.

Electromagnetic fields, alone or in combination with mechanical systems, appear to have potential for innovative application to the continuous casting of steel in large-aspect-ratio shapes. The success achieved in this general area by the aluminum industry provided confidence that electromagnetic technologies can be successfully developed for this purpose. The electromagnetic casting process presently used by the U.S. aluminum industry is based on developments in the USSR in the late sixties¹ and subsequent refinement and development of the process by Alusuisse. Since the present EM casting of aluminum uses a batch rather than a continuous casting system and is designed primarily for the casting of slabs or ingots, the Alusuisse method is unsuitable for EMCC of thin strips of sheets with large aspect ratios. However, aluminum slabs and ingots produced by this process have very smooth surfaces, little liquation, uniform distribution of alloying elements, excellent microstructure (particularly on outer surfaces), and good workability. Economic benefits reported include elimination of scalping, less edge trim, increased rate of metal solidification, and good product consistency. Evaluation and assessment of the critical factors for this process (such as molten metal treatment, molten metal handling and distribution, inductor mold and bottom block design, power supply control, liquid metal hydraulic head, and casting drop rate) are expected to be important for EMCC of steel.

Electromagnetic technology has been successfully applied to the casting of copper. The General Electric Company² has developed an EM process for the continuous casting of small diameter (1-2 cm) copper rod. The process uses

Table 1-1. Chronology of Major Events in Electromagnetic Continuous Casting Project

First Industry/Federal Lab Meeting:	February 1984
Initial EMCC Program Plan:	August 1984
ANL EMCC Progress Review:	March 1985
Federal Funding Allocated to DOE:	July 1986
Draft DOE Management Plan Issued:	September 1986
EMCC Prospectus Issued:	November 1986
Technical Status Meeting at ANL:	December 1986
DOE Management Plan Finalized:	April 1987
Technical Plan Reviewed:	April 10, 1987
Industry/ANL Feasibility Workshops:	April-July 1987
Feasibility Workshops Reviewed:	August 1987
EMCC Program Plan Revised:	October 1987
Contractual Agreements Concluded:	November 1987
AISI Decision not to Participate:	December 1987
Close-Down of EMCC Project:	January 1988

traveling waves and the casting orientation is vertical upward. General Electric has reported that wire cold-drawn from the cast rods is superior to wire produced by the normal process and has lower cost. The Olin Corporation³ has successfully developed an EM process for casting copper-based alloys. This casting technique eliminates the mold-related defects and provides casting with greatly improved hot workability. The Olin process for copper is similar to the EM process for aluminum. The EM process for casting aluminum and copper slabs and bars is fully developed and in commercial operation. However, it should be noted that the goal of the EMCC project surpasses what has been achieved thus far by the aluminum and copper industries. Specifically, this project is directed toward the development of an EMCC process for large-aspect-ratio shapes requiring a minimum of additional thermal-mechanical treatment. Research efforts currently underway at Nagoya University⁴ are more directly related to the goal of this project. Researchers at that university have recently reported some success in the horizontal electromagnetic casting of thin plates using a low melting point alloy (Bi-Sn-Zn). Their long-term goal is to develop an EM process for casting steel sheet.

The concept (or desire) of near-net-shape casting of strip or thin slabs is not new. The earliest concept was the twin roll caster proposed by

Bessemer.⁵ Since that time, considerable effort has been devoted to the development of various near-net-shape casting concepts by numerous companies. Obviously, the incentive for these R&D efforts is the significant cost benefits to be gained by eliminating the need for hot-rolling and reheat furnaces. At this time, both thin strip (single wheel and twin roll) and thin slab (Hazelett twin belt and SMS concast) casters are under development. Extensive feasibility studies of thin strip casting have been conducted.⁶ Both laboratory and pilot operations are now being conducted on some processes. Allegheny-Ludlum is now casting 0.75-mm thick stainless steel strip using the melt-drag technique. Nucor has installed a commercial-size Hazelett twin belt caster. The Japanese steel industry is also devoting considerable effort to the development of thin strip and thin slab casters.⁷

1.3 Description of Conceptual EMCC Process

As noted above, the ultimate goal of this R&D project was the development of an electromagnetic continuous casting process for steel sheet. The research activities were focused on (1) levitation experiments in which a test magnet was used to investigate magnetohydrodynamic (MHD) instability at the interface between a flowing gas coolant and molten metal with and without a magnetic field present, (3) analysis of electromagnetic caster design, (4) development of an electromechanical feed system, (5) fluid flow analysis and experimentation, (6) heat transfer analysis to identify coolant system requirements and acceptable methodologies, and (7) identification of sensors for on-line monitoring and process control requirements.

A conceptual design of the electromagnet for the horizontal caster is shown in Fig. 1-1. The important features of the magnet include the side guards to eliminate the vertical components of the horizontal magnetic field below the liquid strip and the copper shield to reduce the field above the liquid strip. A detailed discussion of the magnet analysis and design is provided in Section 2.

A simplified flow chart for the conceptual EMCC process is shown in Fig. 1-2. A conventional liquid metal source would be utilized to feed the EM caster. The feed system would utilize an EM device for liquid metal flow control and a combination of mechanical and EM devices for stream shaping. The coolant system has to be capable of removing a large amount of heat in a short time and yet not disturb the stability of the levitated molten strip. An automated process with appropriate sensors is required to couple and control the elements of the caster in real time. The solidified strip from the caster would be coiled for later processing in standard cold roll mills. It is recognized that a small amount of hot-finishing may be required to prepare the strip for the cold roll mill. The research activities for the feed system, coolant system, and sensors and process control are discussed in Sections 3, 4, and 5, respectively.

A simplified process flowsheet is shown in Fig. 1-3 for the production of steel sheet. The flowsheet compares the process operations for new technologies now under development with those for the current technology, i.e., the continuous slab caster. For new installations, the economic benefits to be gained by eliminating the reheat furnaces and the hot strip mills are

obvious. It is also obvious that the most economic benefit would be provided by the direct strip casting process such as the twin wheel, single wheel, and EM casting processes. The economic benefits are less obvious in the case of retrofitting an existing installation with a slab caster/hot rolling mill operation. A more quantitative discussion of cost benefits awaits a comprehensive techno-economic assessment of the thin strip casting processes.

Fig. 1-1. Conceptual Design of Electromagnet for the Horizontal Caster

Fig. 1-2.

Simplified Flow Chart for the Conceptual EMCC Process

1.4 Current Status of EMCC Project

In December 1987, the AISI decided that the risk involved in this innovative R&D project was too high to warrant their participation. Since industry participation was a major criterion for continued U.S. Department of Energy funding, it became necessary to initiate closeout of this project effective January 1988.

From the beginning, the research activities were focused on the following major areas: (1) analysis and design of electromagnetic casters, (2) levitation experiments to investigate MHD instabilities, (3) feed system design and fluid flow analysis, (4) coolant system requirements and methodologies, and (5) development of sensors and process control systems. These activities are discussed in the following sections.

Fig. 1-3.

Simplified Process Flowsheet
for Sheet Products

The technical accomplishments of this project at the initiation of closeout are briefly summarized below.

- (1) Extensive computer simulations of many magnet designs for both horizontal and vertical casters have been made in two and three dimensions.

- (2) Using the head-start magnet, studies were completed to determine the maximum tolerable velocity for the coolant gas flow over a liquid metal surface and the influence of a high-frequency magnetic field on suppressing wave formation and, hence, increasing the maximum flow velocity.
- (3) Levitation of a static molten tin sheet has been unsuccessful because of the low frequency and power of the available power supply. (A suitable high frequency power supply was on order at the time of cancellation.) However, solid copper sheet has been levitated, which confirmed some of our design concepts.
- (4) MHD stability analyses were conducted to define conditions of stable levitation. Design of a horizontal bench-top caster was near completion, and design analysis for a vertical caster was well underway.
- (5) Preliminary fluid flow studies with H_2O using different nozzle and tundish designs were completed. A recirculating liquid metal (tin) system was designed and fabricated for studying the flow of liquid metals through open- and closed-channel nozzles of high aspect ratio and for determining the influence of EM fields on the flow parameters.
- (6) Extensive theoretical and numerical analyses have been conducted to identify heat transfer requirements and methodologies that provide sufficient heat removal for reasonable casting rates (>100 tons/h). Results suggest that production scale casters will not require magnet lengths of more than 6 m. Apparatus has been set up to determine the extent of heat transfer augmentation achieved by adding water mist (1% by volume) to the primary coolant (N_2 or CO_2).
- (7) A comprehensive assessment of EMCC sensor requirements and commercial availability was underway. A simple mathematical model of the horizontal EMCC system was derived for process control analysis. This formed the basis for a more in-depth model. The feed system flow and shaping control and coordination of the EM feed system with the roller drive controls for the exiting strip appear to be key control problems.

As noted above, industry/ANL workshops were conducted in FY 1987 to assess the technical feasibility of the EMCC process. The major areas addressed were the EM caster design and experimentation, design of the liquid metal feed systems, and the design of heat transfer and coolant systems. Three working groups composed of steel industry and ANL scientists were established at the April 10, 1987, technical review of the electromagnetic caster R&D program. The purpose of the working groups was to (1) evaluate the technical feasibility of the Argonne EM caster concept at commercial scale, (2) identify and discuss the critical technical issues, and (3) recommend experiments and analyses (or program direction) needed to resolve the technical issues. Each working group met on three separate occasions. The working groups identified and evaluated a broad range of technical issues

related to the feasibility of the three major components in the EM caster concept. The findings of the working groups were reported at the August 6, 1987, technical meeting and a summary report of the workshops was prepared by ANL (Appendix A). Subsequent to this meeting, the program was revised in accordance with the recommendations of the industry participants. However, the new program plan was never initiated because of the AISI decision made in December 1987.

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2.0 ELECTROMAGNETIC TECHNOLOGY

The development of an electromagnetic process for continuous casting of steel in large-aspect-ratio shapes is being pursued with two basic concepts. The first levitates a horizontal sheet of molten metal by the interaction of a horizontal, high-frequency (HF) magnetic field and longitudinal eddy currents, which are induced in the sheet by the HF magnetic field. In the second concept, a vertical molten sheet passes through a vertical HF magnetic field produced by a large-aspect-ratio solenoid. The sheet is shaped by the interaction of a vertical HF magnetic field and horizontal eddy currents induced in the sheet by the vertical field from the solenoid. The effects of gravity are controlled by vertically traveling electromagnetic fields. Theoretical analyses have been done on both the horizontal and the vertical concepts, but experimental effort was limited to the horizontal concept.

2.1 Electromagnetic Principles and Computation

2.1.1 Electromagnetic Principles Applicable to Levitation and Casting

The effects of magnetic pressure, skin depth, and electromagnetic heating (power loss) are central to electromagnetic casting and are reviewed here.

2.1.1.1 Field Penetration

Assume a large, nonmagnetic, conducting plate as shown in Fig. 2-1. The bottom surface is at $y = 0$ and the top surface at $y = \infty$. An alternating magnetic field is applied in the z direction. The field inside the plate is given by:

$$B_z = B_s e^{-y/\delta} \cos (\omega t - y/\delta), \quad (1)$$

where $B_s \cos \omega t$ is the instantaneous external field at the surface, and δ is the skin depth (meters). The skin depth is equal to $(2/\omega\sigma\mu_o)^{1/2}$, where $\omega = 2\pi f$ and f is the frequency (s^{-1}), σ = the conductivity of the material (siemens/meter), and $\mu_o = 4\pi 10^{-7}$ = permeability of space (henry/meter). Equation 1 indicates exponential decay and a phase shift of the field with increasing field penetration.

The instantaneous current density is:

$$J_x = \frac{B_s}{\mu_o} e^{-y/\delta} (2/\delta)^{1/2} \cos (\omega t - \phi), \quad (2)$$

where $\phi = \frac{y}{\delta} + \frac{\pi}{4}$. Hence, the current density also is attenuated by $\exp(-y/\delta)$ and phase shifted by ϕ with increasing depth.

Fig. 2-1. Thick Conducting Plate

2.1.1.2 Levitation Force

The magnetic levitating force is given by the equation:

$$F_y = \frac{B^2}{2\mu_o} A, \quad (3)$$

where A is the surface area, and B is the rms value of the field. This must equal the gravitational force:

$$G_y = mg = \rho Ahg, \quad (4)$$

where h is the conductor thickness, ρ is the density, and g is the gravitational constant. Hence, for a parallel field only on the bottom surface, levitation requires:

$$\frac{B^2}{2\mu_o} = \rho hg. \quad (5)$$

For a field B_B at the bottom and B_T at the top of the conductor, levitation is achieved when:

$$\frac{B_B^2 - B_T^2}{2\mu_o} = \rho hg. \quad (6)$$

The quantity $B^2/2\mu_o$ is called the magnetic pressure. If the skin depth δ is small compared to the thickness of the conducting body (a liquid metal sheet in our case), the magnetic force acts as a surface force.

2.1.1.3 Electromagnetic Heating (Power Dissipation)

The average eddy current power loss per unit surface area is:

$$P = \frac{B_s^2}{2\sigma\delta\mu_o} = \frac{I^2}{2\sigma\delta}, \quad (7)$$

where B_s and I are the rms field and current per unit width, respectively. Since $1/\sigma\delta$ is the resistance per unit length of a layer of thickness w and unit width, the power loss is equivalent to that of a uniform rms current $[(I/2)^{1/2}]$ in a layer of depth δ .

As it is often magnetic pressure ($F/A = B_s^2/2\mu_o$) rather than the field (B) which is of interest, Eq. 7 can be written as

$$P = (F/A)/\mu_o\sigma\delta, \text{ or}$$
$$P = (F/A) (w/2\sigma\mu_o)^{1/2}. \quad (8)$$

For a given magnetic pressure, the power per unit area varies as the square root of the frequency and inversely as the square root of the electrical conductivity.

2.1.2 Electromagnetic Computation at ANL: History and Capability

Table 2-1 shows the chronological development of electromagnetic computation capabilities at Argonne. The programs TRIM, GFUN, and TOSCA have been used solely for magnetostatic computations. In 1967 the computer program TRIM was acquired from the Lawrence Berkeley Laboratory to run on the IBM 360 computers at ANL. This program used a variable size triangular mesh to approximate the two-dimensional (2-D) geometry of steel, air, and coils. At ANL, it was first used to design the 20-foot-long ring magnets of the particle accelerator at Fermilab. Much experience and confidence have been gained in magnet design over the subsequent 20 years. The program GFUN was developed at the Rutherford Appleton Laboratory (RAL). It was installed at ANL in 1976 and is capable of calculating both two and three-dimensional (3-D) magnet geometries. Calculations have been made with GFUN on large bubble chamber and other particle detector magnets. In 1982, ANL obtained the proprietary program TOSCA, developed at RAL, from the British company COMPEDA. It complements the GFUN program in calculating 3-D magnetostatic magnet geometries and has been used primarily for calculations involving particle-accelerator-type magnets.

The programs PE2D, EDDYNET, NMLMAP, and CARMEN are used for eddy current computations. EDDYNET was developed at Argonne for the Fusion Power Program. It employs a wire grid method to calculate eddy currents in electrically conducting material. The NMLMAP program was acquired from the Massachusetts Institute of Technology for use with steady-state eddy

Table 2-1. Electromagnetic Computation Capabilities at Argonne

1967 - TRIM	- Triangular Mesh Using Vector Potentials. (2D, Static)
1976 - GFUN	- Integral Equation Method. (2D, 3D, Static)
1979 - POISSON	- Second Generation of TRIM. (2D, Static)
1979 - EDDYNET	- Wire Grid Method. (2D, 3D, Eddy Current)
1982 - TOSCA	- Mixed Total and Reduced Scalar Potentials. (3D, Static)
1983 - NMLMAP	- National Magnet Laboratory Magnetic Analysis Program. (2D, Eddy Current)
1984 - PE2D	- Poisson Equation Solver.. (2D, Static, Eddy Current) (Used for EMCC Computation)
1987 - CARMEN	- Finite Element Method. (3D, Eddy Current)

current calculations. NMLMAP was superseded soon afterwards when ANL licensed the program PE2D, developed at RAL, which has the capability to calculate problems with dc, ac, or transient magnetic fields. Its pre- and post-processors make it a "user friendly" program, easy to learn and applicable to almost any 2-D device. It is this program and design expertise that allowed ANL to advance so quickly in designing magnets for vertical and horizontal electromagnetic casting. CARMEN, a 3-D ac eddy current program, was obtained by ANL from Vector Fields of Oxford, England, in 1987. It is still being tested at ANL.

The computer program PE2D solves the Poisson equation in two dimensions by using triangular finite elements and has the following parts:

- PP - An interactive graphic pre- and post-processor.
- ST - A magnetostatic solver.
- SS - A steady-state ac eddy current solver.
- TR - A transient eddy current solver.

The SS solver is used in designing electromagnetic casters.

To simulate a horizontal field caster, the cross-sectional geometry of the caster is first defined in terms of the material properties in each region, as shown in Fig. 2-2a. Region 2 is the liquid steel and, in general, has a different conductivity from region 3, the side guard. The eddy current return path is the copper shield plate, region 4. These three regions form the eddy current loop. The driving ac coil regions are 10 and 13. The ferrite yokes and pole of the magnet are regions 5 through

9. All other regions are air. The x and y coordinates of these regions and their magnetic and electrical properties are specified in the pre-processor PP. A finite element mesh is generated by PP. The solver SS then calculates the magnetic vector potential at all mesh points so that PP can plot the flux lines, as shown in Fig. 2-2b. Because of symmetry, only the right half of the magnet need be analyzed with the program.

Other quantities that can be calculated by PE2D include the following:

- Field values along lines or arcs can be output as tables or graphs at time t, or averaged over time.
- Values of current density can be calculated at any point in a conductor.
- Field values can be calculated along lines to get forces on conductors and steel.
- Current density, eddy current power, stored magnetic energy, and forces can be obtained through integration over areas.
- Absolute or relative field errors can be calculated for each triangle and selected ones can be displayed to show the "discretization" errors.

In summary, the capability of simulating electromagnetic devices on the computer has existed at ANL for more than 20 years. Much experience has been gained over the years in designing conventional and superconducting magnets, motors, generators, and other electromagnetic devices.

2.2 Stability of the Levitated Sheet

Designing a system that will overcome the magnetohydrodynamic (MHD) instabilities of the solidifying steel sheet is one of the most difficult problems associated with the development of an EM caster in either the horizontal or vertical configurations. No one has ever stably levitated a horizontal liquid sheet or confined a large-aspect-ratio vertical sheet. The technical feasibility of obtaining stability in either configuration is unknown at this time.

The two EM casting concepts under investigation are vertical and horizontal configurations. The conceptual design for the horizontal configuration is further advanced; hence, in what follows, MHD considerations will be addressed for horizontal castings. In the horizontal concept, stability is provided by means of inductance stabilization and flux compression. Inductance stabilization provides stability for the sheet as a whole, and flux compression provides stability against local disturbances of the sheet shape. Both stabilization methods have time constants significantly smaller than those associated with instabilities. The characteristic time associated with flux compression is in the microsecond range, whereas the fastest local instabilities occur in the magnetoinertial time scale, which is

(a)

(b)

Fig. 2-2. Horizontal Caster Design Modeled for Field Computation:
 a. Ferrite Element Regions.
 b. Magnetic Flux Plot.

in the millisecond range. The inductance time constant is typically less than a second, which is less than the residence time in the caster, even for the most optimistic cooling rates.

An overview of the stability of the horizontal caster is given in Sec. 2.2.1. A more detailed examination of the Rayleigh-Taylor instability follows in Sec. 2.2.2. A summary of experimental studies of liquid metal stability at ANL appears in Sec. 2.5.

2.2.1 Stabilization of the Horizontal Caster

2.2.1.1 Bulk Stabilization

The ANL concept for a horizontal caster uses inductance stabilization for bulk stability because a uniform field, produced by a uniform current sheet, provides no stabilization. In the ANL concept a constant voltage in a high-Q circuit drives the magnet current so that movements of the steel sheet are automatically compensated by changes in the current. Published analyses that show a lack of stabilization for a uniform field, e.g., Ref. 1, assume a constant current for the levitating magnet (see Sec. 2.2.2.).

2.2.1.2 Local Stabilization

The present concept for horizontal casting achieves local stabilization through flux compression between the solidifying steel sheet and a nearby conducting screen. If the screen is too far from the sheet, it will not provide good stability, particularly against the Rayleigh-Taylor instability. If it is too close, it produces large pressure drops and inefficiencies in the gas cooling system. With the limited design and analysis to date, the feasibility for a successful design that meets all constraints is still an open question. The necessity for operating in the vicinity of the high-temperature environment of the molten steel may make the successful design of such a screen more difficult.

2.2.1.3 Surface Wave Instabilities

Other levitational instabilities are associated with the interaction between the metal sheet and the cooling system. The production of waves by the passage of a cooling gas parallel to the steel sheet has been investigated in some detail both theoretically and experimentally at ANL. This work has provided constraints for the maximum gas velocity. In the present horizontal concept, the maximum velocity appears to be about 30 m/s, with a design value of 20 m/s recommended. An additional constraint in the present horizontal concept is the need to closely control the gas pressure on the top and bottom of the sheet. Without knowing all the possible MHD instabilities, one must guess at what the tolerances must be. Present estimates for the tolerance are 1% to 10% of the ferrostatic head before the difference affects levitational stability. While such control appears feasible in principle, it does place a constraint on the design of the cooling system.

2.2.2 Rayleigh-Taylor Instability with Electromagnetic Levitation

The Rayleigh-Taylor (RT) instability is a general instability of an interface between two fluids of different densities. It occurs when the light fluid is "pushing" the heavy fluid,² e.g., a heavy fluid above a lighter fluid with gravity acting down. This type of instability occurs in many different situations, including the overturn of the outer portion of the collapsed core of a massive star, laser implosion of fusion targets, and electromagnetic implosion of a metal liner. More commonly, the Rayleigh-Taylor instability is the mechanism for a fluid running out of an upside-down cup, even though the air pressure is more than adequate to keep it from falling.

In the present context, the Rayleigh-Taylor instability occurs when a slab of heavy fluid (liquid metal) lies on top of a slab of lighter fluid (air). This configuration is unstable. The opposite configuration, with air overlying the metal, is stable. In the horizontal EMCC context, the electromagnetic field must not only provide support against the downward force of gravity, it (or some other mechanism) must also provide restoring forces to prevent this basic Rayleigh-Taylor instability.

2.2.2.1 Analyses and Experiments for Electromagnetic Levitation

Many papers have presented analyses and experimental results of levitation melting concepts, a technology that has been practiced for some years now. Most of these are for a cylindrical geometry.³⁻⁸

The stability of massive conducting liquids levitated by ac fields has long been of interest.⁹ Toroidal geometries and meander coils have been suggested.¹⁰⁻¹¹ These geometries are essentially two-dimensional analogs of the basic circular coil method. They have a magnetic hole between conductors and rely on surface tension to keep the fluid from falling through the hole.

Sagardia¹² investigated the effects of an ac field in the asymptotic limit of infinite frequency (zero skin depth). He showed theoretically and experimentally that large objects could be stably levitated using two perpendicular ac magnetic fields of different frequency. Others¹³⁻¹⁴ also investigated such systems. The magnitude of the magnetic fields required for stability is considerably larger than that required to levitate a 6-mm thick sheet of steel. Such fields could be used by applying a partially opposing field on top; however, the heat input would be much larger than could be removed in a practical system. Garnier and Moreau¹⁵ discussed the effects of a finite conductivity for such applications. Stability is still maintained, but the required magnitude for the magnetic field increases as frequency decreases. This would not alleviate the overheating problem.

As a result of the levitation melting technology and other metallurgical processing concepts, investigators have studied the fluid motions induced within the fluid and on free surfaces. For RT instability problems, the internal flows are not important per se. However, they play an important secondary role in providing energy to perturb the system beyond that

considered in linear stability analysis--in many cases acting as an additional destabilizing force to gravity. There has been growing interest in the problem of understanding coupling between a free surface and an ac magnetic field.^{11, 15-18}

2.2.2.2 Magnetic Rayleigh-Taylor Instability

The basic Rayleigh-Taylor instability for horizontal slabs in the presence of a magnetic field has been discussed by several authors. Chandrasekhar¹⁹ provides a basic analysis of a nonviscous, infinitely conducting fluid when a dc magnetic field is applied either parallel or perpendicular to the direction of gravity. The basic restoring force, an equivalent of surface tension, is provided by the tension in the magnetic field lines. To explain the instabilities seen in some experiments,²⁰⁻²¹ Etay and Garnier²² have investigated the stability for a fluid in a dc magnetic field with an external current source.

Most of the work done on the magnetic RT problem has been with dc fields. DC magnetic fields are essentially independent of the form of the free surface. They react mainly on the velocity field in the bulk of flow or via some externally determined current flow. With a dc field, the induced current is proportional to the velocity of the liquid metal. The use of ac magnetic fields produces quite different phenomena. AC fields control the equilibrium shape of the free surface and react to perturbations of it. The surface and fields are closely coupled. The induced currents with an ac magnetic field are dependent on the frequency of alternation, and in many cases the effect of fluid velocity becomes a secondary consideration.

Related to the RT instability is the discussion of free surface behavior in the presence of a magnetic field.¹⁵

Consider two fluid half-spaces, separated by a horizontal interface at $z = 0$. We ignore viscosity and surface tension to concentrate on the action of a horizontal magnetic field parallel to the interface. We assume magnetic permeability is constant and the same for both half-spaces. We assume that, initially, a constant magnetic field permeates the space in the x direction. We also assume that the electrical conductivity is large enough that the magnetic diffusivity K_m can be ignored.

Analysis shows that disturbances perpendicular to the direction of the magnetic field are not influenced by the presence of the field. The instability for perturbations in this direction is the same as if no field were present. Physically, this makes sense in that when the surface distorts, the magnetic field lines are pushed in the same direction as the surface, but the field lines themselves remain flat. Without a bending of the field lines, there is no magnetic tension.

For disturbances parallel to the magnetic field, the effect of the field is the same as if there were an effective magnetic surface tension T_{mag} acting on the interface:

$$T_{mag} = \mu (H \cos \theta)^2 / k, \quad (9)$$

where θ denotes the angle between the magnetic field H and the wave vector k of the disturbance. We note that the magnetic surface tension is proportional to H^2 and also to the wavelength of the disturbance. In terms of the magnetic induction $B = \mu H$, Eq. 9 becomes

$$T_{\text{mag}} = (B \cos\theta)^2 / (\mu k). \quad (10)$$

If we incorporate fluid surface tension T as well, let $\theta = 0$, and ignore ρ_2 (the density of air relative to ρ_1 , the density of liquid metal), then the condition for stability becomes

$$g\rho_1 < Tk^2 + 2kB^2/\mu. \quad (11)$$

Again the system becomes unstable for short wave numbers (long wavelengths). A finite system can always be stabilized by making B sufficiently large. Note that the height of the slab to be levitated appears indirectly, through the B^2 term.

It is of interest to calculate the effective magnetic surface tension for a practical example using Eq. 10. Let $B = 0.01$ T = 100 G, $\lambda = 1$ m, and $\theta = 0$. Then

$$T_{\text{mag}} = 2500 \text{ N/m},$$

which is much larger than the 1.8 N/m of fluid surface tension for steel. This suggests that the magnetic field can help to stabilize against RT disturbances.

Assume that the fluid to be levitated is 0.25-in. (0.6-cm) thick and has a density of 7000 kg/m³. The rms magnitude of the magnetic field needed to levitate the slab is given by

$$\rho gh = B^2 / (2\mu_0), \quad (12)$$

which yields

$$B_{\text{rms}} = 0.0331 \text{ T} = 331 \text{ G}.$$

We now determine the critical wavelength that such a field can stabilize against. Ignoring fluid surface tension in Eq. 11, and combining with Eq. 12, we have

$$\lambda < 4\pi h. \quad (13)$$

For $h = 0.635$ cm, the critical wavelength is 8 cm.

In the ac case, only half of the field energy goes into the average term, and the magnetic surface tension and thus the critical wavelength would be reduced by a factor of two, in this case to 4 cm.

Note that in the horizontal caster, the presence of the side guards will keep the edges of the liquid metal sheet straight. Hence, any disturbance in the interior of the sheet parallel to the edges (perpendicular to the field) must be accompanied by a disturbance perpendicular to the edges (parallel to the field) of wavelength twice the sheet width or less, and so will be stabilized by the field.

2.2.2.3 Influence of Wavy Interface

Here we examine the effect of a sinusoidal disturbance of the interface on the behavior of the magnetic fields. The results can then be related to the stability equations that include the fluid behavior as described in previous sections. We continue to examine half-spaces. However, we examine the effect of a bottom conducting shield and show that, if such a shield is close enough to the levitated sheet, then it can stabilize against long wavelength disturbances.

It is cautioned that the results so far are indicative only. The real system does not consist of half-spaces.

The magnetic levitation pressure at the bottom of the half-space is given by

$$P_{\text{mag}} = (\mu/2) [(H_0 + h_x)^2 + h_y^2 + h_z^2], \quad (14)$$

where h_x , h_y , and h_z are the components of the field perturbation due to the wavy interface. To lowest order in the perturbed fields this becomes

$$P_{\text{mag}} = (\mu/2) (H_0^2 + 2H_0 h_x). \quad (15)$$

Analysis shows that, under a depression, h_x is positive and, thus, the total magnetic field increases. Similarly, below an elevation, h_x is negative and the total field decreases. The increase (or decrease) is proportional to ϵ , the amplitude of the waves in the interface. Hence, the field acts like a spring to return the interface toward equilibrium. This type of behavior is often termed "flux compression." We note that under most circumstances the field falls off as $\exp(kz)$ or $\exp(2\pi z/\lambda)$. Thus the flux is compressed within a depth λ of the interface. This suggests that the effective spring constant of the flux compression is larger for smaller λ , because a displacement ϵ then occupies a larger fraction of the volume available for compression. This implies a critical wavelength λ_c such that disturbances with wavelengths greater than the critical value are unstable. This was also

the result found by Garnier and Moreau¹⁵ in a more detailed analysis that included the fluid equations.

2.2.2.4 Solution with Infinitely Conducting Bottom Plate

To approach the experimental situation more closely, we must take into account the sheet of copper that is placed below the levitated metal. Sometimes this takes the form of a shield, and sometimes it consists of the driving coil of the magnet. We model the copper sheet as an infinitely conducting surface.

Consider the same problem as before, but now, in addition, we have a surface of a material with infinite conductivity located at $z = -a$. We now have an air gap in the region $-a < z < 0$ and a good conductor half-space for $z > 0$.

If the conducting shield is far away, then, except for the very largest wavelengths, $ka \gg 1$, and the shield will have no influence. However, for $ka \ll 1$ [i.e., for $\lambda \gg 2\pi a$ (say $\lambda > a$)], then the magnetic pressure is

$$P_{\text{mag}} = P_o(1 + 2\epsilon/a). \quad (16)$$

We note that a has taken the place of $\lambda/(2\pi)$. This suggests that if we make

$$a < \lambda_c/(2\pi) , \quad (17)$$

then the system will be stabilized against all long wavelength disturbances. Physically, the conducting plate forces the flux to be compressed into a volume with at most a height a . Subject to more detailed analysis, it is probably correct to assume that Eq. 17 could be directly substituted into a detailed fluid stability calculation. Thus, if $\lambda_c = 8$ cm for a 1/4-in. (0.6-cm) thick sheet of tin or steel, then $a_c = 1.3$ cm. From Eq. 13 and the following, $\lambda_c = 4\pi h$. This results in

$$a_c = 2h, \quad (18)$$

a result that can be derived from much more basic considerations.

2.2.2.5 Vibratory Stabilization

Wolf²³ showed that the RT instability can be suppressed by oscillating the fluids vertically, provided that viscosity of one of the fluids is sufficient to suppress the development of parametric resonances due to otherwise rapidly growing short wavelength modes.²⁴ Wolf²⁵ later showed that the effect of compressibility was usually negligible. The condition for stability²³ is

$$b_m/g > 2^{1/2} \omega/\Omega_k,$$

where b_m is the maximum instantaneous acceleration due to the oscillation of radial frequency ω , and Ω_k represents the eigenfunctions (growth rates) of possible standing surface waves. For rectangular cross sections of horizontal width D , neglecting the density of the lighter fluid results in the lowest value for Ω , given by

$$\Omega^2 = g/D.$$

Therefore,

$$b_m/g > \omega [2D/(\pi g)]^{1/2}.$$

For $D = 1$ m, $b_m/g \sim \omega/4$. So with 60 Hz oscillations, an acceleration many times λ is needed to achieve stability. If delivered by the magnetic field, this would cause very large amounts of heating.

Other investigators also have analyzed this type of vibratory stabilization.²⁶⁻²⁷

2.2.2.6 Dynamic Feedback

Successful suppression of the RT instability in a two-dimensional system has been experimentally demonstrated using solenoidal magnets connected by feedback to position sensors.²⁸⁻²⁹

Using electrohydrodynamics, Melcher³⁰ and Melcher and Warren³¹ successfully demonstrated the use of feedback to stabilize against RT disturbances in a three-dimensional system.

2.3 Magnets for Horizontal Casting

The horizontal casting concept requires a uniform horizontal magnetic field below the liquid metal sheet and a much-reduced field or no field above the sheet. Much of the effort of the project was concentrated on the design of a magnet for a horizontal bench-scale caster and on the design and fabrication of a test magnet embodying the same concept. Some thought was given to how the concept would scale to a production caster.

Key components of the conceptual design for the horizontal caster include:

- A magnet that levitates the molten metal by the interaction of the horizontal HF field and the eddy currents generated within a skin depth of the bottom of the levitated sheet;
- A cooling system;

- A feed system with flow control by mechanical and electromagnetic means; and
- Heat shields that protect the magnet coils and core assembly.

In support of efforts to develop the horizontal bench-scale caster, a test magnet was designed and fabricated for low-temperature levitation experiments. The test magnet was designed to have a very uniform horizontal field and to simulate the conceptual design of the horizontal caster magnet. The primary purpose of the test magnet was to investigate liquid metal MHD stability. Other purposes include verification of calculated current and flux distribution, verification of eddy current losses, and optimization of magnetic circuit components (side guards, heat shields, eddy current shields, etc.). Test results with this magnet are reported in Sec. 2.5.

2.3.1 Magnet Analysis and Design

Much of the analysis carried out was devoted to the horizontal bench-scale caster. Also, some of the detailed design of the test magnet, particularly the power losses in the excitation coils and the eddy-current shielding of those coils, should apply to the horizontal bench-scale caster. Description of the coil design appears in Sec. 2.3.3 and is not repeated here.

2.3.1.1. Design of Choice

Levitating a sheet of molten metal requires a uniform horizontal field below the metal and a much smaller field above it. A conceptual magnet design to produce such a field is shown in cross section in Fig. 2-3. With only the ac coils, ferrite yokes, and poles present, this kind of magnet is known as a "window frame" or "picture frame" magnet and has been used extensively in particle accelerators. It produces a very uniform horizontal magnetic field in the region between the bottom and top coils, directed from pole to pole. The field falls off linearly across the coil and reverses direction in the yoke. The current is perpendicular to the plane of the figure and of opposite directions in the top and bottom ac coils. These two conductors are connected at the ends of the magnet in a suitable way.

The liquid steel and side guards provide parallel paths for the eddy current induced in them. They are connected to the copper shield at the ends of the magnet and form a single-turn eddy current loop in the magnet. As the ac coil tries to drive magnetic flux through the loop, nearly all of the flux is excluded by the currents induced in the loop. Hence, the magnetic field between the copper shield and liquid steel is small in comparison to the field below the liquid steel. This produces a uniform vertical force on the liquid steel except near the sides. If the liquid steel extended from pole to pole, the vertical force would be extremely uniform.

2.3.1.2 Side Guards

The side guards should consist of material with electrical conductivity much like the liquid steel. They essentially extend the sides of the liquid steel to the poles, except for the small air gap between

side guards and liquid steel. Computer modeling of this geometry has shown that the vertical force on the liquid steel can be made uniform near the steel edge by adjusting the relative vertical position of the liquid steel and side guard. Further refinements in the uniformity of the field could be made by driven side guard coils, not shown in Fig. 2-3.

Fig. 2-3. Cross Section of Conceptual Magnet Design for Horizontal Caster

2.3.1.3 Current Return Path and Current Contacts

If there is to be net levitation with the horizontal caster, the currents induced in the bottom skin of the liquid metal sheet must have an external return path. The copper shield provides that return path.

The liquid metal, copper shield, and the upstream and downstream current contact can be thought of as comprising the one-turn secondary of a transformer, the magnet coils being the primary. There will be no field above the sheet if the skin depths in the liquid steel sheet and copper shield are small compared to their thickness, if the resistance of the current contacts is low, and if the entire current loop lies inside the good field region of the magnet. If one of these conditions fails to hold, there will be some field above the steel. Some field may be useful to suppress wave motion and produce a good surface quality on the upper surface of the steel.

The current density in the bottom skin of the levitated steel sheet must be the same over the sheet width. Therefore, any variation in contact resistance and/or in contact uniformity over the width of the steel sheet would degrade the operation of the caster.

The uniformity of the field below the sheet and the small ratio of skin depth to sheet thickness tend to force a uniform current density. Large variations in contact uniformity might overcome this tendency.

If so, uniform current density can be imposed over the width of the liquid sheet by placing a large number of uniformly spaced contacts on the solidified surface of the sheet. The distance from these contact points to the point where the metal is still liquid is large enough for the current to diffuse to uniform current density. Equal current sharing between the contact points may need to be forced. This can be done by connecting in series with each contact a reactor with an impedance much larger than the resistance change due to contact variations. A better solution is mutually coupled reactors; they will induce equalizing voltages in the reactor windings, and thus force current sharing.

To conserve power, the upstream and downstream electrical contacts to the steel sheet should be as close together as practical. The development of an upstream contact is seen as challenging but clearly feasible. This contact might be, for example, a high melting point metal encrusted with steel inserted into the liquid metal of the tundish. Alternatively, it could be in the liquid metal further downstream but far enough upstream that flow perturbations caused by the contact would die out before reaching and destabilizing the levitated liquid.

Downstream, the metal must have a skin strong enough to contain the pressure of the contacts on the bottom of the steel sheet and the counter force applied on the top of the sheet by a roller. It may not be practical or desirable to arrange the downstream contact mechanism inside the magnet.

The downstream contact could consist of rollers or closely spaced brushes. The solidified sheet can pass through rollers at a temperature of 1200°C , or possibly higher.³² Oxidation of the surface would increase the contact resistance between the sheet and the rollers; the resistivity of wustite (FeO), the major part of the oxide coating, is $25 \Omega\cdot\text{cm}$ at 1300°C and $100 \Omega\cdot\text{cm}$ at 1100°C .³³

The feasibility of the downstream contact, rollers or brushes, can only be determined by experiment.

The effect of the electrical contact resistance on levitation was studied using a simple circuit model. In the model, the upstream and downstream resistances are combined into a single resistance R_o . The currents on the outside surface (bottom of steel, top of copper shield) and inside surface (top of steel, bottom of copper shield) of the loop are treated as two currents that combine to flow through the contact resistance. The time-varying flux driving each current and the resistances and self- and mutual-inductances are determined by the geometry. The amplitude and phase (actually the real and imaginary parts) of each current are variables.

For a steel length of 5 m, all within the magnet, a width of 1 m, and a frequency of 100 kHz, the model predicts that levitation is unaffected by a contact resistance of 0.1Ω or less, but that no levitation occurs if the contact resistance is about 1Ω . The resistivity values for wustite given above are consistent with a resistance well below 1Ω . Predictions of the model show that the critical resistance varies directly with

the length between contacts, inversely with the width of the sheet, and directly with the frequency.

Confidence in these results is shattered when power losses at the contact are considered. The model assumes that the magnet power supply can provide sufficient current to the magnet to provide a field of 0.03 T (300 G), no matter what the power dissipation in the caster. Also, the model does not treat the consequences of heating at the contact. From the contact resistance and the currents computed with the model, the power dissipation at the contact can be found. For a resistance of 0.1 Ω , acceptable from consideration of levitation requirements, the power loss is 45 MW at 25 kHz and 56 MW at 100 kHz. The corresponding losses per centimeter of contact length are 450 and 560 kW/cm at 25 and 100 kHz, respectively. These heating levels are unacceptable. An acceptable heating level would require a contact resistance significantly less than 0.1 Ω . At this time, it is not apparent how such a low contact resistance would be achieved.

2.3.1.4 Power Supply Requirements

Operation of the bench-scale caster requires a power supply of 300 kW capability. Electromagnetic heating increases with increasing frequency, but stable levitation becomes easier with increasing frequency and is probably unobtainable at 10 kHz and below. Frequencies of 25 kHz, 50 kHz, and 100 kHz are required to fully test the horizontal caster. Operation at 200 kHz or higher is probably essential for the vertical caster.

2.3.1.5 Alternative Magnet Geometries

Other ways of achieving the conditions required for horizontal casting (uniform field below the metal sheet, reduced field, or no field above sheet) have been studied. One such variation is shown in Fig. 2-4a. In this configuration, the top half of the magnet is removed and the ac coil is wound around the bottom yoke. The side poles are extended downward past the copper shield. The eddy current loop formed by the liquid steel, side guards, and copper shield is now on the outside of the loop formed by the ac coils. In Fig. 2-3, the eddy current loop was inside the ac coil loop.

Another variation of the geometry is shown in Fig. 2-4b. The ac coil is wrapped around the bottom yoke and produces a uniform field below the liquid steel. The eddy current loop prevents a large magnetic field from appearing above the liquid steel. One disadvantage of this geometry is that it produces a large leakage flux below the lower coils. To prevent this, the magnet can be enclosed in a copper shield as shown in Fig. 2-4c.

If a larger field is desired on top of the liquid steel, two magnets can be used, with one magnet placed on top of the other as shown in Fig. 2-4d. The ac coil wrapped around the top yoke would have a smaller current than the ac coil wrapped around the bottom yoke and adjusted to produce the correct levitating force.

The magnet can also be driven with dc coils, as shown in Fig. 2-5. In this configuration, the magnet produces a large uniform field on

(a)

(b)

(c)

(d)

Fig. 2-4. Alternative Magnet Designs: (a) with Open Top, (b) with Driver Coil on Bottom Yoke, (c) with more Shielding, and (d) with one Magnet on Top of Another.

Fig. 2-5.

Conceptual Horizontal Caster
with DC Fields and Currents

the top, bottom, and inside of the liquid steel. A small dc current in the liquid steel will provide the necessary levitating force. An alternative configuration of the dc magnet would use the liquid steel as the top dc coil. This reduces the magnet geometry to a single loop. Although dc operation produces less EM heating, it is harder to stabilize.

2.3.2 Extension to a Production-Scale Caster

The concept for horizontal casting can be extended to a production-scale caster, but some additional considerations arise because of the greater width of the liquid steel sheet and because of the greater length of the magnet that accompanies a faster casting velocity.

A sheet width of up to 2 m may be desirable for a production caster, requiring a comparable coil separation. End effects could cause a transition region of 0.3 m or so between the magnet end and the beginning of the "good-field" region at each end of the magnet. End guards on each end of the magnet could reduce these end regions, but the end guards themselves could interfere with the feed system and the cooling system for the steel leaving the magnet.

The combination of realistic cooling rates and high casting velocities (0.3 to 1 m/s) could require magnets 10-m long or longer. Such magnets are technically feasible (magnets 30-m long have been built at ANL and elsewhere), but the capital costs and operating costs (electrical power) of such magnets begin to influence the total cost of casting for magnet lengths greater than 10 m. In the parametric studies of production casting, magnet lengths were limited to 10 m or shorter.

There may be reasons to make the height of a production caster greater than that of a bench-scale caster. That too is feasible, as long as a conducting screen is located a small distance below the liquid steel sheet to maintain flux-compression stabilization (see Sec. 2.2).

2.3.3 Design and Construction of Test Magnet

For the experimental study of several stability questions, we built and operated a test magnet with a design similar to that of the bench-scale caster.

Figure 2-6 is a photograph of the test magnet. A schematic cross section of the magnet is shown in Fig. 2-7; its ferrite core is 30-cm long. The aperture for experiments is 20-cm wide by 13-cm high. The good-field region, with a field error $|\Delta B/B_0| < 0.5\%$, is 15-cm long. The magnet coils are made from pairs of copper sheets 7.6-cm wide and 0.025-cm thick. These sheets are arranged in six layers, each layer having 28 pairs of insulated sheets. By connecting the layers in series and/or in parallel, we can change the magnet turns between one, two, three, and four to match different experimental setups. An eddy current shield surrounds the coil to reduce losses due to leakage flux. Figure 2-8 shows the magnet core (on the left), an experimental setup for liquid tin (right), and the magnet coil (in the background).

Fig. 2-6. Photograph of Horizontal Test Magnet

The calculated losses in a sheet of tin (0.6 cm x 16 cm x 30 cm) levitated inside the magnet by a 100 kHz field are ~7.7 kW; for liquid steel, the losses would be ~33 kW.

The remainder of this section addresses eddy current losses in the magnet excitation coil. These losses are calculated for test magnet coils wound from copper sheets and from LITZ wire; they are also estimated for a coil wound from water-cooled copper tubing. It will be shown that, at 100 kHz, these losses would be ~150 kW, which is 19 times larger than the losses in a levitated sheet of tin and ~380 times larger than the losses caused by the magnet excitation current. These losses are reduced significantly with an eddy current shield.

2.3.3.1 Losses in Thin Copper Sheets Due to Eddy Currents

By winding the coil from a large number of thin, insulated, parallel-connected copper sheets, as shown in Fig. 2-9a, the I^2R losses

Fig. 2-7. Cross Section of Schematic for Horizontal Test Magnet

Fig. 2-8. Photograph of Test Magnet Core (left), Experimental Insert (right), and Magnet Coil (behind)

due to the high-frequency excitation current can be made relatively small (<500 W). However, these sheets are exposed to magnetic fields parallel to the surface of the sheets. As shown in Fig. 2-9b, the flux, ϕ_2 , rises from zero, at the coil surface next to the magnet core, to its maximum value at the inside of the coil. For a typical copper sheet, the current path of the

Fig. 2-9. Magnet Excitation for Horizontal Caster:
a. Cross Section and Flux Path.
b. Plot of Flux Along Center Line.

excitation current (which causes relatively small losses) and the path of eddy currents due to leakage flux (causing large losses) are shown in Fig. 2-10. With the coordinate axis in the middle of the copper sheet and a sinusoidally varying field of amplitude H_0 applied parallel to its surface, the rms value of the field B is given by³⁴

$$\vec{B} = \mu \vec{H} = \mu_0 H_0 \frac{\cosh \beta(1+j)y}{\cosh \beta(1+j)d/2}, \quad (19)$$

where

$$\beta = (\mu \pi f \rho^{-1})^{1/2}$$

μ_0 = permeability of space

f = frequency
 ρ = resistivity
 j = $(-1)^{1/2}$.

The rms current density is

$$|\vec{J}| = J = \beta \sqrt{2} H_o \left(\frac{\cosh 2\beta y - \cos 2\beta y}{\cosh \beta d + \cos \beta d} \right)^{1/2} \quad (20)$$

Figure 2-11 illustrates the distribution of the amplitudes of J and B over the cross section of the sheet.

The peak value of the total sheet flux is given by

$$\sqrt{2} |\phi| = \frac{2 \mu b H_o}{\beta} \left(\frac{\cosh \beta d - \cos \beta d}{\cosh \beta d + \cos \beta d} \right)^{1/2} \quad (21)$$

The average flux density in the sheet is defined as the peak value of the flux divided by the cross-sectional area, bd ,

$$B_m = 2 \mu H_o \frac{1}{\beta d} \left(\frac{\cosh \beta d - \cos \beta d}{\cosh \beta d + \cos \beta d} \right)^{1/2} \quad (22)$$

The eddy current losses in the volume, V , of the sheet can be calculated from Eq. 20 if we express H_o with the average flux density from Eq. 22:

$$P = V \pi^2 f^2 d^2 B_m^2 F(\beta d) / 6\rho. \quad (23)$$

The function

$$F(\beta d) = \frac{3}{\beta d} \frac{\sinh \beta d - \sin \beta d}{\cosh \beta d - \cos \beta d} \quad (24)$$

is plotted in Fig. 2-12. For copper sheets at 100 kHz,

$$\beta d = d/\delta = 0.025/0.021 = 1.19.$$

For small values of βd , Fig. 2-12 indicates that $F(\beta d) \sim 1$. Equation 23 can then be simplified to

$$P = V \pi^2 f^2 d^2 B_m^2 / 6\rho. \quad (25)$$

The losses in a copper sheet that is 15.2-cm wide, 30-cm long, and 0.025-cm thick in a peak field of 412 G at 100 kHz are, from Eq. 25, 1156 W. For the 28 sheets in parallel that make up one layer, the losses are 32.4 kW.

Fig. 2-10.

Current Paths and Fields in Copper Sheet

Fig. 2-11.

Current and Field Distribution in Copper Sheet

Fig. 2-12.

Variation of $F(\beta d)$ for Eddy Current Losses in Metal Sheets

The six layers which make up one-half of the coil have nominal flux densities of 35, 112, 187, 262, 337, and 412 G, as illustrated with the dashed lines in Fig. 2-9b. The corresponding eddy-current losses in the six layers at 100 kHz are 0.27, 2.4, 6.7, 13.1, 21.7, and 32.4 kW. This brings the total eddy current coil losses induced by leakage flux to 153 kW. The coil losses at various operation frequencies are:

f	10	25	50	100	200	300	kHz
P	1.53	9.6	38.2	153	612	1280	kW

2.3.3.2 Losses Due to Excitation Current

The magnet coil is designed to operate continuously at frequencies ≤ 100 kHz. At 100 kHz, the skin depth for copper is 0.021 cm. By winding the coil with copper sheets of effective width $w = 15.2$ cm and thickness $d = 0.0254$ cm, eddy current losses for the magnetizing current are negligible at 100 kHz. For a magnetic field of $B = 350$ G (rms), the magnet requires excitation ampere-turns of 5.56 kA. The flux path in the magnet core is ~ 42 -cm long and has a relative permeability of $\mu_r > 4000$; it requires less than 10 ampere-turns. Losses due to the magnet excitation current are, with a coil resistance of $R \sim 13 \mu\Omega$, $I^2R = (5.6 \text{ kA})^2 \times 13 \mu\Omega = 407 \text{ W}$. This is 376 times smaller than the losses due to leakage flux calculated in Sec. 2.3.3.1.

2.3.3.3 Eddy Current Shields to Reduce Leakage Flux Losses

Enclosing the excitation coil with a copper shield, as shown in Figs. 2-13a and 2-14a, prevents leakage flux from entering the coil by means of eddy current shielding. The magnet flux distribution is now as shown in Fig. 2-13b. Losses in the ~ 0.4 -cm thick copper shield were calculated with PE2D as 3.1 kW for 100 kHz and $B_m = 494$ G. Inside the shield, each of the six layers of the excitation coil is exposed to magnetic fields generated by the current flowing in the other five layers. Figure 2-14b illustrates the resulting magnetic fields, which cause eddy current losses of 34.4 kW in the coil layers.

Enclosing each layer with a copper shield, as illustrated in Fig. 2-15, eliminates these mutual fields and reduces the eddy current losses in the coil to 7.6 kW.

With operation at 350 G and 100 kHz and for an arrangement as shown in Fig. 2-14a, the total losses in the shield and in the coil layers are 37.5 kW; for the one shown in Fig. 2-15, the losses are 9.9 kW.

2.3.3.4 Coil Wound from LITZ Wire

Eddy current losses due to core leakage flux can also be reduced by winding the coil with a large number of insulated wires connected in parallel, the so-called LITZ wire. These losses have been calculated for parallel-connected wires that carry the same current density as the copper sheets in Sec. 2.3.3.3 and with a wire diameter equal to the thickness of the sheets.

Fig. 2-13. Magnet Excitation with Coils in Eddy Current Shield

Fig. 2-14. Six-Layer Coil Enclosed by an Eddy Current Shield:
 a. Arrangement of Layers.
 b. Field in Each Layer Produced by Currents in Other Layers.

With a nominal flux density distribution in the six layers of the coil of 35, 112, 187, 262, 337, and 412 G, the total coil losses at 100 kHz are 113.7 kW; they are distributed as follows:

layers	1	2	3	4	5	6	
P	0.40	3.6	10.0	19.5	32.2	48.0	kW

Fig. 2-15. Six-Layer Coil with Each Layer Enclosed by Eddy Current Shield:
a. Arrangement of Layers.
b. Field in Each Layer Produced by Current in That Layer.

For different frequencies, the losses due to leakage flux are:

f	10	25	50	100	200	300	kHz
P	1.14	7.1	31.3	113.7	455	1032	kW

These losses are 74% of the losses calculated for the coil wound from thin copper sheets. Therefore, LITZ wire does not offer a much better solution than the thin copper sheets of Sec. 2.3.3.3 and would also require an eddy current shield.

2.3.3.5 Coil Wound from Water-Cooled Copper Tubes

Even with shielded layers, the eddy current losses due to leakage flux (> 9.9 kW at 100 kHz) are much larger than those due to the excitation current (> 0.5 kW at 100 kHz). Therefore, the excitation coil for the bench-scale magnet design was made from water-cooled copper tubes enclosed by a shield. The tube diameter and wall thickness were chosen to minimize the total losses; the excitation current losses were increased to reduce the coil volume and, with it, eddy current losses due to leakage flux.

2.3.4 Design and Construction of the "Head-Start" Magnet

The "Head-Start" magnet was designed and fabricated from readily available tape-wound cores. The magnet was used to apply a horizontal magnetic ac field to the top surface of the liquid metal, as shown in Fig. 2-16. The ac magnet coil was designed to match the voltage and current output of an existing portable 10 kHz, 30 kW motor generator set. The coil was wound on the top yoke of the magnet. A copper shield plate at the top of the pole edge confined the magnetic field to the region between the poles above the liquid metal. Further copper shielding on the outer surfaces of the tape-wound cores and ac coil prevented leakage flux around the magnet. The eddy current loop consisted of the liquid metal, side guards, and copper plate on the bottom.

The experiments performed with the "Head-Start" magnet are described in Sec. 2.5.1.

2.4 Design Analysis for Vertical Casting

For vertical casting, the problems of confinement and levitation can be analyzed separately, and hence instabilities should be controllable in ways not available for horizontal casting. Moreover, the vertical caster has the advantage that the eddy currents all form closed loops in the steel sheet. There is no need for an external current return path and the troublesome electrical contacts described in Sec. 2.3.1.3.

Only a small effort was expended on vertical casting. Electromagnetic and liquid metal instabilities have scarcely been considered. Only bench-scale casting of a sheet having a width of 15 to 30 cm and thickness of 6 mm has been studied, but changing the thickness of the sheet appears easier with a vertical caster than with a horizontal one.

Three concepts for electromagnetic containment and levitation were explored and are described here. In the first, described below in Sec. 2.4.6, containment is provided by a high-frequency stationary magnetic field, and levitation is achieved by having the field increase downward to counteract an increasing ferrostatic head. Despite this method's advantages of simplicity and self-centering, the large electromagnetic heating it entails renders it infeasible.

In the second concept, described in Sec. 2.4.5, both confinement and levitation are provided by a high-frequency magnetic field traveling upwards. With this method, the electromagnetic heating is less, but still troublesome.

In the concept of choice, illustrated in Fig. 2-17 and described in Sec. 2.4.1-2.4.4, the sheet is contained by a high-frequency stationary magnetic field of low amplitude and levitated by a low-frequency traveling magnetic field that fully penetrates the liquid metal sheet. Electromagnetic heating from the containment and levitation magnets is not excessive. Near the edge of the sheet, the levitation force diminishes, and additional means for edge support are needed.

The vertical casting concept requires three distinct kinds of magnetic fields, namely:

- (1) A high-frequency, low-amplitude field to provide containment of the liquid metal sheet (Sec. 2.4.1).
- (2) A low-frequency traveling field that, over most of the width of the liquid metal sheet, offsets the effect of gravity (Sec. 2.4.2).
- (3) A high-frequency traveling field to offset gravity near the edges of the sheet (Sec. 2.4.3).

All three of these would be needed for the experiments on levitation, confinement, and casting.

Fig. 2-16. Design of the Head-Start Magnet

2.4.1 High-Frequency Containment Field

The high-frequency field is used to define the surface of the molten metal and confine the molten metal within that surface. The frequency is chosen to produce a skin depth that is a small fraction of the thickness of the sheet. The field is spatially uniform over the surface of the metal and parallel to it. One geometry of coil and steel to do this is shown in Fig. 2-18. The "race track" coil completely surrounds the molten sheet and produces a vertical high-frequency field at the surface of the metal. The horizontal eddy currents in the surface of the metal perimeter interact with the vertical field to produce a horizontal force directed normally inward. This contains the molten metal. A typical frequency would be in the range from approximately 100 kHz to 400 kHz.

An alternative configuration of the coil could have the coil conductors on each side of the molten metal, carrying current in the direction of movement of the liquid metal. These conductors would be connected at the top and bottom of the caster. This coil produces a uniform horizontal magnetic field and vertical eddy currents in the molten metal. The interactions of the eddy currents and field produce a compressive force on the molten sheet.

In either coil configuration, the high-frequency coil is placed inside the low-frequency coil to reduce the power losses in the copper.

Fig. 2-17. Design of the Vertical Caster. This figure shows the steel sheet (40), the high-frequency containment coils (6), the low-frequency coils (16, 18, 20) and poles (22) for levitation, and the high-frequency coils (30) for edge support. For clarity, the ferrite core of the edge support coils is not shown.

Fig. 2-18. Coil, Yoke, and Liquid Metal Sheet for the High-Frequency Containment

2.4.2 Low-Frequency Traveling Magnetic Field

For this caster, the low-frequency traveling magnetic field must produce a uniform body force in the molten metal. This body force is used to reduce or cancel the ferrostatic pressure head or may be used to push the metal upwards against gravity. The effect is similar to that of a linear synchronous motor, which is used to propel trains and other devices, or an electromagnetic pump for liquid metals.

2.4.2.1 Design of Choice

A design study was made of the geometry of coils and steel required to produce a uniform body force on the liquid metal. The results of the study on a section of one wavelength of the traveling wave, located far from the ends of the magnet, yielded the geometry shown in Fig. 2-19. The magnet section consists of 10 steel teeth with tapered caps attached to a steel yoke to provide a low reluctance path for the magnetic flux. Three layers of coils are positioned in the slots between the teeth, each layer being 120 degrees different in phase from the other two layers. Each layer consists of a "race track" coil with current density j_1 , "nested" inside another "race track" coil with current density j_2 , where $j_1 = 0.618 j_2$. These "nested" pairs of coils are positioned to give the best approximation of a cosine distribution of current using two coils. Hence, this arrangement gives the best sinusoidal field distribution along the vertical length of the liquid metal. This, in turn, produces the most uniform body force on the liquid metal.

For the magnet to have a high efficiency, the distance between the molten metal centerline and the tooth caps must be one tenth of a wavelength or less. As this distance increases, the magnetic flux tends to circle the conductors, instead of passing through the molten metal, and becomes less efficient. Another consideration is the choice of frequency for the coils. The design study showed that a frequency in the range of 10 to 100 Hz would limit the horizontal force to a small fraction of the vertical force. This range of frequencies also produced the most uniform vertical force on the liquid metal. Because of its ready availability, 60 Hz was chosen.

2.4.2.2 Magnet End Effects

The analysis described above represented one wavelength of the magnet, far from the ends. Some preliminary analysis of the end region showed a deterioration of the uniform body force near the end of the magnet. Time did not permit design studies to be made to determine how the body force could be made more uniform in the end region of the magnet.

2.4.2.3 Magnet Edge Effects

The eddy currents produced in the molten metal by the traveling magnetic field appear as shown in Fig. 2-20. The horizontal component of the eddy currents interacts with the horizontal magnetic field to produce the vertical force on the molten metal when not near the edge of the sheet. Near the edge of the sheet, the eddy currents are mostly vertical and

Fig. 2-19.
Design of Coils and Yoke for
Low-Frequency Levitation Magnet

tend to produce a horizontal force instead of vertical. This problem will be addressed in Sec. 2.4.3.

2.4.2.4 Other Design Options

A simpler design for a traveling wave levitation magnet is shown in Fig. 2-21. This design does not have the teeth and caps shown in Fig. 2-19 and is less efficient. In this design, the placement of the coils and relative current densities needed to produce a sinusoidal current distribution are more important. However, the construction is much simpler.

2.4.3 Edge Support by High-Frequency Traveling Fields

Because the horizontal component of current density J_x is zero at the edges of the liquid steel, the traveling field will provide no levitation there. Moreover, it will produce reduced levitation over a distance of approximately $k^{-1} = \lambda/2\pi$ from the edge, where λ is the wavelength of the traveling field. Variation of the upward magnetic force per unit volume F_m is given by

$$F_m = B_y J_{ox} [1 - \cosh kx / \cosh (kw/2)], \quad (26)$$

Fig. 2-20.

Eddy Current Pattern in Levitated Sheets. Because the currents are vertical near the edge, no levitating force occurs there.

Fig. 2-21.

Alternative Design for Traveling Field Magnet for Levitation

where B_y is the LF field independent of x , w is the full width of the sheet, x is measured from the middle of the sheet, and J_{ox} is the LF current density induced by B_y when $kw/2 \gg 1$.

An HF traveling magnetic field at the edges of the steel sheet can provide levitation to overcome the reduced levitation there from the LF field. Section 2.4.3.1 shows how magnets such as that in Fig. 2-22 can generate such a field. The combined fields yield a levitation force that is uniform from edge to center to within a few percent or less. Electromagnetic heating by these magnets is expected to be high.

Fig. 2-22. Conceptual Design of HF Traveling Wave Magnet for Edge Support

Alternatively, a strip of high conductivity in electrical contact with the edge can lead to uniform levitation. This solution is probably infeasible for production casting, but may simplify early experiments on vertical casting and may be acceptable for some applications. It is described in Sec. 2.4.3.2.

2.4.3.1 High-Frequency Edge Coils and Net Levitation

The third magnet system has HF traveling field coils that levitate the edges of the sheet. The coils were modeled by the ribbon geometry shown in Fig. 2-23, and the parameters were varied to give the desired field and force pattern. The field in air was calculated by the Biot-Savart law.

Section 2.4.5 describes the levitating force from an HF traveling field that does not vary with x . Here, the x variation is included; x is measured from the center of the sheet and increases along the steel

Fig. 2-23.

Single-Filament Model of HF Edge Support System. Only one phase is shown.

sheet. The variable z increases vertically upward; y is perpendicular to the steel; $y > 0$ in the steel, $y < 0$ in the air.

Induced currents and fields are incorporated by modeling, not the entire coil but the portion in the air ($y < 0$) and its reflection in the surface of the steel ($y = 0$). Recall that a mirror is a conducting surface that reflects an HF traveling EM field.

Consider first the field in the air. All three components (B_x , B_y , and B_z) have the z variation of a traveling field: $B_z \sim \cos(\omega t - kz)$, B_x and $B_y \sim \sin(\omega t - kz)$. In order that the force be largest near the edge (large x) and die out near the center of the steel (small x), the components B_x , B_y , and B_z are all given an exponential variation in x , $\exp(\gamma x)$, with γ to be determined. The surface of the steel, $y = 0$, is a plane of symmetry. Hence, B_x and B_z are independent of y near $y = 0$, and $B_y \sim \beta y$. We shall see that the levitating force is proportional to β .

Inside the steel, all components of the field (and of the current density J as well) decrease in amplitude as $\exp(-y/\delta')$ and vary in phase as y/δ . For the traveling field, these two skin depths, δ and δ' , are not exactly equal. Their geometric mean is the classical skin depth δ_0 , and their difference can be related to the y variation outside the steel, β .

With the approximation that $\delta = \delta' = \delta_0$, the levitating force per unit area is found to be

$$F_x/A = - \beta \delta_o B_{zo}/8 \mu_o, \quad (27)$$

and the pressure is

$$F_y/A = (B_{xo}^2 + B_{zo}^2)/4 \mu_o, \quad (28)$$

where B_{xo} and B_{zo} are the amplitudes of B_x and B_z , respectively.

Parameters for the ribbon coil are the half-pitch (half-wavelength) c , the ribbon width w , coil length b , and coil half-widths a and f at the inside and outside ends of the coil, respectively (see Fig. 2-23). In Fig. 2-23, the half-widths a and f are equal.

Desired results for the force are that

- (1) The amplitude of the force should be independent of z , and the phase should vary linearly as z .
- (2) The coil position should be near the edge of the liquid metal sheet.
- (3) The levitating force should increase with x to offset the declining force from the LP coils, as given by Eq. 26.
- (4) The ratio of pressure to levitating force, as given by Eqs. 27 and 28, should be small.

Parameter values $a = 7.5$ cm, $b = 15$ cm, $c = 11.25$ cm, $f = 12.5$ cm, $w = 2.5$ cm satisfied the first three of these four criteria. In particular,

- (1) The distance from the edge of the sheet to the coil is only 2 cm. See Fig. 2-23.
- (2) The maximum variation of combined LF and HF force across the sheet is only $\sim 2.5\%$ and can be improved even more. See Fig. 2-24.
- (3) The ratio of pressure to lifting force is less than 20 over most of the sheet (less than 70 everywhere). But that ratio is still too large.

Some other problems in addition to the force ratio remain:

- (1) The best coil geometry yet found requires a peak current of 60 kA, a peak field of 7,000 G in the z direction, and a peak field gradient of 30 G/mm in the y direction.
- (2) The HF magnets (three phase) and LF magnets (three phase) must be arranged to avoid mechanical interference with each other. See Fig. 2-17.

- (3) The expression relating the fields and forces inside the liquid metal to the fields outside were obtained under the assumption that all three components of field varied the same way (exponentially) in x . The field components found with the computer model do not all vary the same way, which raises doubt about the validity of the results.

2.4.3.2 Edge Support with Conducting Strip

In some experimental situations, it may be convenient to have the edges of the liquid metal in contact with a high conductivity metal strip as shown in Fig. 2-25, rather than to construct the edge support magnets described above.

With the strip, the eddy currents in the steel may flow into the strip to turn around there rather than in the liquid metal. In fact, the eddy currents, and hence the levitating force, can be made to increase, decrease, or remain constant near the edge, depending on the conductivity and width of the strip. A uniform force results for liquid tin and a copper strip if the strip width is 1.4 cm for an LF field pitch of 10 cm, or 5.6 cm for a pitch of 40 cm.

2.4.4 Consistent Design

The analyses of the three kinds of magnets described above were done at different times and under different assumptions about the magnet geometry. There was no opportunity to repeat these analyses with a consistent set of assumptions. In this section, the parameters for a consistent design are discussed. Requirements on the field of the levitation magnet impose constraints among the dimensions of the caster.

2.4.4.1 Pole Separation and Pole Pitch

The most promising geometry for the levitation magnets (a tooth, slot, and pole-cap design) is described in Sec. 2.4.2.1. The pole pitch (field wavelength) is 0.2 m, and the gap between the pole caps is 40 mm.

In practice, that gap must accommodate the high-frequency coils as well as the sheet of molten metal. (It is much better for the high-frequency coils to experience the low-frequency field than vice versa.) The gap between the pole caps should be increased, say to 80 mm, to accommodate the high-frequency coils. The wavelength would then increase to 0.4 m.

The problem of end effects has been identified but not solved. Proper design of the ends is a major problem, but one that is treated in the literature. The length of the magnet may have to be of the order of three wavelengths, or 1.2 m.

2.4.4.2 EM Heating and Frequency

The levitation magnet design gives a satisfactory field at 60 Hz. From the viewpoint of liquid metal displacement during a cycle, 60 Hz is satisfactory as well.

Fig. 2-24.

Force Variation as a Function of Distance (x) across the Sheet with LF, HF, and Combined Magnets

Fig. 2-25.

Edge Support with Conducting Strip. The molten steel, conducting strip, and high-temperature intermediate layer are shown.

For a given force density (F), the density (P) of EM heating is given by

$$P = vF,$$

where v is the phase velocity of the traveling field,

$$v = \lambda \nu,$$

where λ is the pitch of the magnet (wavelength of the traveling field) and ν is the frequency. For a force density equal to the gravitational force density ($\rho g = 69000 \text{ N/m}^3$), a wavelength of 0.4 m, and a frequency of 60 Hz, the density of EM heating is a modest 1.65 W/cm^3 .

2.4.4.3 Sheet Width

The computations in Sec. 2.4.2.1 are two dimensional, i.e., for an infinitely wide sheet. Section 2.4.2.3 gives the force density F for a sheet of finite width as

$$F = B_y J_{ox} (1 - \cosh kx / \cosh kb),$$

where b is the half-width of the sheet, x is the distance across the sheet measured from the center, k is equal to $2\pi/\lambda$, B_y is the low-frequency field perpendicular to the plate, and J_{ox} is the current density at the center of the plate when $kb \gg 1$. Figure 2-26 shows the variation of the force density ($F/B_y J_{ox}$) with x for the three cases $b = 0.075 \text{ m}$, 0.15 m , and 1 m . In each case, $\lambda = 0.4 \text{ m}$.

Fig. 2-26. Force Variations across Liquid Metal Sheets of Half-width 0.075 m, 0.15 m, and 1.0 m

Note that for half-widths $b = 0.075 \text{ m}$ and 0.15 m (widths of 6 in. and 12 in.), the force at $x = 0$ is less than the force on a wide sheet, $B_y J_{ox}$. Hence, if the vertical bench-scale caster is to combine

low-frequency support at the center and high-frequency support at the edge, then the width of the liquid metal sheet must be at least 12 in. ($b > 0.15$ m).

2.4.4.4 Conclusions

The liquid metal sheet in the vertical bench-scale caster must be about 0.6-cm (1/4-in.) thick and at least 30-cm (12-in.) wide and 1.2-m (48-in.) long. The gap between the poles of the low-frequency magnet must be at least 8 cm to accommodate the liquid metal and the high-frequency magnet. The pole pitch (wavelength) must be several times the gap, say 40 cm. The length must be several wavelengths (120 cm), and the width of the metal about a wavelength, say 30 cm. These dimensions can be reduced if computation shows that the ratio of pole pitch to gap can be reduced.

For these dimensions, the electromagnetic heating from the containment magnet is:

$$2 \text{ sides} \times 20 \text{ W/cm}^2 \times 30 \text{ cm} \times 120 \text{ cm} = 144 \text{ kW},$$

well within the capacity of the envisioned power supply. For comparison, the heating for the horizontal bench-scale caster with a current path in the liquid metal of 100 cm is:

$$1 \text{ side} \times 70 \text{ W/cm}^2 \times 15 \text{ cm} \times 100 \text{ cm} = 105 \text{ kW}.$$

2.4.5 Vertical Casting with High-Frequency Traveling Field

Before the edge support methods described above were thought of, vertical casting with a low-frequency traveling field appeared infeasible. Under this circumstance, the method described here was considered.

For a vertical, high-frequency field, the eddy currents flow horizontally along one face of the liquid steel, around the edge, and back along the opposite face. If such a field were traveling vertically upwards and exerted an upward force on the metal, that force would be undiminished at the edge of the liquid steel sheet.

Such a scheme is indeed possible, but for reasonable values of the parameters (thickness = $2a = 6$ mm, skin depth = $\delta = 1$ mm, wavelength = $\lambda = 50$ mm), the eddy current heating is large (375 W/cm^2). For a smaller wavelength (20 mm) and larger skin depth (2 mm), the heating is still marginal (38 W/cm^2). Also the vertical upwards force is a surface force, and the scheme depends on the viscosity or effective viscosity to transfer the force to the interior.

2.4.5.1 Analysis

Consider a coordinate system with z vertical, x parallel to the surface of the steel, and y positive into the steel, with $y = 0$ on the

steel surface. Although the advantage of the scheme is the behavior at the edge of the steel, in this analysis the steel is taken to be infinitely wide in the x direction. The eddy current density has only an x component J_x .

The field B_z must be traveling in the z direction, i.e.,

$$B_z = B_0 \cos (\omega t - kz),$$

with $k = 2\pi/\lambda$. To satisfy Maxwell's equations, the field must have a y component B_y as well. The vertical force arises from the interaction of J_x and B_y .

In addition, J_x , B_y , and B_z must all satisfy the diffusion equation and all have the same y, z, and t variation. Here,

$$B_z = B_0 \exp [j(\omega t - kz - y/\delta) - y/\delta']. \quad (29)$$

If k were zero, then $\delta = \delta' = \delta_0$, the classical skin depth

$$\delta_0 = [2/\omega\mu_0\sigma]^{1/2}, \quad (30)$$

where σ is the electrical conductivity. For nonzero k, set

$$\delta = \text{phase skin depth} = \delta_0 (1 + \epsilon) \quad (31)$$

$$\delta' = \text{amplitude skin depth} = \delta_0 (1 - \epsilon) \quad (32)$$

with $\epsilon \ll 1$. In fact $\epsilon = (0.5 k \delta_0)^2$. Under the assumption that the half-thickness $a \gg \delta_0$, the average pressure is

$$F_y/A = B_0^2 (1 - 2\epsilon)/2\mu_0. \quad (33)$$

The vertical force per unit is

$$F_z/A = k\delta_0 B_0^2 (1 - \epsilon)/2 \mu_0, \quad (34)$$

and the average power per unit area is

$$P/A = \omega\delta_0 B_0^2 (1 - \epsilon)/2 \mu_0. \quad (35)$$

2.4.5.2 Results

For steel, the constants are $\rho = 7200 \text{ kg/m}^3$, $\sigma = 0.714 \times 10^6 \text{ S/m}$, $a = 3 \text{ mm}$, $\delta_o = 1 \text{ mm}$, $\omega = 2.23 \times 10^6 \text{ s}^{-1}$, and $\nu = 350 \text{ kHz}$. For $\lambda = 50 \text{ mm}$, $k\delta_o = 0.126$ and $\epsilon = 0.004$. The vertical force must be $F_z/A = 0.02117 \text{ N/cm}^2$ to offset gravity. Then, by Eqs. 33-35, $F_y/A = 0.168 \text{ N/cm}^2$ and $P/A = 375 \text{ W/cm}^2$.

2.4.6 Shaped-Field Magnet Design

To levitate a column of molten metal of height y requires a magnetic pressure, $B^2/2\mu_o$, equal to the gravitational pressure $\rho g y/A$, where A is the area of the column. Thus $B^2/2\mu_o = \rho g y$ or $B = (2\mu_o \rho g y)^{1/2}$, where ρ is the density, μ_o is the permeability of free space, and g is the acceleration of gravity. The eddy current power loss per unit surface area increases linearly with y , the distance from the top of the liquid metal, when the field increases as $y^{1/2}$. The power also depends inversely on the skin depth, so the frequency should be chosen to make the skin depth about one-quarter the thickness of the molten metal sheets.

Start with the requirement that the vertical component of the magnetic field, B_y , must equal $ky^{1/2}$ along the y axis pointing downward at the liquid metal surface. In two dimensions, that condition determines the field everywhere. The conditions $B = -\nabla\phi$ and $B = \nabla \times A$ then determine the scalar potential ϕ and vector potential A . In polar coordinates, the expressions are

$$\phi = kr^{3/2} \left(\sin \frac{3\theta}{2} = \cos \frac{3\theta}{2} \right) \quad (30)$$

$$A = kr^{3/2} \left[\sin \frac{3\theta}{2} + \cos \frac{3\theta}{2} \right]. \quad (37)$$

Choose a point $P_1 (r_1, \theta_1)$ that the top magnet pole tip must pass through. Substitute this point in the expression for ϕ to get a value of ϕ_1 . A line of constant ϕ_1 defines the shape of the top pole of the magnet. Repeat this procedure for a point on the bottom pole tip of the magnet. Select a third point $P_3 (r_3, \theta_3)$, where the edge of the coil should be located. This defines a vector potential value A_3 , and the curve of constant A_3 defines the edge of the coil. Repeat this for the other edge of the coil.

Figure 2-27 shows these coils and the yoke of the magnet needed to return the flux from the bottom pole to the top pole. This is placed at a sufficient distance from the coil so that flux leakage to the yoke is avoided. The cross-sectional area of the yoke must be sufficiently large to carry the flux from pole to pole and not saturate. On the other side of the molten metal is a mirror image of this geometry. The conductors form "race track" coils around the molten metal sheet. Horizontal eddy currents are induced around the perimeter of the molten metal sheet with a small skin depth. These interact with the vertical field to produce the horizontal force on the metal.

Fig. 2-27. Vertical Caster with Magnet to Produce Field Varying as $ky^{1/2}$

From the mathematical expressions in Sec. 2.1.1.3, it follows that, in casting molten steel with frequencies of 100 kHz and above, the electromagnetic heating is intolerable for ferrostatic heads of a few centimeters, much less the tens of centimeters this stationary field caster would entail.

2.5 Levitation Experiments

It was realized from the beginning of the project that stable levitation was the major issue of technical feasibility for EMCC, and that analysis alone would not resolve the issue. Consequently, an experimental program was begun early to explore the stability of the molten metal sheet under magnetic forces. The experiments focused on levitation of a horizontal sheet.

2.5.1 Preliminary Levitation Experiments Using Head-Start Magnet

Initial levitation experiments were conducted with the head-start magnet, a simple and inexpensive device. It was intended to be used to investigate the impact of a high-frequency magnetic field on wave formation at the interface of a molten metal and a high-velocity cooling gas. The field of this magnet was spatially quite nonuniform. Nevertheless, since it was the only device available at the time, this magnet was used to conduct some very preliminary levitation experiments on solid and liquid metal samples.

The solid metal specimens were made in the form of hollow rectangular channels or open-ended boxes (10 cm by 10 cm by 2.5 cm). These boxes constituted single, electrically shorted turns. When placed in the nonuniform fringe field of the head start magnet, current was induced in the box and magnetic flux was excluded from the enclosed space. As a consequence of this flux exclusion and the reduction in field strength with distance away from the magnet, the magnetic pressure below the box was greater than that above, and the pressure difference could be adjusted to support the weight of the box. Sufficient power was available to levitate both Al and Cu boxes having masses of 93 g and 185 g, respectively. However, due to the highly nonuniform nature of the magnetic field, the levitation was unstable and the boxes tended to tilt and slip out of the peak field region.

Attempts were also made to levitate liquid metal samples in the 10 kHz field of the head-start magnet. To provide a closed current loop and a flux exclusion region, an inverted U-shaped channel was placed in a rectangular dish of liquid metal (both tin and Indalloy 136 were used). This arrangement formed an open-ended box similar to that used with the solid metal samples except that the lower surface was liquid metal. This arrangement allowed the liquid metal sheet to move vertically while maintaining electrical contact with the current loop. Consequently, only the liquid metal portion of the current loop needed to be levitated, not the entire loop, as was the case with the solid metal boxes.

Because the effect of atmospheric pressure would tend to prevent the liquid metal from being lifted off the bottom of the dish, the dish containing the liquid metal and the inverted U-shaped current return path was placed in a small vacuum chamber, which was then placed in the magnetic field.

Because of surface tension effects, the liquid metal samples had to be at least 3/16-in. (0.5-cm) thick. Thinner liquid pools tended to pull away from the electrodes (ends of the inverted U-shaped current return path) or failed to conform to the rectangular shape of the dish.

Several types of materials were used as dishes. These included glass, Teflon, fiberfrax, lava, and graphite. Both Teflon and lava were easy to work with and proved to be good choices for dish materials.

The consequence of these experiments with liquid metals was unstable levitation. As the magnetic field was increased to near levitation strength, a portion of the liquid metal sample would be lifted off the dish, forming a bulge. Such a bulge presumably conformed to a nonuniformity in the field strength. The bulge would not always occur in the same place in the sample. In any case, liquid metal would flow away from the bulge, causing a thinning and finally a tearing or splitting of the liquid shear. Once initiated this tear would propagate rapidly along the direction of the field lines until the sheet was divided in two parts and the current loop was severed. This mode of disruption of the liquid metal sheet was referred to as the "edge-tear" instability.

As had been anticipated, these very preliminary attempts at magnetic levitation provided some insights to the problem of levitating liquid

metal sheets and also supported the contention that stable levitation would require a more sophisticated magnet design that produced a uniform horizontal magnetic field. Such a magnet was subsequently designed and constructed in FY 1987, and became available for use after January 1987.

2.5.2 Levitation Experiments with Test Magnet

The test magnet was designed to be operated over a frequency range of 10 to 50 kHz or more. However, since no power supplies were available in this frequency range, it was necessary to use the existing 10 kHz, 30 kW power supply that had been used previously for the Head-Start experiments. It was recognized that this would place severe limitations on the scope of the experiments because of both the low output power, which effectively limits the mass of material that could be levitated, and the low frequency, which makes successful stable levitation of a liquid metal pool unlikely. Nevertheless, it was believed that until funding was obtained to purchase the required power supply, experimental techniques could be developed and much could be learned by conducting experiments with the existing power supply in the interim. The experiments are summarized below.

A removable insert was designed to hold a small liquid tin sample in the "good field" region (i.e., uniform field region) of the test magnet as shown in Fig. 2-28. The insert consisted of a closed current loop that produced a region nearly free of field within its enclosed space. The insert contained a test section that supported a window frame constructed of stainless steel (SS) within which a sample of tin could be placed. A ceramic base plate was placed below the window frame opening to support the tin until it was fully melted by eddy current heating within the magnet and until the magnetic field was adjusted to the proper levitation strength. Many fine holes were drilled in the base plate to allow equalization of atmospheric pressure above and below the liquid tin. Field measurements with the insert in place yielded the following results:

Field below the tin (B_{below}) = 235 G_{rms}

Field above the tin (B_{above}) = 64 G_{rms}

Fig. 2-28. Insert for Test Magnet

Application of Eq. 6 shows that the magnetic pressure difference under this condition is 203 Pa. The minimum pressure required to levitate a 3/16-in. (0.5-cm) thick sheet of liquid tin, for which $\rho = 7000 \text{ kg/m}^3$, $g = 9.8 \text{ m/s}^2$, and $h = 4.76 \times 10^{-3} \text{ m}$, is 327 Pa. Consequently, the minimum required pressure is 327 Pa, which is greater than that available from the test magnet driven by the existing power supply.

The air gap within the test magnet was then reduced from 8 in. to 6 in. (20 cm to 15 cm) by adding additional blocks of ferrite. This was expected to increase the maximum field strength by the ratio of 8/6. The insert was reduced in width from 8 in. to 6 in. and also in length somewhat. In addition, the all SS window was replaced with a window having Cu at the back and front and SS at the sides (i.e., SS side guards). The net effect was to increase the maximum value of B_{below} to 316 G_{rms} (a ratio of 1.34) and to reduce the field B_{above} somewhat. Again, application of Eq. 6 shows that the maximum available pressure difference should now be ~367 Pa.

First, a 1/4-in. (0.6-cm) thick slab of tin was soldered into the window in the insert and the perforated base plate was fixed below the window to contain the liquid tin pool. The insert was then placed in the field, and the tin was heated by eddy current heating to the liquid state. The field was then gradually increased. At 80% V_{max} (maximum rated voltage of the power supply), large-scale undulations were observed in the liquid tin with a wavelength (λ) similar to the liquid pool length in the field direction. A small vertical deflection of the central region of the surface was also observed. The field was increased to 100% V_{max} without incident. On subsequent trials, tin was progressively removed until the pool thickness was ~3/16 in. (0.5 cm). As the field was again increased, at ~95% V_{max} the small surface vertical deflection was again observed, but without the previously observed large-scale undulations. At 100% V_{max} the pool suddenly erupted from the central region without warning.

Unfortunately, at the time of these experiments, no equipment was available to record such events for future detailed study. Consequently, standard VHS-format video recording equipment was procured. In addition, a remote vernier control was added to the power supply to provide finer control of the field strength near the critical levitation field strength.

Efforts were also undertaken to find a more effective way of removing all physical support from under the liquid tin after the levitating field strength had been reached. A number of simple, manually operated mechanical devices were designed, fabricated, and tested, but none proved very effective. The primary difficulty was that the operation of the device was too disruptive to the liquid tin pool. In addition, the available power supply did not yield sufficient field strength to displace the liquid pool vertically upward enough to provide a good indication that the pool was fully free of the base plate prior to its removal. This was in contrast to the solid plate experiments, described below, in which the plates were light enough to be displaced vertically by relatively large amounts. Further efforts at making a removable support device were then believed to be unfruitful.

2.5.3 Early Experiments of Side Guard Effects

The experiments that were recorded on video tape tested the use of insulated side guards. The purpose of this set of experiments was to see if previously observed instabilities that tended to start along the interface between the SS side guards and the tin could be avoided. Also, the experimental setup more closely simulated the noncontacting side guard configuration that would likely be used in an actual EMCC. As shown in Fig. 2-29a, strips of Fluorosint (mica-filled Teflon) were placed between the SS side guards and the tin so that electrical contact with the tin occurred only along the front and rear interfaces with the Cu. An alternative arrangement for the Fluorosint insulators, shown in Fig. 2-29b, may have provided a more uniform current distribution but was not tested due to lack of time and materials.

Fig. 2-29.

Insert Window Frame (a) with
Fluorosint Insulators and
(b) with Slot a for Fluorosint
Insulation

Two experiments ended in eruption of the liquid tin pool at moderate field strengths (222-245 G_{rms}). Prior to eruption, very small wave action (a sort of surface fluttering) and some long-wavelength surface undulations were observed. These small- and large-scale motions were not disruptive. In both cases, the eruptions began at a noticeable defect in the pool that also appeared to be a site for localized stirring action. It was found that the presence of such defects (presumably pieces of tin oxide, grid, burned solder paste, etc.) had a very significant impact on the outcome of a levitation experiment. Invariably, such defects were associated with sites of localized vigorous stirring and with the initiation of eruptions of the pool.

Further work with insulated side guards was regarded as important, but was postponed in favor of other, somewhat more pressing experiments.

2.5.4 Computational Analysis of Side Guard Effects

As described in Sec. 2.3.1.2, the purpose of the side guards is to keep the field under the molten metal, and thus the electromagnetic force

on the metal, as uniform as possible. The PE2D code was used to compute the effects of varying the resistivity of the side guard material relative to that of the liquid tin. Cases with and without air gaps between the side guards and the liquid tin pool were considered. The results showed that the levitating force F_y varies across the lower surface of the tin with a stainless steel side guard that depends upon the gap between the tin and side guard. This variation in F_y together with a horizontal force F_x at the interface would tend to distort the liquid metal pool physically, as illustrated in Fig. 30, and possibly lead to an instability in the pool.

Fig. 2-30.

Instabilities That Can Result
from Variations in Horizontal
and Vertical Forces

Additional computations showed that variation in F_y occurs even if no gap exists between the tin and stainless steel side guard. Computations showed that changes in resistivity of the side guard material had a major impact on the spatial dependence of F_y and on the direction of F . Consequently, experiments utilizing both copper and monel side guards were planned. Copper has a resistivity substantially lower than liquid tin. Monel has resistivity intermediate between liquid tin and stainless steel. Unfortunately, no suitable, commercially available alloy had a resistivity exactly that of liquid tin. Copper side guards in contact with the tin were predicted to produce a levitation force (F_y) slightly greater in the pool's center than at the sides.

Also, it was conjectured that both F_y and F_x could be modified by changing the shape of the copper eddy current shield that sits on top of the lower field coil below the insert. This conjecture was confirmed in calculations with PE2D. It was suggested that the proper matching of the shape of the lower copper eddy current shield could compensate for nonuniformities created by the liquid metal/side guard interface and thereby increase the stability of the system.

2.5.5 Experiments with Copper Side Guards

The first complete experiment with the copper side guards began with a liquid pool devoid of any obvious defects. The field was increased to 98% $V_{\max}$ without any noticeable surface disturbances or levitation. The experiment was stopped, as was the normal practice when the maximum allowable temperature was reached.

In an additional experiment, the power supply output was increased to 103% $V_{\max}$ (roughly 290 G_{rms}) before an eruption was initiated along the front interface. Calculations using PE2D indicated that, because of the significant difference between resistivities at the copper/tin interface, a

vertical component of the current occurred in the tin as the current expanded from a low skin depth in copper to a larger skin depth in the tin. This vertical component of current acts with the horizontal magnetic field to produce a horizontal force acting to pull the tin away from the interface. It was postulated that this force caused the observed instabilities.

2.5.6 Experiments with a Monel Metal Window Frame

Following the experiments with the all-copper window described above, 1/4-in. (0.6-cm) thick monel metal was acquired and a monel metal window frame was machined. A new insert was fabricated with a removal test section that contained the monel metal window frame. This new insert greatly simplified levitation sample preparation. Levitation experiment setup time was further reduced by a second innovation in which samples of tin were rolled and cut to the proper dimensions (11 cm x 6 cm x 0.5 cm). The first levitation experiment with the new insert and the monel window frame was conducted in September 1987. Before melting, a depression was noted in the tin surface on the right-hand side. An eruption terminated the experiment at $\sim 93\% V_{\max}$ (~ 257 G) without any prior surface disturbance. The eruption was initiated at the right-hand side, but because of a poor viewing angle with the video camera, the precise origin was not discernible.

A second experiment was conducted with a better viewing angle. At $50\% V_{\max}$, a small stirring motion was discernible in the rear, right corner. This motion persisted to higher field strengths and was the site of the start of an eruption at $96\% V_{\max}$. A detailed analysis of this eruption was subsequently conducted. The eruption started as a series of localized vertical undulations at the initiation site, which grew in amplitude over the period of a few video frames. It then grew into the shock-like wave that propagated across the 4.5 in. (11 cm) pool in about eight video frames (0.27 s). As it moved across the pool, this wave plowed away all the tin, forming a narrow channel parallel to the field lines. For this propagation time of 0.27 s, the mean propagation velocity was about 43 cm/s. Since the characteristic shallow fluid wave speed is $(gh)^{1/2} = 21.6$ cm/s, this observed velocity supports the shock-like nature of the disturbance. It is interesting to compare the observed event times to the magneto-inertial characteristic time, which is defined as $(L(\rho)\mu B^2)^{1/2}$. Evaluated in terms of the pool depth and length, this expression gives, at $270 G_{\text{rms}}$, the values 0.02 s and 0.4 s, respectively. The observed times, namely, the period of local vertical oscillation prior to the shock wave onset, and the shock wave propagation time, were very roughly 0.03 s and 0.27 s. Whether this approximate agreement is coincidental or meaningful would require further, more careful measurement than can be made with the existing video equipment.

Following the experiment described above, a mirror was placed inside the insert to provide a bird's-eye view of the tin pool through the video camera. In an experiment utilizing this mirror, the magnetic field was very slowly and carefully increased. The power supply finally reached a value of $108\% V_{\max}$, corresponding to ~ 293 G, before the pool erupted. The eruption started at the front interface near the left corner and propagated along the field lines as previously described. There was no significant wave action or surface undulations preceding the eruption (changes in surface elevation could

not be discerned in the bird's-eye view). The mirror provided an excellent view of the top surface of the tin during the eruption.

2.5.7 Experiments to Test Stabilization Strategies

Theoretical analyses described in Sec. 2.2 suggested two stability conditions:

1. The pool thickness (h) should be of the order of two to three skin depths (δ).
2. The air space within which the levitation magnetic field thickness (d) is confined should be less than twice the thickness (h) for effective stabilization against the Rayleigh-Taylor instability by flux compression.

In addition, two other considerations influencing pool stability were discovered during the course of the work:

3. Inductance stabilization requires that the power supply load draw a lagging current so that a lower inductance caused by a reduction in d would increase the current and field strength, and tend to restore d to its unperturbed values.
4. Pool thicknesses of less than 3/16 in. (0.5 cm) were unstable because of surface tension forces. For $h < 3/16$ in., the pool tended to pull away from the wetted interfaces with the window frame, or to form a hole in the central region of the pool when perturbed.

The above four conditions could not all be satisfied with liquid tin and the existing 10 kHz, 30 kW power supply. The available power together with condition 4 above limited the pool depth to $\sim 3/16$ in. (0.5 cm). Even at that thickness, the power supply had to be operated at or near resonance, so that condition 3 could not generally be adhered to. At 10 kHz the skin depth (w) in liquid tin was 0.133 in. (0.338 cm). Consequently, $h = 1.4\delta$, which did not satisfy condition 1. Condition 2 could, however, be met and some experiments were designed to look at the impact of meeting that condition.

Several experiments were conducted with d/h ranging from ~ 2.7 to 1. In all cases, where proper care was taken to ensure that the pool was level and there were no obvious defects, the power supply output could be increased to 100% $V_{\max}$ (~ 300 G_{rms}) without any pool disturbances. However, in several cases, pool eruptions occurred when the output voltage reached the range of 100 to 105% $V_{\max}$.

These final results suggested that the maximum degree of stability obtainable under the circumstances ($h = 3/16$ in., $f = 10$ kHz) had been achieved. An alternative experimental approach, which was not undertaken because of program termination, was the use of liquid aluminum in place of liquid tin; with aluminum, all four conditions can be satisfied simultaneously with the existing power supply.

2.5.8 Summary

Several general observations can be made from the experiments. These observations are expected to change with higher frequency fields (i.e., $h/\delta > 1$). First, nonuniformities in the field of the order of several percent led to instability. Avoiding this effect required a careful match between the electrical resistivity of the liquid tin and the surrounding window. It also required care in inserting the tin. Instances in which the bottom part of the tin had even one spot that did not make good electrical contact with the window frame invariably led to instability. Second, upper surface imperfections caused by nonwetting at the window frame or nonconducting "dirt" embedded in the tin seemed to cause field nonuniformities, often associated with electromagnetic stirring observable on the upper surface. With such surface stirring, instability always occurred at magnetic field strengths below that required for levitation. Finally, in the case of a uniform field (i.e., no surface stirring observable, field strength sufficient to levitate, etc.), the instability occurred as a Rayleigh-Taylor type instability. The initial instability would occur as a surface wave in the center of the slab, with the wave vector of the disturbance perpendicular to the magnetic field lines. The wavelength of this initial disturbance was of the order of 1 cm, and the time for the disturbance to develop was approximately equal to the magneto-inertial time.

Further evidence for the presence of the Rayleigh-Taylor instability was seen in an experiment in which a thin copper sheet was placed at the bottom of the liquid tin. This sheet was free to levitate. The sheet and the fluid levitated together. No instability was observed until the solid sheet became tilted. This indicates that the basis for the observed fluid instabilities is associated with the lower free surface of the tin.

At this time, development of both the horizontal caster and the vertical caster with three magnet systems appears feasible. Both require a great deal more analysis and experimental study.

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3.0 FEED SYSTEM DESIGN AND FLUID FLOW ANALYSIS

An important component in the electromagnetic (EM) caster is the liquid metal feed system, which serves as the transition from the liquid metal source (ladle) to the caster. The primary function of the feed system, which includes the tundish, refractory nozzles, and controls, is to provide a suitable liquid metal stream to the EM caster. The key technical issues related to the successful development of a feed system employing EM flow control and shaping are (1) structural design and materials for refractory nozzles of large-aspect-ratio shape and (2) suitable fluid flow control (e.g., rate, shape, thickness, velocity profile, turbulence level).

The requirements for stable levitation and subsequent solidification of a moving liquid-metal stream in terms of the stream's flow parameters are uncertain at this time. It is expected that the tolerances for fluctuations in stream shape are small (of the order of 1-2%) and that the velocity profile must be uniform to within a similar tolerance. These requirements will have to be better determined through dynamic flow-through/levitation experiments with model fluids and liquid steel.

Development efforts included feed system design analysis, fluid flow analysis, and experimentation. Work in each area is described below.

3.1 Feed System Design Analysis

The initial work of this effort was focused on fluid flow analysis and design of a feed system that would meet the requirements of the experimental bench-scale casters. The original approach was to conduct a series of analyses and experiments that would identify and address the basic feed system design issues for the horizontal bench-scale caster, whose design was well along. Afterwards, the effort would focus on a feed system for the vertical bench-scale caster, whose design was still in a very preliminary stage. At the April 10, 1987, technical review meeting, a Feed System Working Group was formed to assess the technical feasibility of a commercial-scale EM caster. Results from the workshops held by this group indicated the need to expand the scope of the work on feed system and fluid flow analysis. Appendix A summarizes the feed system workshops.

3.1.1 Design Considerations for Model Fluids and Steel

In the initial plans, it was assumed that a conventional liquid metal feed system would provide the required liquid metal stream to the bench-scale casters. This system would operate in the batch mode and have a capacity of about 100 kg of liquid metal. Assuming a stream cross section of 6 by 150 mm, a 100 kg heat would last about 150 s at a casting rate or linear stream velocity of 0.1 m/s. This same heat would last 15 s at 1.0 m/s. One possible feed system design that appeared, at first, to be simple and yet adequate for the bench-scale casters was a relatively shallow tundish designed to eliminate most of the turbulence created at the inlet before the fluid reached the outlet. The liquid metal would enter a rectangular nozzle and then be delivered into the caster in the form of a stream having suitable shape and flow parameters. Some preliminary analysis, to be discussed in

greater detail later, as well as some preliminary experiments with a physical water model designed specifically for this purpose, indicated that a shallow tundish together with a rectangular nozzle of open- or closed-channel design would provide steady-state flows with effective fluid heads at the tundish outlet down to about 1 cm. For this condition, the stream velocity at the exit of a 30-cm long nozzle would be about 20 cm/s. Lower effective heads did not yield suitable streams.

Shallow tundishes are simple to fabricate and suitable for water and liquid tin. However, they are not suitable for liquid steel for several reasons. Tundishes for liquid steel must provide low turbulence levels for good stream quality and steady-state flow, as well as good inclusion removal and minimal heat loss. These requirements called for a relatively deep tundish for steel (see Sec. 3.1.4 for tundish design charts), which, in turn, indicated the need for precise fluid head and flow control. Furthermore, liquid steel flow through a high-aspect-ratio nozzle presents a number of problems, such as erosion, inclusion buildup, and freeze off of the liquid metal. These problems were either nonexistent or easily controlled in the case of the model fluids. These special design considerations for a liquid steel feed system, together with the anticipated need for control of stream parameters to meet the EMCC requirements, indicated that some form of EM flow, stream shape, and turbulence control would be essential.

During the meetings of the Feed System Working Group, the feed system design activities were expanded to include a feasibility study of a commercial-scale EMCC process. The results of these workshops indicated that, while a bench-scale feed system was technically feasible, there was insufficient information available to resolve some technical issues critical to the design of a feed system for a commercial-scale EMCC process. First and foremost, a detailed design of a commercial-scale EMCC process did not exist. Second, the requirements that such a process would impose upon the stream quality emerging from the feed system were essentially unknown. Third, a means did not exist to convey a liquid steel stream of suitable shape and properties into the caster. It was argued that use of a refractory closed-channel rectangular nozzle of large-aspect ratio was not feasible if the width was greater than 5 in. (13 cm). Larger-width refractory nozzles have been constructed, but they used internal supporting ribs, which resulted in stream separation. There is no reported experience with large-width nozzles having only external supporting structure. The problem of how to convey liquid steel from the tundish to the good field region of the EM caster must be regarded as unresolved at this time. It is relatively certain that the method of choice will have to incorporate an EM flow control and stream shaping device in combination with an externally supported nozzle. A feed system of this type would probably use an open-channel rectangular nozzle that is externally supported by the EM flow and stream shaping device and by the EMCC magnet housing. Obviously, the design of any feed system must account for materials compatibility, cooling system requirements, and preheating requirements associated with startup of the caster.

The Feed System Working Group developed the following guidelines for the tundish design: (1) the tundish-wall slant angle should be about 7° ; (2) there should be a means to empty the tundish (the debris floating on the

surface of the steel should not be pumped through the feed system); (3) the minimum acceptable fluid height above the tundish exit should be ≥ 12 cm; (4) there is no intrinsic limit on the maximum fluid height above the tundish exit; (5) the minimum acceptable fluid depth in the tundish during a ladle change is ~ 50 cm; (6) the maximum acceptable fluid depth in the tundish is not limited except for the fact that the shroud (used to transmit fluid from ladle to tundish) must penetrate below the minimum level and, therefore, must not be so long that it cannot be easily changed when needed; and (7) the dynamic range of the feed system control devices is constrained by the linear induction pump (LIP) capacity and the ladle change time.

3.1.2 Conceptual Designs

With the considerations of Sec. 3.1 in mind, a number of feed system concepts have been investigated. Two examples of possible feed systems are shown Fig. 3-1. The first illustrates a purely mechanical feed system and involves conventional concepts and materials. Several variations of this general concept were considered. For the other concepts, an electromagnetic (EM) device is used to control both the flow rate and the stream shape (lower illustration in Fig. 3-1). For this device, the upstream conduit has a small aspect ratio (round or elliptical in cross section), and the downstream conduit is a large-aspect-ratio nozzle with open- or closed-channel design.

Fig. 3-1.

Examples of Feed System Concepts

A conceptual design for an overall feed system is illustrated in Fig. 3-2. It utilizes a conventionally designed ladle and tundish that are fully enclosed to reduce oxidation. These vessels could be pressurized if desired. A large LIP provides coarse flow control and a second EM device provides fine flow control and stream shape and turbulence control. The latter device, shown in Fig. 3-3, has a component that penetrates part way into the EMCC magnet. The nozzle itself penetrates to the good field region of the EMCC magnet.

Fig. 3-2. Schematic of Conceptual Feed System for EM Caster

Fig. 3-3.

Schematic Diagram of Portion of Feed System Inserted into EM Caster. An externally supported, open-channel refractory nozzle is shown.

3.1.3 Electromagnetic Shaping and Flow Control

As noted earlier, the feed system for an EM caster will probably have to incorporate an EM flow control and stream shaping device in combination with an externally supported nozzle. Here the term "flow control" includes all relevant stream parameters, including velocity profile and turbulence level.

Magnetic fields interacting with a conducting fluid have the potential to produce many useful fluid flows, many of which appear applicable to the EM casting designs. There are many possible types of magnetic fields to choose from. They use, either singly or in combination, direct current, alternating current at different frequencies, and traveling waves at different wavelengths and frequencies. The magnetic fields can be used to (1) control mass flow rate, (2) shape the fluid surfaces, (3) control the velocity profile of the flow, and (4) affect the degree of turbulence in the flow.

Experience to date has been mostly concerned with the use of dc magnetic fields with channel flows. Very little experience exists on the use of ac fields in channel flows. There is essentially no experience with the introduction of a fluid jet into a nearly frictionless environment where gravity does not accelerate the mean flow velocity. Coupled with the paucity of experience on the effect of non-dc magnetic fields on channel flow, this makes evaluation of the use of electromagnetic control in the feed system difficult. The potential exists for using electromagnetics to provide the "proper" (undefined at present) flow into the EM caster. Clearly, more experience is necessary before evaluation of these techniques can be made.

In view of the lack of reported experience with the use of ac fields in channel flows, it was decided that high priority should be given to conducting experiments that would determine the nature and extent of liquid metal stream shape and flow control. An experimental approach is described in Sec. 3.3.3. Unfortunately, the program was terminated before the approach could be implemented.

Two EM flow control devices--one for coarse control, the other for fine control--are likely to be used as part of the feed system, illustrated in Fig. 3-2. Preliminary analysis indicated that LIPs could provide either coarse or fine control of flow rate. For example, it was estimated that a low-frequency LIP could provide a pressure variation equivalent to ± 10 cm of steel about a given tundish fluid level and could also be capable of pumping the tundish empty if necessary. A ferrostatic pressure equivalent to ~ 1.0 m of steel would be required to accomplish this task. However, this high pressure would entrain floating debris into the caster.

The second EM flow control device, independent of the first, would be driven at a higher frequency to provide stream shape and turbulence control and would provide only small pressures to avoid excessive eddy-current heating. Although the feasibility of the primary flow control LIP is well founded, experimentation is required to determine the feasibility of controlling the thickness, shape, velocity profile, and turbulence of the stream emerging from the secondary EM flow control device. Some work on EM thickness control has apparently been conducted by researchers at Grenoble; however, no details have been reported in the literature as of yet. Basically, they use an application of Bernoulli's equation, i.e., a sudden change in magnetic pressure, to produce a corresponding change in velocity and a change in thickness.

An additional question that requires experimental investigation is the optimum shape of the conduits used to convey the steel from the tundish to the secondary EM flow and control device. Some very preliminary theoretical calculations regarding the design aspects of the LIP were conducted, but much additional analysis is needed.

3.1.4 Design Charts for Tundish

In continuous casting operations, the tundish serves as an intermediate reservoir for the liquid steel between the ladle and the caster mold. The tundish must provide a continuous source of liquid steel for

steady-state operation, including the time required for ladle changes. To cover a wide range of possible design parameters and to aid in the design of tundishes for bench-scale, laboratory-scale, and prototypic casters, six nomograms (see Table 3-1) have been constructed to cover a range of capacities. These nomograms are useful for selecting design parameters relevant to steady-state operations (Nomograms 1-3) and ladle change operation (Nomograms 4-6).

Table 3-1. Nomograms Constructed for Selecting Design Parameters

	Normal Operation	Ladle Change Operation
Prototypic (0-50 tons)	Nomogram 1 (Fig. 3-4)	Nomogram 4 (Fig. 3-7)
Laboratory Scale (0-20 tons)	Nomogram 2 (Fig. 3-5)	Nomogram 5 (Fig. 3-8)
Bench Scale (0-2 tons)	Nomogram 3 (Fig. 3-6)	Nomogram 6 (Fig. 3-9)

The following equations were derived to construct these nomograms:

$$\dot{m} = 0.00768 A_s V_c, \quad (1)$$

$$V_t = 0.0754 \, m t_r, \quad (2)$$

$$\begin{aligned} C_t &= 0.0167 \, m t_r \\ &= 0.0184 \, h_t A_t, \end{aligned} \quad (3)$$

Fig. 3-4. Nomogram 1 for Large Tundish in Normal Operation

Fig. 3-5. Nomogram 2 for Intermediate Tundish in Normal Operation

Fig. 3-6. Nomogram 3 for Small Tundish in Normal Operation

Fig. 3-7. Nomogram 4 for Large Tundish in Transient Operation

Fig. 3-8. Nomogram 5 for Intermediate Tundish in Transient Operation

Fig. 3-9. Nomogram 6 for Small Tundish in Transient Operation

$$\Delta V_t = 0.0753 \ m \ \Delta t_L \quad (4)$$

$$= \frac{A_t \ \Delta h_t}{12},$$

where

- m = Casting rate (tons/h)
- A_s = Cross-sectional area of casting slab (in.²)
- V_c = Casting speed (in./min)
- V_t = Tundish volume (ft³)
- t_r = Average residence time (min)
- C_t = Tundish capacity (tons)
- h_t = Maximum liquid level in tundish (in.)
- A_t = Tundish cross-sectional area (ft²)
- ΔV_t = Volume change in tundish (ft³)
- Δt_L = Ladle change time (min)
- Δh_t = Tundish level change (in.)

In deriving the above equations, we assumed that the tundish is rectangular and the density of liquid steel is 0.256 lb/in.³ (7.08 x 10³ kg/m³).

The line A-B-C-D-E-F in Nomogram 1 (Fig. 3-4) illustrates the relationship among the various parameters during steady-state operation for a large tundish. We can see that, for a casting speed of 35 in./s (89 cm/s) and a slab cross-sectional area of 12 in.² (77.4 cm²), the line AB indicates that the casting rate is 193.5 tons/h. The line BC indicates that, for the above casting rate and a residence time of six minutes, the required tundish volume is 87.5 ft³ (2.458 m³). The construction of vertical line CD then gives the tundish capacity as 19.4 tons. For a liquid height of 40 in. (100 cm), construction of line DEF indicates that the tundish area should be 26.3 ft² (2.44 m²).

Similarly, the line A-B-C-D-E-F in Nomogram 4 (Fig. 3-7) illustrates the relationship among these design parameters during the ladle change operation. Line AB indicates that, for a casting rate of 300 tons/h and a ladle change time of two minutes, the change in tundish volume is 45.2 ft³ (1.28 m³). Line BC indicates that liquid level will drop by 13.6 in.

(34.5 cm) for the above volume change and tundish area of 40 ft² (3.7 m²). If the minimum liquid level (height) in the tundish is required to be 30 in. (75 cm), then line CD shows that the minimum liquid level at the start of ladle change should be 43.6 in. (110 cm). Correspondingly, the minimum tundish volume at the start of the ladle change is obtained at 145.2 ft³ (4.11 m³) by the construction of the line DEF.

The above illustrations are considered representative of a full-scale operation. The other nomograms are useful for design of bench-scale and laboratory-scale casters.

3.2 Fluid Flow Analysis

3.2.1 Fluid Flow Considerations

Fluid flow behavior will have a significant effect on the quality of the final product and productivity of the continuous casting process. Since the tundish is one of the major components of the feed system, we decided that flow phenomena in a tundish should be studied first.

In a modern casting process, the tundish performs several functions besides serving as a reservoir during ladle change operations. Among them, the three functions that strongly depend on fluid flow behavior are

- Distribution of flow at the outlet nozzle.
- Separation of nonmetallic inclusions.
- Reduction of air entrainment and subsequent reoxidation.

For a tundish to perform these functions, the design must be such that fluid flow

- Is vortex and turbulence free, specifically near the free surface and in the vicinity of the outlet nozzle, to prevent air entrainment and subsequent reoxidation.
- Has a long travel path (increased residence time) to allow separation of nonmetallic inclusions by flotation.
- Is streamlined, with minimum turbulence intensity in the vicinity of outlet nozzle, to provide uniform streamlined flow at nozzle outlet.

The geometrical parameters that control the fluid flow behavior in a tundish are

- Location of outlet nozzle.
- Location of inlet nozzle.

- Locations of baffles, weirs, and dams.
- Shape, cross-sectional area, and height of a tundish.

As a part of this effort, a parametric study was performed by numerically simulating the velocity field in a tundish under different geometric conditions. These simulations were performed using the COMMIX computer code developed at Argonne.

The COMMIX computer code is designed to analyze three-dimensional, steady-state/transient, single-phase/multiphase heat transfer and fluid flow for a single-component/multicomponent system. It solves the (1) conservation equations of mass, momentum, and energy and (2) transport equations with turbulence parameters and provides detailed description of the velocity, temperature, and pressure field. The code has been developed and refined over the last ten years, and a large number of computations for complex flow and heat transfer conditions have been performed. Because of its wide range of applicability, the code is being used by over a hundred organizations internationally.

3.2.2 Parametric Study

The geometrical parameters and the tundish design used as a reference for comparison are shown in Fig. 3-10. Four parametric studies were performed to determine the effects on the velocity distribution of submerged entry depth, inlet section width, addition of baffle, and addition of weirs and dams.

In the first parametric study, the velocity distributions were obtained for three submerged entry depths ($h = 10, 5, \text{ and } 0.6 \text{ cm}$). This analysis showed that, with a decrease in entry depth (smaller h), the turbulence in the lower-level region increases, the very slow moving vortex flow (stagnant region) increases in the upper-level region, and the average residence time decreases. However, the effect of the submerged entry depth on velocity distribution diminishes as the fluid flows away from the point of entry and is completely eliminated by the time fluid arrives at the nozzle (Fig. 3-11).

In the second parametric study, the velocity distributions were obtained for tundish widths (W) of 35 and 20 cm. This analysis showed that the velocity distribution at the tundish exit was similar for both cases (Fig. 3-12.). However, the change in the tundish width did affect the residence time. Decrease in width caused a decrease in the residence time.

The third parametric study was performed to determine the effect of inclusion of one and two baffles on the velocity field. There were no significant differences in the velocity distribution at the tundish exit between one and two baffles (Fig. 3-13). However, the tundish with two baffles exhibited more streamlined flow, less stagnant (slow moving) space, and increased residence time. Also, as observed in later experiments performed with the water model fluid, inclusion of the second baffle reduced the level of surface disturbance near the nozzle outlet, which was initially caused by the turbulence at the inlet nozzle.

Fig. 3-10.

Reference Tundish and Parameters
used for Numerical Study

Fig. 3-11.

Calculated Effect of Entry
Depth (h) on Fluid Flow

$h = 4 \text{ in. (10 cm)}$

$h = 2 \text{ in. (5 cm)}$

$h = 0.25 \text{ in. (0.6 cm)}$

W = 14 in. (35 cm)

Fig. 3-12.

Calculated Effect of Width (W)
on Fluid Flow

W = 8 in. (20 cm)

Fig. 3-13.

Calculated Effect of Additional
Baffle A on Fluid Flow

Without Baffle A

With Baffle A

The final parametric study was performed to determine the effect of weirs and dams on the velocity distribution in the central vertical plane of the last reservoir section of the tundish. This analysis showed that insertion of weirs and dams increases the travel path (increase in residence time) and reduces the stagnant space but also increases the turbulence (Fig. 3-14).

Without Weirs and Dams

Fig. 3-14.

Calculated Effect of Weirs and Dams on Fluid Flow

With Weirs and Dams

3.2.3 Tundish Design Considerations

Because flow behavior during the continuous casting process has important implications, the steel industry has devoted extensive effort in tundish design. The approaches used have included mathematical modeling, radioactive tracer studies, and water modeling. Based on these studies, many design considerations have been identified. The following is a list of some important ones.

1. The intensive mixing condition in a tundish is desirable so that liquid steel has uniform temperature, composition, and dynamic behavior at all strands, regardless of their locations. However, mixing conditions are unsuitable for the separation of nonmetallic or reaction products. The tundish, therefore, should be designed such that the intensive mixing region is confined to a small volume near the ladle entry, and plug flow is produced in the balance of the tundish region, i.e., from the ladle entry to the exit nozzle. This can be achieved by proper locations of baffles, weirs, and dams.

2. A long travel path between ladle stream inlet and exit nozzle and high residence time are desirable because they provide time for separation of inclusions by flotation and thus reduction in the size of inclusions which can be carried over.
3. Submerged nozzles and/or gas shrouding from ladle to tundish are preferred because they reduce air entrainment and the reoxidation of steel.
4. The use of a closed-end or multiported ladle nozzle provides control of fluid flow within a tundish.
5. High liquid level with deep submerged entry into a tundish is desirable because it reduces surface turbulence.
6. Slow-moving stagnant regions in a tundish must be avoided to reduce heat loss and skull formation and to prevent decrease in residence time.
7. Large-scale eddies and vortices should be avoided, especially near the surface and near the exit nozzle. This can be achieved by inserting rods, baffles, or porous walls in the tundish.

3.3 Experimentation

Experimental activities related to feed system development were conducted in the following areas: (1) wave formation and suppression at the gas/liquid-metal interface and (2) water flow through open- and closed-channel nozzles of high-aspect-ratio under small effective liquid heads. With regard to the latter, facilities were designed and fabricated for studying liquid metal flow through nozzles and for determining the effect that EM fields have on that flow.

3.3.1 Wave Formation and Suppression

Two critical issues were identified during the early studies on the technical feasibility of the EMCC concept: what was the maximum tolerable velocity for coolant gas flow over a liquid metal surface, and what was the influence of a high-frequency magnetic field on that maximum flow velocity? The "Head Start Experiment" was conceived to address those issues.

3.3.1.1 Experimental Apparatus

The apparatus was designed and fabricated and some early experiments were conducted in FY 1986. Additional experiments were conducted in FY 1987-FY 1988. The apparatus consisted of a gas handling system to monitor and control the gas temperature and flow parameters; a rectangular glass test section designed to simulate the gas cooling channel of a bench-scale caster; and a high-frequency C-shaped magnet with a large air gap (referred to as the "head-start" magnet). The glass test section consisted of a rectangular gas channel (61-cm long, 9-cm wide, 1-cm deep) and a rectangular glass dish (25-cm long) containing a pool of liquid metal about 0.9-cm

(3/8-in.) deep that was heated from below. The head-start magnet could be placed over the rectangular glass dish so that a magnetic force could be exerted downward on the liquid metal surface. Two orientations were possible, $B \parallel V$ and $B \perp V$.

A schematic diagram of the wave-measuring system is shown in Fig. 3-15. Figure 3-16 is a photograph of the entire system. Nitrogen gas was supplied from a compressed gas cylinder fitted with a special high-volume regulator. The gas-line temperature was controlled from the gas cylinder to the round-to-rectangular transition section. Figure 3-17 is a close-up view showing the head-start magnet in position over the glass dish and oriented so that $B \perp V$. The magnet is excited with a 10 kHz, 30 kW power supply. Figure 3-18 is a photograph of surface waves in liquid tin created by the flowing N_2 gas.

Fig. 3-15. Cross-Sectional Schematic of Wave-Measuring System. This view extends from the gas inlet fitting to which a flexible, 2.5-cm (1-in.) dia high-pressure tube is connected on the upstream end to one-half the glass test section. Not shown is the downstream probe section.

A capacitance-type wave detector system was especially designed for this experiment. It consisted of a probe wire mounted above the liquid metal, a dc power supply, an amplifier, and a Fourier transform wave analyzer to analyze the signals. Figure 3-19 shows a schematic diagram of the system. The magnetic field strength could be adjusted to values almost as high as needed for levitation in a horizontal caster; but, due to the magnet design, the magnetic restoring force against surface disturbances in the liquid metal is much less in magnitude and much less spatially uniform. The restoring force arises from compression of the nonuniform fringe field of the magnet.

3.3.1.2 Experimental Procedure

An experiment typically began by heating tin to a temperature 20 to 40°C above its melting temperature of 232°C. The magnetic

Fig. 3-16. Photograph of Wave-Measurement System. Power supply on left, gas flow system in foreground, and compressed N_2 cylinder on right.

Fig. 3-17. Close-Up View of Wave-Measuring System. The head-start magnet is placed above the glass N_2 channel so that $3[V]$. The probe section is on the right along with a thermocouple wire and hot film anemometer probe holder and cable.

Fig. 3-18. Photograph of Wave Action Caused by High-Velocity Coolant Gas Flowing over Liquid Tin Surface

Fig. 3-19. Block Diagram of a Capacitance-Type Wave Detector System

field is set to a given value, the wave detector noise level is measured, the N_2 gas flow is then turned on, and the velocity increased until the ratio of the wave amplitude to background noise level reaches a value of 10. This signal-to-noise ratio was taken as the criterion for wave action and, indeed, corresponded to the formation of very small but visible waves in the liquid tin. The gas velocity required to generate waves at this signal-to-noise ratio is referred to as the critical velocity V_c . Because of rapid cooling of the tin surface by the high-velocity N_2 gas, it is necessary to complete a particular measurement of V_c in a relatively short time (of the order of 30 s). Three parameters were varied during the course of the experiments:

1. The orientation of B relative to the gas velocity V . (Both B and V remained in the horizontal plane although, due to field fringing, significant vertical components of B were present near the magnet pole faces.) The two orientations, $B \parallel V$ and $B \perp V$, are illustrated in Fig. 3-20.
2. The vertical spacing (y) between the surface of the tin and the bottom edges of the magnet pole pieces. (Because of space constraints, most of the experiments were conducted with the tin surface located below the lower edges of the magnet pole face, i.e., in the magnet fringe field, not in the region directly between the pole faces.)
3. The depth of the N_2 gas channel (values of 1.0 cm and 0.698 cm were used).

In the case where $B \perp V$, most of the tin surface (8.9 cm by 25 cm) was exposed to the magnetic field (10.8 cm by 20 cm, with the field lines parallel to the 10.8-cm dimension). However, since the field was nonuniform, only about 10 cm along the magnet length ($\perp B$) was exposed to the maximum field strength. Consequently, when the N_2 gas velocity was increased beyond the value of V_c for zero field strength, waves formed upstream and downstream of the maximum field region. The downstream wave amplitude was the

Fig. 3-20. Schematic of Magnet and Glass Test Section Orientation with (a) $\vec{B} \perp \vec{V}$ and (b) $\vec{B} \parallel \vec{V}$

limiting quantity in the experiment, because even with complete wave suppression in the maximum field region, the downstream wave amplitude in the nearly field-free region became so large that the N_2 gas forced liquid tin out of the dish and into the downstream gas channel. This condition was exacerbated in the case where $\vec{B} \parallel \vec{V}$. In that case, only about one-third of the tin surface was exposed to the magnetic field. The magnetic pressure exerted by the field on the tin surface depressed that portion of the surface exposed to the field and elevated that portion outside the field. This raised the fluid level at the upstream and downstream edges of the liquid pool and reduced the tolerance for large wave amplitudes. The elevation of the liquid surface above the lower surface of the N_2 channel also presented an obstruction to the free flowing gas, which tended to enhance wave formation. For this reason, and because of space limitations (the magnet had to be above the glass dish instead of straddling it as in the case of $\vec{B} \perp \vec{V}$), the range of the parameters used with the $\vec{B} \parallel \vec{V}$ experiments was more limited than for the $\vec{B} \perp \vec{V}$ experiments. The more-pronounced surface deformation in the case of $\vec{B} \parallel \vec{V}$ also complicated the experimental results somewhat.

The magnetic field strength and the total force exerted by the magnet on the tin surface were measured as a function of position above the tin surface. The magnetic field was determined with a small search coil fixed to a probe. The search-coil output voltage was monitored with an rms voltmeter. These search coil measurements were used to estimate the local magnetic pressure exerted on the region of the tin surface in the vicinity of the wave detector probe wire. The total force exerted by the magnetic field on the total tin surface was directly measured by placing the entire dish on a large balance.

3.3.1.3 Data Analysis and Results

The critical velocity measurements were analyzed in terms of the field strength, magnetic pressure ($\propto$ field strength squared) at a

point, the magnetic pressure averaged over the vicinity of the probe wire, the total force exerted on the whole tin pool, and the pressure gradient. The mean pressure in the vicinity of the wave detector is given by

$$\bar{P} = \frac{\overline{B^2}}{2\mu_o} = \frac{(C.F.)^2}{2\mu_o} \bar{V^2}, \quad (5)$$

where μ_o is the permeability of free space ($4\pi \times 10^{-7}$ in MKS units), C.F. is the calibration factor of the search coil (Tesla/volt), and $\bar{V^2}$ is the mean square search coil voltage given by

$$\bar{V^2} = \frac{1}{3} \left[V_1^2 + V_2^2 + V_3^2 \right], \quad (6)$$

where the V_i is the search-coil output voltages at locations $i = 1, 2, 3$ along the probe wire. The gradient of the mean pressure (γ) is given by

$$\gamma = \frac{d\bar{P}}{dy} = \frac{(C.F.)^2}{2\mu_o} \frac{d\bar{V^2}}{dy}. \quad (7)$$

The values of the derivative of $\bar{V^2}$ with respect to y were obtained by measuring the slopes of the $\bar{V^2}$ versus y curves constructed for each combination of orientation, spacing (y), and power-supply output voltage ($\%V_{max}$).

For convenience, a parameter called the "suppression factor" (SF) was defined as follows:

$$SF(\gamma) = V_c(\gamma)/V_c(\gamma=0). \quad (8)$$

Several sets of data were obtained at various times and for various parameter values. The use of the SF eliminates the variation of $V_c(\gamma=0)$ with tin surface condition for these data sets. The results are tabulated in Table 3-2. Plots of the data are given in Figs. 3-21 to 3-27.

Figure 3-21 shows a plot of critical velocity V_c vs. the square of the power-supply output voltage ($\%V_{max}$) to the magnet for the two orientations and several values of y (spacing between tin surface and copper shield surrounding pole pieces). Figure 3-22 shows the same data but plotted as V_c vs. the mean pressure gradient near the wave detector probe wire (γ). Notice how the curves for $B \perp V$ collapse down to a relatively narrow band of data. The substantial difference between $V_c(\gamma=0)$ in the cases of $B \perp V$ and $B \parallel V$ is associated with the fact that the tin surface was new and very smooth

Fig. 3-21.

Critical Velocity for Wave Formation as Function of Square of Power-Supply Output Voltage (N_2 channel depth, 1 cm)

Fig. 3-22.

Critical Velocity for Wave Formation as Function of Pressure Gradient (N_2 channel depth, 1 cm)

Fig. 3-23.

Critical Velocity for Wave Formation as Function of Pressure Gradient with $B \parallel V$ (N_2 channel depth, 1 cm)

Fig. 3-24.

Critical Velocity for Wave Formation as Function of Pressure Gradient with $B \perp V$ (N_2 channel depth, 1 cm)

Fig. 3-25.

Critical Velocity for Wave Formation as Function of Pressure Gradient with $B \parallel V$ (N_2 channel depth, 0.698 cm)

Fig. 3-26.

Critical Velocity for Wave Formation as Function of Pressure Gradient with $B \perp V$ (N_2 channel depth, 0.698 cm).

Fig. 3-27.

Wave Suppression Factor (SF)
as Function of Pressure
Gradient

in the B||V experiments but used and scaly in the B⊥V experiments. The scatter in the data for B||V is only slightly reduced in the V_c vs. γ plot as compared to the V_c vs. $(\%V_{\max})^2$ plot. This finding suggests that the γ -dependent wave suppression mechanism seen for B⊥V is not the only mechanism present in the case where B||V. The surface deformation effect (which, as already noted above, tends to enhance wave formation) is believed to be responsible for this scatter in the B||V data. Other data sets in which substantial differences were seen between the B⊥V and B||V cases are illustrated in Figs. 3-23 and 3-24.

Figures 3-25 and 3-26 show plots of V_c vs. γ for the case where the N_2 gas channel depth was reduced from 1.0 to 0.698 cm (0.40 to 0.275 in.). In both the B⊥V and B||V orientations, the dependence of V_c on γ appears to be somewhat stronger than in the plots previously shown. There is no indication of the surface deformation effect for B||V as was seen in Fig. 3-22 to 3-24.

Figure 3-27 shows a plot of the suppression factor vs. the pressure gradient. Two groups of data are distinguished for discussion purposes. One group of data consists of the three data sets represented by the vertical error bars. This group of data is for B⊥V and an N_2 gas channel depth of 1.0 cm (0.40 in.). The other group of data is for an N_2 gas channel depth of 0.698 cm (0.275 in.). These data are plotted as circles. Of course, these latter data have errors associated with them as well, and those errors should be comparable to the error bars associated with the data for the 1.0-cm channel depth. Nevertheless, the data suggest that the dependence of SF on γ may be somewhat different for the two channel depths. Unfortunately, there was not enough data to resolve this question.

Table 3-2. Critical Velocity of Coolant Gas (V_c) vs. Mean Pressure Gradient (γ). Note: the estimated errors are ± 0.15 m/s for V_c and $\pm 10\%$ for γ .

Data Set No.	N ₂ Channel Depth, ^a cm	Orientation of $\bar{B}$ Relative to $\bar{V}^2$	V_c , m/s	γ , Pa/m
1	1.0 (0.4)		10.7-11.9	0
			10.1-11.1	212
			11.2	472
			9.75	831
			11.3	917
			10.8	1130
			9.8	1270
			14.3	1650
2	1.0 (0.4)	⊥	9.5-10.3	0
			9.5-10.8	212
			10.9-11.2	323
			12.4	776
			14.4	909
			-	917
			15.6	1630
			11.3	0
3	0.698 (0.275)	⊥	11.7	323
			12.5	909
			13.8	917
			>15.7	1450
			18.2	1630
			11.9-12.2	0
			12.9	212
			13.2	472
4	0.698 (0.275)		15.4	685
			13.5	689
			17.8	831
			>15.7	835
			16.7-17.1	870
			13.3-14.6	0
			15.8-20.1	212
			16.85	268
5	1.0 (0.4)		18.8	472
			16.8	685
			17.4-19.8	689
			18.3-19.0	870
			8.6-9.0	0
			9.4	212
			10.4	776
			12.2-14.3	1270
6	1.0 (0.4)	⊥	13.4-14.3	1630
			15.4	1820
			18.3	2340
			16.6	2370

^aUnits for numbers in parentheses are inches.

below:

The results for all the measurements are summarized

1. For $B \perp V$, the wave action is strongly suppressed for relatively low field strengths and mean pressure gradients. Maximum values of B and γ used in these experiments were about 0.0108 T and 2360 Pa/m, respectively, above the center of the tin surface. The value $\gamma = 2360$ Pa/m resulted in an SF value = 1.95 ± 0.1 (i.e., $V_c \sim 20$ m/s). To place these values of B and γ in perspective, it takes about 0.033 T to balance the force of gravity on a quarter-inch (0.635 mm) sheet of steel. In addition, a value of $\gamma = 6.9 \times 10^4$ Pa/m is required to satisfy the Raleigh-Taylor criterion for stable levitation of the liquid sheet (essentially a doubling of the magnetic pressure within a distance equal to one sheet thickness). Hence, the values of B and γ used in these experiments are well below those required for a horizontal levitation-type caster. This suggests that small fields above the tin surface can be used to suppress coolant-gas wave formation during levitation.
2. The condition of the liquid metal surface influences the value of V_c , i.e., the onset of wave formation. Smooth, clean surfaces have higher values of V_c . The value of V_c in the absence of any magnetic field ranged from about 8.5 to 12 m/s, depending on the tin surface condition.
3. Plots of SF vs. γ showed a dependence of the form $SF = a\gamma^b + 1$, with $b \geq 1$ for $B \perp V$ and a N_2 channel depth of 1.0 cm. With the narrower channel depth (0.698 cm), there was an indication that b in the above relation was somewhat higher. However, the data were too limited to arrive at a definitive conclusion.
4. The data for $B \parallel V$ were more difficult to interpret, largely because of surface deformation effects. The results showed the existence of two opposing effects: one tending to suppress wave formation (the γ -dependent effect that was clearly dominant in the case of $B \perp V$), and one tending to enhance wave formation (the surface deformation effect not seen in the case of $B \perp V$). In the case where the tin surface was quite clean and smooth, the γ -dependent effect dominated at low values of $\bar{P}$ and γ , and the deformation effect became increasingly important at higher values of $\bar{P}$. In cases where the tin surface had become quite rough and scaly, the surface deformation effect appears to neutralize the γ -dependent

effect and even to dominate it at low values of γ and $\bar{P}$. That is, both the surface deformation effect and surface roughness tend to enhance wave formation, whereas the presence of the magnetic field and surface smoothness tended to enhance wave suppression. For example, the data set plotted in Fig. 3-22 for $B||V$ and a channel depth of 1.0 cm showed a relatively large V_c ($\gamma=0$) and dominance of the γ -dependent effect at low values of γ and $\bar{P}$. This case corresponded to a very smooth tin surface. The data shown in Figs. 3-23 and 3-24 correspond to a case with a rougher tin surface. The data set plotted in Figs. 3-25 and 3-26, which was for the channel depth of 0.689 cm, showed a very strong γ dependency. In general, when the behavior of V_c was strongly controlled by the γ -dependent suppression, the data in a plot of V_c vs. γ fell within a relatively narrow band.

5. Had the liquid tin pool size been chosen to just fit the good-field region of the magnet, the γ -dependent wave suppression would probably have been stronger in the case of $B||V$ than $B\perp V$.

3.3.1.4 Conclusion

These experiments showed that wave formation at the interface between the high-velocity coolant gas and the hot liquid metal is strongly suppressed by relatively modest values of magnetic pressure and pressure gradient produced by 10 kHz excitation. The values of $\bar{P}$ and γ used in these experiments were well below those expected to pertain in stable levitation of a liquid metal sheet. The suppression was observed for both $B\perp V$ and $B||V$. In the latter orientation, the results were somewhat complicated by experimental artifacts, but the results suggested that the suppression effect was larger with $B||V$ than $B\perp V$. The degree of surface smoothness also appeared to significantly affect the threshold gas velocity for wave formation. Brand new liquid tin surfaces showed substantially higher values of the threshold velocity. There was some evidence to indicate that the dependence of V_c on γ was affected by the N_2 gas channel depth, although the number of data obtained in these experiments was too limited to draw any definitive conclusions.

3.3.2 Fluid Flow Analysis with Water

The objective of this effort was to investigate the effect of tundish and nozzle geometries on the velocity and shape of the liquid stream leaving the feed system. Experiments were designed to aid in the final design of the feed system for the bench-scale horizontal and vertical casters.

3.3.2.1 Water Modeling

To investigate molten steel flow phenomena in a tundish, water is usually used as the modeling fluid because it is easy to handle,

readily available, and easy to trace. But more than that, with water as a modeling fluid, it is possible to attain dynamic, geometric, and kinematic similarity to molten metal. In a full-scale tundish, this is because the kinematic viscosity of water is close to that of liquid steel. Thus, water modeling satisfies both of the needed similarity relations:

$$(F_r)_{\text{water}} = (F_r)_{\text{steel}} \quad (9)$$

$$(Re)_{\text{water}} = (Re)_{\text{steel}}, \quad (10)$$

In these relations, F_r is the Froude number,

$$F_r = \frac{V^2}{gL} = \frac{\text{Inertia force}}{\text{Gravity force}}, \quad (11)$$

and Re is the Reynolds number,

$$Re = \left[\frac{VL}{\nu} \right] = \frac{\text{Inertia force}}{\text{Viscous force}}, \quad (12)$$

where

- V = stream velocity
- g = gravitational acceleration
- L = characteristic length
- ν = kinematic viscosity

3.3.2.2 Experimental Equipment

The water model apparatus (Fig. 3-28) of the horizontal bench-scale feed system was designed and fabricated to investigate the effects of tundish and nozzle geometry on the velocity profile, turbulence, and shape of a liquid jet leaving the feed system. The data obtained from these experiments should thus aid in the final design of a feed system for the EMCC process. The schematic layout of the recirculating flow system is shown in Fig. 3-29. The water model apparatus contained a shallow tundish (15 x 50 x 50 cm) with baffle plates and a 15-cm wide outlet for connecting nozzles, a catch basin, a recirculating pump with flow meter and control valve, and a submerged inlet nozzle.

The main geometrical factors for the nozzle that may influence the shape and velocity distribution of the emerging liquid stream include (1) the aspect ratio of the nozzle cross section, (2) the area contraction ratio from inlet to exit, (3) the length of straight section,

Fig. 3-28. Photograph of Water Model Apparatus for Feed System Study

and (4) the corner curvatures of the exit cross section. Another factor, of course, is whether the nozzle is of the open- or closed-channel type. To determine the effects of these geometrical factors and to compare fluid flow between open- and closed-channel nozzles, eleven plexiglass nozzles were built and tested. The geometry and dimensions of the nozzles were selected (see Table 3-3 and Figs. 3-30 through 3-33) so that a broad range of conditions could be studied, e.g., nozzle length, stream thickness, and converging and straight nozzles.

The experimental equipment included a dye injection port in the pipe leading to the tundish inlet for flow visualization and for determination of residence time distribution. Instrumentation also included a spectrophotometer, thermal conductivity probes, an ultrasonic pulse echo reflection device, a mechanical device to measure the cross-sectional shape of the exit stream, and a hot wire anemometer to measure the velocity and turbulence distribution.

The steady-state flow rate was measured as a function of the liquid height in the tundish for five nozzles. The data are plotted in Figs. 3-34 through 3-36, along with their fit to smooth curves by the method of least squares.

Fig. 3-29. Schematic Layout of Water Modeling Experiment

Table 3-3. Lengths "b" and "f" of Nozzles A, B, C, D, E, and G^a

	Length, in.					
	A	B	C	D	E	G
b	11 $\frac{15}{32}$	11 $\frac{15}{32}$	5 $\frac{15}{32}$	5 $\frac{1}{2}$	11 $\frac{15}{32}$	0
f	$\frac{1}{4}$	$\frac{1}{8}$	$\frac{3}{16}$	$\frac{1}{4}$	1	$\frac{1}{4}$

^aDefined in Fig. 3-30.

3.3.2.3 Observations

Although only a limited number of experiments were conducted, the following qualitative observations have been made: (1) immediately on leaving the rectangular nozzle, the liquid stream begins to accelerate downward under the influence of gravity and starts to form a "dog-bone" shape

Fig. 3-30. Schematic Representation of Nozzles A, B, C, D, E, and G

Fig. 3-31. Schematic Representation of Nozzle F

(Fig. 3-37); (2) because of gravitational acceleration, the width of the liquid stream starts decreasing and the thickness starts increasing as the stream moves further away from the nozzle; (3) the free surface roughness is more when the velocity and turbulence are higher and when the straight section of the nozzle is longer.

Fig. 3-32. Schematic Representation of Nozzles H, I, and J (1.3-cm long)

Fig. 3-33. Schematic Representation of Converging Nozzle K

Fig. 3-34. Volumetric Flow Rate as Function of Water Head for Nozzles A, D, and G

Fig. 3-35. Volumetric Flow Rate as Function of Water Head for Nozzles A and B

Fig. 3-36. Volumetric Flow Rate as Function of Water Head for Nozzles C and D

NOZZLE C - FLOW RATE = 11.15 gpm

NOZZLE B - FLOW RATE 5.22 gpm

NOZZLE A - FLOW RATE = 12.2 gpm

Fig. 3-37.

Liquid Jet Shape Formed 3.8 cm (1.5 in.) from Exit of Nozzle A, B, and C. (Dimensions in figure are inches unless otherwise stated.)

The effect of the nozzle length on surface roughness can be attributed to boundary layer formation on the solid wall: the essentially flat profile at the end of the nozzle contraction (inlet of straight section) starts becoming nonuniform as fluid moves through the straight section. At the nozzle exit, the wall constraint is removed, and the process of velocity profile relaxation (changing back from a nonuniform velocity profile to a uniform one) begins to redistribute the momentum. The lateral motion of fluid elements associated with this redistribution of momentum or profile relaxation continues to a point past the original stream surface to produce surface roughness. Preliminary velocity profile measurements with a hot-film anemometer indicated that the free-stream velocity profile became uniform very close to the nozzle exit plane.

Some flow experiments with the water model were conducted to compare flows through open- and closed-channel rectangular nozzles. The results were recorded on video tape. Exit stream quality was essentially the same for both open and closed channels provided that the Froude number was less than one. For Froude numbers greater than one, the stream quality at the channel exit was not as good for open as for closed channels. The open-channel stream surface showed characteristic standing wave patterns for Froude numbers greater than one. A hydraulic jump was observed near a Froude number of unity, and its position within the open channel could be controlled. Upstream of the jump, the flow was supercritical, and the stream surface displayed the characteristic standing wave pattern. Downstream, the flow was subcritical and the stream surface was much smoother. It may be possible to utilize such hydraulic jumps in combination with EM stream shaping to attain desirable stream characteristics.

3.3.3 Liquid Metal Flow Studies

As a result of literature reviews and meetings of the Feed System Working Group, it became clear that there was a need for experimental information regarding molten metal flow at relatively low fluid velocities through nozzles having large aspect ratios and a need for information regarding the impact of EM fields on such flows. These perceived needs led to the formulation of plans to conduct a series of experiments culminating in a bench-scale demonstration of stable levitation of a flowing liquid metal.

The initial experiments in this planned series were to focus on the flow of closed-channel nozzles of various sizes. These were to be followed by some experiments designed to investigate the use of EM devices to control various liquid metal stream parameters. The liquid metal flow studies were only partially completed because of termination of program funding.

In order to perform these experiments, we designed and fabricated a recirculating liquid tin system in a nitrogen-atmosphere glove box. This system is illustrated in Fig. 3-38. The system had a tundish of the same size and shape as was used in the water model apparatus so that the results from the two model fluids (water and liquid tin) could be readily compared. Water is a good modeling fluid for steel, as explained in Sec. 3.3.2, because it has the same kinematic viscosity as steel. Tin is a good modeling fluid for steel flows involving EM fields because its density, surface tension, and resistivity are similar to those of steel.

As illustrated in Fig. 3-38, liquid tin flows from the tundish, through a nozzle and EM flow control device, and into a catch basin, where it passes through a porous ceramic filter and is subsequently pumped through stainless steel tubing back into the tundish with an EM conduction pump. The tundish, nozzle, catch basin, and tubing are insulated and separately temperature regulated with thermostatically controlled heaters. A flange is fitted to the tundish with a 15-cm wide outlet for connecting nozzles of lengths up to 30 cm. The system, with the exception of the EM pump, was contained within a nitrogen glove box. The EM pump was a vintage 1950 unit that was taken from an old NaK recirculation system built for reactor experiments.

Fig. 3-38. Schematic of Experimental Recirculating Tin Feed System

Since a variety of different nozzle designs were to be used with this facility, a simple method of nozzle fabrication was sought. The nozzle material had to be easy to machine and work with, resistant to wetting by liquid tin, capable of withstanding temperatures in the 230-250°C range, and nonmagnetic. Material choices included Teflon, Fluorosint, machinable ceramics, and moldable refractories. A Teflon design was first tried and found to be unsuitable due to shape distortions at operating temperatures. A Teflon nozzle reinforced with Fluorosint and aluminum strips provided much better dimensional stability, but, when subjected to flowing liquid tin, developed leaks at the tundish/nozzle interface because of thermal distortion and poor interface design. Following this test, the interface design was changed and a manually operated slide gate was added. The slide gate was

fabricated of fired lava components. A nozzle was also constructed of lava, which is easy to machine in the unfired state and undergoes only a slight change in dimension during firing. It was found that the lava nozzle parts underwent predictable dimensional changes and maintained shape integrity. Hence, lava appears to be a suitable material. Under operating conditions, the fired lava slide gate and nozzle performed very well. However, because of the brittleness with this fired material, it must be handled with care.

During test of the system using an open-channel nozzle, all components performed well until a leak developed at a pipe joint upstream of the pump. This leak was believed to be the cause of erratic EM pump behavior and excessive oxidation of the tin. A shortcoming of the EM conduction pump was that it required continuous and complete contact with the pipe sidewalls that served as current electrodes in the pump. If air is entrained in the liquid stream through a leak, it could seriously degrade the pumping action by interrupting the contact between the fluid and the current electrodes. It was not possible to repair the leak and retest the system before the program was terminated.

Following this initial series of glove box experiments, the plan was to construct a recirculating tin feed system for use with a modified version of the test magnet and to then study the interaction of high-frequency magnetic fields (10-100 kHz) with a continuous stream of tin having a large aspect ratio. This series of experiments would have led to a demonstration of stable levitation of liquid tin. A schematic diagram of the conceptual flow-through levitation demonstration system is shown in Fig. 3-39. This system was not constructed.

3.4 Future Work

3.4.1 Feed System

Three issues related to the feed system require further experimental investigation:

1. The development of refractory nozzles and/or channels to conduct large-aspect-ratio liquid metal streams into the levitation caster. Of primary interest are externally supported open channels that can carry the molten metal through the EM flow control device and into the levitation magnet.
2. The development and evaluation of various options for electromagnetically controlling stream flow parameters before the stream enters the good field region of the levitation magnet.
3. The development and testing of a coarse EM flow control device and a suitable-shaped conduit for liquid steel.

In addition, systems to regulate temperature will have to be developed for the above-mentioned components of the feed system.

Fig. 3-39. Conceptual Design for Recirculating Flow-Through System for Demonstrating Levitation of Liquid Tin

3.4.2 Fluid Flow Analysis

3.4.2.1 Wave Formation and Suppression

Although this work is substantially completed, there are some aspects that are still worthwhile pursuing. These include wave formation and suppression in the presence of a uniform, horizontal magnetic field. Such an experiment would require the use of the test magnet or a similarly constructed magnet having a uniform, horizontal magnetic field. A special test section would have to be built to direct a flow of N_2 over a pool of liquid metal. Investigations should be initiated on both $B||V$ and $B\perp V$ orientations, a greater range of values of N_2 -channel depth, and the influence of placing a magnetic shield in the form of a conducting screen above the molten metal surface.

3.4.2.2 Flow-Through and Closed-Channel Nozzles

Only qualitative studies have been conducted with 6-in. (15-cm) wide nozzles so far. Quantitative experiments are required in which flow parameters such as the velocity and turbulence profiles are measured as a function of channel and nozzle design.

3.4.2.3 Liquid Metal Flow Studies

Qualitative and quantitative studies of both model fluids and liquid steel are required to test conduit channel and nozzle designs, evaluate materials, and determine performance of EM devices designed to control various flow parameters such as velocity and turbulence profiles. Probes will have to be developed to conduct measurements of flow parameters in liquid metals.

A flow-through system should be designed (1) to operate in conjunction with the test magnet for conducting flowing metal levitation experiments with model fluids and (2) to operate in conjunction with a modified version of the test magnet for flowing steel levitation experiments. It is recommended that preliminary flow-through levitation experiments be conducted with a model fluid and a closed-loop recirculating system similar to the apparatus described in Sec. 3.3.3 so that sufficient time will be available for investigating MHD stability under transient and steady-state flow conditions.

4.0 HEAT TRANSFER AND COOLANT SYSTEM

A key element in the development of the electromagnetic continuous casting (EMCC) process is a heat transfer and coolant system able to remove a large amount of heat in a short time. Development of this system is further complicated by the fact that additional heat is imposed by the induced eddy currents. Radiative cooling is insufficient to meet the requirements and must be augmented with convective cooling. Only nonoxidizing gases are permissible with the EMCC process. In addition, there are restrictions on the upper boundary of the coolant mass flow rate (velocity and density) due to the possible detrimental effect of the coolant flow on the stability of EM levitation. These restrictions, which result in poor heat transfer coefficients, make the design of a coolant system more difficult. Extensive theoretical and numerical analyses have been conducted to define the coolant requirements and identify possible solutions to these design problems.

Based on an initial evaluation of the coolant system requirements, reference operating conditions were selected. Consistent with these operating conditions, work has been directed toward (1) parametric investigations for establishing the cooling requirements in terms of casting speed, magnet length, coolant mass flow rate, and degree of heat transfer augmentation, (2) experiments to obtain supporting data for heat transfer augmentation, and (3) development of nomograms for studying the effect of various operating parameters on the EMCC process. A description of the efforts in the above three areas is presented below.

4.1 Parametric Analysis

The success of continuous casting of steel depends, to a large extent, on the rate of heat transfer from the superheated liquid steel. Because of the reactive nature of the liquid steel, compatibility of the coolant with the liquid steel is one of the primary considerations in selection of a coolant. In addition, the geometry of the electromagnetic confinement of liquid steel and possible integration between the levitated liquid strip with a high-velocity coolant stream impose severe limitations on the coolant mass flow rates. During the course of the initial phases of the EMCC project, a large number of parametric studies were carried out to select a coolant and a coolant system for the bench-top caster. Detailed study showed some of the original cooling concepts (e.g., high-pressure, high-velocity coolant) to be incompatible from the standpoint of solidification requirements within the electromagnetic confinement. It is expected that this summary of the preliminary analyses will guide the future activities in this field if the EMCC project gets activated in the future.

4.1.1 Development of Mathematical Model

A schematic representation of a coolant system is shown in Fig. 4-1. A mathematical model to study the solidification phenomenon and the casting characteristics of the EMCC mold was developed based on the following assumptions:

- One-dimensional heat flow.
- Negligible convection in liquid.

- Uniform coolant velocity and casting speed.
- Negligible axial conduction.
- EM heat flux on only one side for the horizontal caster.
- Heat removal by convection and radiation.

Fig. 4-1. Schematic of EMCC Coolant System

The governing equations and the boundary conditions are listed below:

$$\frac{q_s}{dX} + q_v + \frac{\partial}{\partial X} \left(K \frac{\partial T}{\partial X} \right) = u\rho \left(\frac{\partial H}{\partial Z} \right) \quad (1)$$

$$H = \int_{T_{ref}}^T C_p dt \quad (2)$$

$$Z = u\theta \quad (3)$$

$$\rho \frac{\partial H}{\partial \theta} = \frac{\partial}{\partial X} \left(K \frac{\partial T}{\partial X} \right) + \frac{q_s}{dX} \quad (4)$$

where
 T = temperature
 X = thickness of slab

u = casting speed
 ρ = density of steel
 Z = direction of flow
 K = thermal conductivity
 H = enthalpy
 C_p = heat capacity
 θ = time
 T_{ref} = reference temperature
 q_s = heat flux per unit surface area
 q_v = heat flux per unit volume

The boundary conditions that are necessary for solving the above equations are:

$$X = 0, \quad \frac{\partial T}{\partial X} = 0 \quad (5)$$

$$X = \frac{L}{2}, \quad -k \frac{\partial T}{\partial X} = \Sigma Q \quad (6)$$

where L is the thickness of the strip, and ΣQ is the summation of all modes of energy transfer at the steel strip/coolant interface. In general, two basic approaches have been used to characterize the solidification phenomena. For an alloy which solidified over a temperature range, the solution method based on enthalpy equations is preferred. A computer program was developed based on the finite difference method for solving the enthalpy equations. The results were compared with a method using temperature equations. The results showed that both methods are acceptable for analysis of the EMCC process. Since the temperature method of solution is simpler, it was used for the EMCC studies.

4.1.2 Calculation of Heat Transfer Requirements

During the ANL/Steel Industry Workshops on Heat Transfer and Coolant Systems, a set of reference conditions (see Table 4-1) was established as the basis for calculating heat transfer requirements and as an aid in determining methodologies to obtain the required cooling. During the initial phase of the EMCC analyses, the coolant systems were based on more optimistic conditions, such as higher coolant pressure, higher coolant velocity, H_2O additive to coolant gas, and higher mean outlet temperature. In addition to the reference conditions set at the workshops, options at higher velocity and higher pressure were included in Table 4-1 for comparison of effects. Extensive parametric studies have been carried out based on these conditions. The mean outlet temperature of 1455°C is based on the belief that complete solidification is required before the strip can be mechanically supported. Since

Table 4-1. Reference Operating Parameters

Mean Outlet Temperature	2650°F (1455°C)
Strip Size	Any width x 6-mm thick
Casting Speed	30 cm/s (67 tons/strand•h for 1.2-m wide strip)
Coolant Pressure	20, 30 ^a psia (140, 210 kPa)
EM Heat Flux	50 W/cm ²
Emissivity of Steel	0.4, 0.6 ^a
Coolants	Nitrogen, Carbon Dioxide
Coolant Velocity	30, 40 ^a m/s
Magnet Length	4, 6, 8, 10 m
Coolant Channel Height	10 to 12.5 cm

^aHigher pressure, emissivity, and velocity options.

it may be feasible to develop a mechanical support system for a partially solidified strip, an exit temperature of 1455°C may be an overly conservative restriction. The emissivity (ϵ) value of 0.4 for steel is low, even for ultrapure surfaces. Hence, illustrations have also been included for $\epsilon = 0.6$ because the emissivity will increase owing to surface contamination and the formation of a solid skin. Higher coolant velocity (40 m/s) and pressure (210 kPa) options were included to examine the effects of some evolution in technology.

The heat transfer coefficients estimated from empirical equations are shown in Table 4-2 for nitrogen coolant. The heat transfer coefficients that are required to meet the operating conditions of Table 4-1 are graphically presented in Fig. 4-2. Comparison of the required heat transfer coefficients (Fig. 4-2) with the feasible ones (Table 4-2) clearly shows that some heat transfer augmentation is necessary for magnets less than 10-m long.

Figure 4-3 illustrates the required augmentation factors for four different cases (A-D, defined in Table 4-2) as functions of magnet length at $\epsilon = 0.4$. As shown in Fig. 4-3, Case A requires an augmentation factor of 3 for a 10-m long magnet, whereas Case D requires an enhancement factor of only 2 for a magnet length of less than 6.5 m. Also, for magnet lengths that do not exceed 10 m, Fig. 4-3 shows that Cases B, C, and D require a heat transfer augmentation factor of only 2, which should be easily achievable.

Figure 4-4 presents similar calculations for the higher emissivity value ($\epsilon = 0.6$). Even for the most-conservative coolant conditions (Case A), the required magnet length is reduced to about 8 m for an enhancement factor of 2. For the optimistic coolant system scenarios (Cases C and D), Fig. 4-4 shows that it is feasible to design an EMCC device with a magnet that is less than 10-m long and does not require heat transfer augmentation. Of course,

Table 4-2. Estimated Heat Transfer Coefficients

Case ID	Operating Conditions		Heat Trans. Coeff. for N ₂	
	Pressure, ^a psia	Velocity, m/s	Btu/(h·ft ² ·°F)	W m ⁻² K ⁻¹
A	20 (140)	30	15	85
B	20 (140)	40	19	108
C	30 (210)	30	21	120
D	30 (210)	40	26	148

^aNumbers in parentheses have units of kPa.

Fig. 4-2.

Required Heat Transfer Coefficients (HTC) as Function of Magnet Length

Fig. 4-3.

Required Augmentation Factors
as Function of Magnet Length for
 $\epsilon = 0.4$

Fig. 4-4.

Required Augmentation Factors
as Function of Magnet Length
for $\epsilon = 0.6$

this requires verification of the velocity and pressure limits in terms of the dynamic stability of the levitated strip. Also, it should be noted that the development of a mechanical support system for partially solidified strip would significantly reduce the magnet lengths discussed above.

In sum, the heat transfer analyses show that heat transfer enhancement is required to design an EMCC magnet less than 10-m long with operating conditions limited to the reference values in Table 4-1. The data presented in the next section show that attaining heat transfer enhancement by a factor of 2 to 3 is relatively easy.

4.1.3 Augmentation of Heat Transfer

Great technological advances have been made in heat transfer augmentation techniques that cover a wide spectrum of operating conditions and heat transfer modes. Two conditions are of special interest to certain emerging industrial applications: where only convective cooling by a gaseous coolant is acceptable, and where no augmentation devices or turbulence promoters are permissible because they may significantly disturb the boundary layer. Augmentation of heat transfer by adding fine droplets of a liquid (e.g., water) to a gaseous coolant appears to be suitable for such applications. It is generally believed that heat transfer enhancement by mist coolants (gas + water droplets) is due to evaporation of droplets, larger heat capacity of the mixture compared with the gas alone, and microconvection at the boundary layer; however, the exact contribution by each mechanism is difficult to assess. A survey of the literature on mist coolants was conducted and the results found in the literature are summarized in the next section.

4.1.3.1 Mist Coolants

Augmentation of heat transfer by adding fine droplets of a liquid (e.g., water) to a gaseous coolant has been found to greatly increase the cooling potential of inherently poor gaseous coolants. Therefore, applying a mist coolant over a partially solidified strip within the EM confinement would significantly reduce the total length of the magnet. Because of the high heat of vaporization of water, calculations show that evaporation of droplets can significantly enhance heat transfer (by lowering the bulk temperature), especially in situations where high surface temperatures and long residence times for the mist coolant are involved (e.g., EMCC). A study of the literature¹⁻⁹ showed that the effectiveness of mist coolants (up to 30-fold increase in heat transfer coefficients in some cases) at low temperatures is well established. However, several experimental studies¹⁰⁻¹³ have indicated a sudden and significant decrease in the effectiveness of mist coolants in the temperature range of 150 to 500°C, depending on the experimental conditions. This has led many designers to conclude that mist cooling is ineffective at elevated temperatures (>600°C), even though experimental data^{14,15} show a monotonic increase in heat flux with rise in surface temperature. Significant progress has been made in developing analytical models for complex two-phase, two-component systems, yet no satisfactory models exist that can be utilized to design a coolant system at these high

temperatures. Many experiments^{16,17} have been conducted to investigate the characteristics of spray nozzles and mist coolants, especially in the secondary cooling of steel, but no consensus exists on the best secondary cooling techniques. In view of the above facts, there is a need to gain a better understanding of mist coolants beyond the Leidenfrost temperature regime. The experimental program described in a later section is expected to shed some light on mist coolants.

4.1.3.2 Augmentation Devices

In addition to augmentation of heat transfer by adding fine droplets of a liquid to a carrier gas, many novel techniques have been developed to modify the boundary layer so that the convective transport of energy is increased. A brief survey of the literature on heat transfer enhancement was carried out, with particular emphasis on methods that do not lead to an associated increase in frictional pressure drop. The literature¹⁸⁻²¹ shows a wide selection of such techniques and devices if one requires only moderate enhancement (a factor of 2 to 3). Table 4-3 lists four methods and their experimental augmentation enhancement factors. These results show that heat transfer enhancement by a factor of two to three can be easily obtained. It is recognized that the augmentation method used must not interfere with the dynamic stability of the levitated strip, and experimental verification of this will be required.

Table 4-3. Methods for Heat Transfer Augmentation and Their Augmentation Factors

Method ^a	Augmentation Factors	Ref. No.
Swirling Flow	4	18
Displaced Device	>5	19
Scrapping Boundaries	~1.8	20
Novel Promoter	2.5	21

^aMany references exist, but four selected here.

4.1.4 Coolant System Methodologies

The coolant channels are located between the thermal radiation shields that protect the electromagnet against the high-intensity thermal radiation from the liquid steel. For the purposes of thermal analysis of the steel strip within the electromagnet, the radiation shields are assumed to be cooled either by an inert gas (the same as the EMCC system coolant) or by water. An approximate mass flow rate of the gas can be obtained based on assumptions regarding the total gas temperature rise and the coolant channel width. For the parametric studies, the coolant channel width was assumed to vary between 4 and 6 cm, and the coolant temperature rise was assumed to vary

between 500 and 700°C. The coolant is assumed to be diathermic so that the total thermal energy is absorbed by the radiation shields, which are considered to be black bodies. To prevent direct impingement of coolant jets against the liquid strip, the coolant manifold design assumes that the coolant is introduced through porous walls. The liquid droplets are introduced into the coolant stream (mist cooling) after a solidified layer is formed on the steel strip.

The relative merits of gaseous coolants can be evaluated from the conventional empirical equations that form the basis of calculation of the heat transfer coefficient. Since both nitrogen and carbon dioxide react with liquid steel to some extent, one might consider the use of argon as a potential coolant. Because of the poor thermal transport properties of argon, one should consider improving the heat transfer coefficients by using a mixture of argon and helium (which has excellent transport properties). The heat transfer coefficients for a mixture of argon and helium are presented in Table 4-4 for the same operating conditions as listed in Table 4-1.

The data presented in Table 4-4 show that one can use a mixture of helium and argon, which is completely inert to liquid steel, to obtain essentially the same heat transfer coefficients as for 100% N₂ or CO₂. However, a mixture of helium and argon will be more expensive to operate, even for a recirculating coolant system with very little leakage losses. Extensive parametric studies have been carried out using coolants of both CO₂ and a mixture of He and Ar. These results are not included here because the heat transfer characteristics of these gases are similar to those of nitrogen.

Table 4-4. Estimated Heat Transfer Coefficients for Two He-Ar Coolants

Case No. ^b	Heat Transfer Coefficients, ^a Btu h ⁻¹ ft ⁻² °F ⁻¹	
	10% He + 90% Ar	20% He + 80% Ar
A	14 (79)	18 (102)
B	18 (102)	22 (125)
C	20 (113)	25 (142)
D	25 (142)	31 (176)

^aNumbers in parentheses have units of W m⁻² K⁻¹.

^bDefined in Table 4-2.

4.2 Parametric Nomograms

Extensive parametric analyses have been conducted to identify the interactions of various parameters in the EMCC process. The focus of these analyses has been to (1) perform heat transfer analysis, (2) determine important physical and geometric parameters, (3) examine how they affect

cooling of liquid steel, and (4) develop design charts that will aid in the optimum design of a coolant system for the EMCC process. These analyses provide information on the total heat extraction requirements and heat transfer coefficients needed as a first step in the design of a cooling system for the EMCC process. Further, they address the feasibility of the EMCC process from a heat transfer consideration. The analyses have been performed in a very generalized fashion to provide sufficient flexibility in the selection of geometrical and physical parameters and to aid in the design of a cooling system for an EM caster ranging from bench scale to production scale.

4.2.1 Total Heat Extraction Rate for Solidification

To solidify a pound of liquid steel, the amount of cooling (heat extraction) required is

$$\begin{aligned} Q &= C_{p_{liq}} (T_{in} - T_{liq}) + C_{p_{mush}} (T_{liq} - T_{sol}) \\ &\quad + C_{p_{sol}} (T_{sol} - T_{out}) + L_s \\ &= 131.63 + 0.160 (2723 - T_{out}), \end{aligned} \tag{7}$$

where Q = required cooling (heat extraction) (Btu/lb of steel)
 $C_{p_{liq}}$ = specific heat of liquid (~ 0.165 Btu/lb $^{\circ}$ F)
 $C_{p_{mush}}$ = specific heat of steel in the mushy zone (0.160 Btu/lb $^{\circ}$ F)
 $C_{p_{sol}}$ = specific heat of solid (~ 0.160 Btu/lb $^{\circ}$ F)
 T_{in} = inlet temperature ($\sim 2826^{\circ}$ F)
 T_{liq} = liquidus temperature of steel (2796° F)
 T_{sol} = solidus temperature of steel (2723° F)
 T_{out} = outlet temperature ($^{\circ}$ F)
 L_s = latent heat (~ 115 Btu/lb)

In the EMCC process (Fig. 4-5), if $\dot{m}$ is the mass flow of liquid steel and A_s is the total surface area of slab for cooling in the magnetic zone, then the heat extraction rate, $\dot{q}_s$, required for solidification is

$$\dot{q}_s = \frac{Q (3600 \text{m})}{(A_s / 144)}, \tag{8}$$

where $\dot{q}_{st}''$ = heat extraction rate (Btu/h ft²)

$\dot{m}$ = ρtwu = liquid steel flow rate (lb/sec)

ρ = density of steel (~0.256 lb/in.³)

t = slab thickness (in.)

w = slab width (in.)

u = casting speed (in./sec)

A_s = $2 Lw$ = total cooling surface area in the magnetic zone (in.²)

L = magnetic zone length (in.)

Substitution of the expressions for $\dot{Q}$, $\dot{m}$, and A_s in the above relation gives

$$\dot{q}_{st}'' = 6.636 \times 10^4 \frac{ut}{L} \left[131.63 + 0.160 (2723 - T_{out}) \right]. \quad (9)$$

It can be seen from this relation that the desired outlet temperature (T_{out}), slab thickness (t), casting speed (u), and magnet length (L) are the four major parameters that determine the heat extraction rate required for solidification in the EMCC process. To cover a wide range of values of these parameters, a generalized nomogram was constructed (Fig. 4-6). The following case illustrates how this nomogram can be used to obtain the required heat extraction rate. The line A-B-C-D-E-F is constructed assuming an outlet temperature of 2650°F (1454°C), a slab thickness of 0.25 in. (0.635 cm), a casting speed of 10 in./s (25.4 cm/s), and a magnet length of 200 in. (5.08 m). The termination of the line at F indicates the required heat extraction rate for this case, which is 1.19×10^5 Btu/h ft² (3.75×10^5 W/m²).

4.2.2 Convective Heat Transfer Coefficient

Once the total heat extraction requirement has been determined, the convective heat transfer requirement can be calculated if one knows the electromagnetic heating and radiative heat transfer. This is because, from the energy balance,

$$\dot{q}_{conv}'' = \dot{q}_{st}'' + \frac{1}{2} \dot{q}_{em}'' - \dot{q}_{rad}'', \quad (10)$$

where $\dot{q}_{conv}''$ = convective cooling (Btu/h ft²)

$\dot{q}_{em}''$ = electromagnetic heating (Btu/h ft²)

$\dot{q}_{rad}''$ = radiative heat transfer (Btu/h ft²)

In the above equation, a multiplier of $1/2$ is used in the electromagnetic heating contribution because all of the electromagnetic heat is generated near the bottom surface (half of the total surface area) of the slab.

Fig. 4-5. Schematic Showing Important Parameters for Cooling Requirements with EMCC

Fig. 4-6. Nomogram for EMCC Cooling Requirements

The convective, radiative, and electromagnetic contributions can be expressed as

$$\dot{q}_{\text{conv}} = h \Delta T \quad (11)$$

$$\dot{q}_{\text{rad}} \sim \epsilon \sigma (T_s + 460)^4 \quad (12)$$

$$\frac{1}{2} \dot{q}_{\text{em}} \sim 1.0784 \times 10^4 \sqrt{f}, \quad (13)$$

where h = convective heat transfer coefficient (Btu/h ft² °F)
 ΔT = surface temperature - coolant temperature (°F)
 T_s = surface temperature (~2725°F)
 f = frequency (kHz)
 ϵ = emissivity
 σ = Stefan-Boltzmann constant = 0.1714×10^{-8} Btu/[h ft²(deg.abs.)⁴]

Three frequencies ($f = 26, 56,$ and 106 kHz) were considered as possible design values. The electromagnetic heating for these frequencies are listed in Table 4-5.

Table 4-5. Electromagnetic Heating at Three Frequencies

Freq., kHz	Electromagnetic Heating on One Side	
	W/cm ²	Btu/h ft ²
26	35	11.09×10^4
54	50	15.85×10^4
106	70	22.19×10^4

Substitution of the expressions of all heat transfer rates $\dot{q}$ into the energy balance equation, after simplification, results in

$$h = \frac{10^4}{\Delta T} \left[6.636 \frac{ut}{L} \left(131.63 + 0.160 (2723 - T_{out}) \right) + 1.078 \sqrt{f} - 17.64 \epsilon \right]. \quad (14)$$

This equation indicates that the heat transfer coefficient required for cooling depends on seven parameters:

$$h = f (\Delta T, u, t, L, T_{out}, f, \text{ and } \epsilon).$$

To cover a wide range of possible design parameters, two generalized nomograms have been constructed: one for slab thickness $t = 0.25$ in. (0.63 cm) and outlet temperature $T_{out} = 2650^\circ\text{F}$ (1454°C) (Fig. 4-7), and the other for slab thickness $t = 0.25$ in. (0.63 cm) and outlet temperature $T_{out} = 2600^\circ\text{F}$ (1427°C) (Fig. 4-8). These nomograms provide estimation of required heat transfer coefficient for a range of casting speed u , magnet length L , emissivity ϵ , electromagnetic heat, and temperature difference ΔT . The line A-B-C-D-E-F in Fig. 4-7 illustrates how to use these nomograms to determine the required convective heat transfer coefficient. For a 0.25-in. (0.63-cm) thick slab, outlet temperature of 2650°F (1454°C), casting speed of 10 in./s (25 cm/s), and magnet length of 200 in. (5.08 m), the cooling requirement is 1.19×10^5 Btu/h ft² (3.75×10^5 W/m²). For this cooling requirement, a surface emissivity of 0.4, electromagnetic heat generation on one surface of 50 W/cm², and a temperature difference between slab and coolant of 2625°F (1440°C), the termination line indicates that the convective heat transfer coefficient required is 48.9 Btu/h·ft²·°F (277.7 W/m²·K).

4.2.3 Feasible Region

In the previous section, the energy balance equation, Eq. 14, was used to determine the required convective heat transfer coefficient. The same equation when rearranged as

$$\phi = \frac{ut}{L} = \frac{h\Delta T - 10^4 \left[1.078 \sqrt{f} - 17.64 \epsilon \right]}{6.636 \times 10^4 \left[131.63 + 0.160 (2723 - T_{out}) \right]} \quad (15)$$

can be used to determine the feasible region for a given convective heat transfer coefficient. For the EMCC process to be feasible, the cooling system must be designed to provide convective heat transfer greater than a minimum required value. Therefore, Eqs. 14 and 15 can be interpreted as

$$h_{\text{cooling system}} \geq h_{\text{reqd}} = f \left(\phi_{\text{sys}}, \epsilon, f, T_{\text{out}}, \Delta T \right)$$

or

$$\phi_{\text{system}} \leq \phi_{\text{max}} = f \left(h_{\text{cooling system}}, \epsilon, f, T_{\text{out}}, \Delta T \right).$$

From heat transfer consideration, ϕ ($= ut/L$) is, therefore, a very important design parameter. The magnitude of ϕ determines what is the minimum value of heat transfer coefficient h required to make the EMCC process feasible. Alternatively, for a given heat transfer coefficient h , the equation provides a maximum value of ϕ that is acceptable for the EMCC process. In an implicit way, ϕ represents the reciprocal of the residence time for a given slab thickness because

$$\phi = \frac{\text{slab thickness}}{\text{residence time}},$$

and the tonnage for a given slab width and magnetic length because

$$\phi \left(\frac{\text{in.}}{\text{sec}} \right) = \frac{\text{tonnage/h}}{714.2 \text{ width (m) length (m)}}.$$

Figure 4-9 plots the feasible region of the EMCC process for a surface emissivity of 0.4, an electromagnetic heating of 50 W/cm² ($f = 54$ kHz), and a slab outlet temperature of 2650°F (1454°C). The dotted line illustrates that, for the $\phi_{\text{sys}} = 0.0125$, the minimum h_{reqd} is 48.9 Btu h⁻¹ft⁻²°F⁻¹ (277 W m⁻²K⁻¹). Alternatively, for $h_{\text{sys}} = 48.9$ Btu h⁻¹ft⁻²°F⁻¹, the ϕ_{sys} must be less than 0.0125. The feasible regions for other values of emissivity, electromagnetic heat, and outlet temperatures are plotted in Figs. 4-10 to 4-12.

4.3 Experimentation

As pointed out in Sec. 4.1.3, there is not only a need for an understanding of the nature of the mist coolants but also for experimental information on how mist coolants can be effectively used to shorten the length of the electromagnet or increase the casting speed for a given size of the electromagnet. The experimental program described below is directed toward a study of heat transfer augmentation for gaseous coolants by addition of fine droplets of a liquid (e.g., water) to a carrier gas.

4.3.1 Experimental Apparatus

The purpose of the experimental program is to assess the cooling characteristics, especially at elevated temperatures (up to 1500°C), of mist coolants consisting of a mixture of air, nitrogen or carbon dioxide, and fine droplets of water. The experimental setup is shown schematically in Fig. 4-13. The experimental apparatus consists of an electrically heated stainless steel test section (25-mm dia by 0.6-m long) with power supplied

Fig. 4-7. Heat Transfer Coefficient Requirements with Outlet Temperature of 2650°F (2454°C)

Fig. 4-8. Heat Transfer Coefficient Requirements with Outlet Temperature of 2600°F (1427°C)

Fig. 4-9. Feasible Region for EMCC

Fig. 4-10. Effect of Radiation on EMCC Feasible Region

Fig. 4-11. Effect of EM Heat on EMCC Feasible Region

Fig. 4-12. Effect of Outlet Temperatures on EMCC Feasible Region

from a 100 V, 5000 A dc power source. The outer surface of the test section is polished and chrome plated, and the test section itself is enclosed by an outer stainless steel tube, 60 mm in dia. The annular space between the test section and the enclosure is evacuated during tests. The coolant mixture is generated upstream of the test section in a spray chamber (see Fig. 4-14). The fine droplets of water formed either by a pneumatic nozzle or an ultra-sonic nozzle housed in the spray chamber are mixed with the bulk gas stream. The instrumentation system consists of (1) Chromel-Alumel and platinum-platinum + 10% rhodium thermocouples to measure the test section surface temperatures, coolant inlet and outlet temperatures, and spray water temperature, (2) humidity meter, (3) pressure transducers, (4) ammeter and volt meter, (5) voltage taps across the test section, (6) guard heaters, (7) flow meters, and (8) auxiliaries such as on-off valves, control valves, pressure regulator, and safety interlocks. The first phase of the experiments up to 600°C has been carried out using the stainless steel test section. Initially, both visual and photographic methods will be used to characterize the mist coolant (droplet size and volume fraction of droplets). During the later phases of the experiments, laser Doppler anemometry will be used to measure droplet size, size distribution, and velocity.

Fig. 4-13. Schematic of Experimental Setup for Assessment of Mist Cooling

The operating parameters for the first phase of the tests include temperatures between 200°C and 600°C, gas velocity of 10-200 m/s, droplet volume fraction of 0-1%, water droplet diameters varying from 10 μm to 150 μm , and three orientations (upward, downward, and horizontal flow) of the test section. The experimental data were expected to provide a basis to verify the

existing correlations and the existing data, especially at elevated temperatures, when tests during the second phase are completed.

Fig. 4-14. Schematic of Test Section for Assessment of Mist Coolant

4.3.2 Experimental Results

Tests were conducted using ambient air and ambient air mixed with water droplets and air velocities up to 200 m/s. The preliminary results showed that by addition of less than 1% by weight of water droplet, the heat transfer coefficients increased by more than fivefold. A detailed analysis of the results will be presented in a forthcoming ANL report.

4.4 Future Direction

The success of EMCC will depend on development of a cooling methodology which requires augmentation of heat transfer. It would be essential to show that mist coolants and augmentation devices have no detrimental effect either on the quality of the steel product or stability of EM levitation. If one is to rely on mist cooling as the chosen method of heat transfer augmentation, verification of the effectiveness of mist cooling at the EM cast temperatures is essential. Similarly, it would be necessary to verify experimentally that augmentation devices are compatible with EM levitation. It has been suggested that, by providing mechanical support to a partially solidified steel strip, the length of the electromagnet can be significantly reduced. Since there are no data to support the above contention, verification of mechanical support within the EM confinement is essential.

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5.0 SENSORS AND PROCESS CONTROL

The primary objective of this effort is to develop the sensors and control systems required for on-line process monitoring and automatic control of the EMCC process. The sensors and controls should permit safe and efficient operation of the caster, with improved product yield and quality. Efforts to date were focused on the sensors and control systems needed for the horizontal casting magnet and liquid metal feed system.

The scope of this development effort entails (1) identification of sensor needs and requirements, (2) review, selection, and/or development of needed sensors, (3) development of a process control model, (4) development of appropriate control schemes, and (5) installation and testing of a complete system.

5.1 Definition of Requirements

A prerequisite to defining the sensor and control requirements of a process is that the process be well defined and its dynamics adequately characterized. But, when a new technology is being developed, as in the case of electromagnetic casting, definition and characterization of the process dynamics require experimentation with various sensors and controls. Hence, the definition of requirements for sensors and controls must be established interactively by a systematic integration of the sensors and controls with the process. In this report, a preliminary definition of the sensor and control requirements is presented from a conceptual understanding of the EMCC process, as well as from the knowledge gained through the head-start and test-magnet experiments.

Consider Fig. 5-1, which shows the general schematic of a horizontal EMCC process. The major components of the process are (1) the feed system consisting of ladle, tundish, and EM flow control device; (2) the EM caster where the liquid metal stream is levitated; (3) the heat transfer and coolant system, which must remove the heat from the flowing liquid metal stream so that partial or complete solidification can be achieved before the stream leaves the caster; and (4) the withdrawal system, which rolls out the solidified strip for coiling or further processing in a cold mill. The key sensors required for process monitoring and control are the tundish liquid level, flow velocity and flow profile at the exit of the feed system nozzle, on-the-fly thickness, on-the-fly width, liquid strip surface topology, position of the onset of solidification, thickness of the solidified skin, vertical positions of the levitated strip, and the roll-out velocity of the solid strip. The requirements of these sensors vary, depending on the location of the sensors in the process flow path, as well as on their functions. The front-end sensors of the feed system, such as the ladle flow rate and tundish level, are similar to the ones used in the conventional continuous casters in the steel industry,¹ as are the sensors downstream of the caster. The sensors used in the EM caster region, however, have unique and tough requirements. The EM caster geometry consists of a rectangular magnet frame; a coil on the top and bottom; a heat shield to protect the coils and the magnet; limited spacing, especially at the bottom of the liquid strip because of the requirements of a conducting screen within a distance of twice the thickness of the strip; and a coolant channel that must surround the liquid strip. Added to the physical

Fig. 5-1. Schematic Representation of the Conceptual Horizontal EMCC Process

constraints, the sensors must monitor the conditions of a high-temperature flowing liquid metal stream in the environment of a high-frequency magnetic field and high-velocity coolant flow (gas or gas mixed with water droplets). The sensors should not affect the magnetic field distribution or the coolant flow, so they should be nonintrusive.

Table 5-1 gives an assessment of the sensor needs, requirements, availability, and feasibility for a commercial-scale EMCC process.² The ranges of sensor measurement requirements were derived from the reference operating state of a commercial-scale caster as listed in Table 5-2. The presently used sensors in the steel industry, given in Table 5-1, refer to the ones used in conventional casters, rolling mills, and strip mills. Because of the special requirements and physical constraints discussed above, most of these commercial sensors cannot be used as such in the EMCC process. Some of them may be adapted to the process with suitable modification, while others may require entirely new approaches. Some potential new techniques and environmental and other parameters that may impact their feasibility are also given in Table 5-1.

The conditions for stable levitation of a liquid metal stream appear favorable if the feed stream entering the caster magnet has a uniform cross section and flow profile. As a result, the feed system flow control becomes a key element for the success of the EMCC process. Since the flow velocity at the exit of the feed system nozzle is a function of the casting pressure head, the latter must be accurately controlled and fast enough to correct for any flow disturbances upstream or downstream of the feed system without exceeding the allowable tolerances. The casting pressure head is the difference in the ferrostatic pressure of the tundish and EM pump (see Fig. 5-1). By a proper control of the EM pump (which is considered faster than the tundish level control system), it is possible to reduce the sensitivity of the tundish level changes on the downstream flow velocity. Furthermore, the EM pump control allows for required tundish level variation during ladle change. During normal operation, the tundish level is kept within a certain tolerance (± 25 mm) by controlling the ladle flow rate. The EM pump is envisioned to provide a fine control of the net casting pressure with a tighter tolerance

Table 5-1. Assessment of Sensor Needs, Availability,
and Feasibility

	Measurement Requirements	Presently used Sensors in the Steel Industry and Their Adequacy	Potential Techniques	Parameters Impacting Feasibility
Tundish liquid level	Range: 13-51 cm Acc: ± 0.2 cm Resp: ~ 1 s	Electromagnetic (EMLI) - - - - - adequate	Ultrasonic, IR, microwave	Slag thickness
Flow velocity and flow profile at the nozzle exit	Range: 0 to 1 m/s Acc: 1% Resp: < 1 s Magnetic field, limited space.	None	Optic, ultrasonic, eddy current	High temp., limited space (2-12 in.)
On-the-fly thickness	Range: 0.317-0.952 cm Acc: 0.1 to 0.5% Resp: 50 ms Magnetic field, limited space, coolant flow.	Nuclear (IGCI, Weston, Gamma Instrum., Sens Raymike) - - - - - adequate	Fiber optic	Coolant flow, limited space, high temp.
On-the-fly width	Range: 61-200 cm Acc: ± 0.13 cm Resp: 100 ms Magnetic field, limited space, coolant flow.	Optical (EES, KELK, QUALIMATRIX, MEA) - - - - - adequate	Fiber optic	Coolant flow, limited space, high temp.
Velocity of the solid strip	Range: 0-1 m/s Acc: $\pm 1\%$ Resp: < 1 s Magnetic field.	Optical (ZYGO, TSJ) - - - - - adequate	Electromagnetic (roller speed) Optic (toothed wheel)	None

Table 5-1 (continued)

	Measurement Requirements	Presently used Sensors in the Steel Industry and Their Adequacy	Potential Techniques	Parameters Impacting Feasibility
Vertical positions of the levitated strip	Range: 0 to 5 cm Acc: ± 1 mm Resp: < 1 s Magnetic field, coolant flow, limited space.	Optical (MEA) - - - - Satisfactory	Fiber optic, capacitive	Coolant flow, limited space
Position of the onset of solidification	Range: 0 to 1 m Acc: $\sim 5\%$ Resp: ≤ 1 s Magnetic field, limited space, coolant flow.	None	Ultrasonic, microwave, eddy current, surface waves	Temperature, limited access, surface nonuniformities
Thickness of solidified skin	Range: 0 to 0.952 cm Acc: $\sim 1\%$ Resp: < 1 s Magnetic field, limited space, coolant flow.	None	Laser generated ultrasound, eddy current, EMAT	Temperature, limited access, surface nonuniformities
Surface topography	Resp: < 1 ms Limited space, high temperature.	None	Fiber optic high-speed camera, speckle pattern	Temperature, limited access

Table 5-2. Reference Operating State
of Commercial-Scale Caster

Variable	Range
Casting speed	0.1 to 1.0 m/s
Strip thickness	3.2 to 9.5 mm
Strip width	0.61 to 2.0 m
Magnet length	2.0 to 10.0 m
Coolant channel gap	1.3 to 30.5 cm
Coolant velocity	15 to 40 m/s
Coolant pressure	1 atm

(± 0.1 mm). The stream shape and flow profile control may require a separate EM flow shaping device.

Another key control problem appears to be in coordinating the EM pump and roller motor controls in such a way that the liquid jet velocity at the exit of the feed system nozzle is dynamically matched with the solidified strip velocity as it is pulled by the roller motor. This could be critical during (1) start-up, when there will be a ramp-up of the casting speed, and (2) during ladle change, when the EM pump must maintain the prescribed flow velocity in the face of a large decrease in the tundish head. Any mismatch between the inlet and exit velocities will alter the cross-sectional dimensions of the liquid strip, which, when coupled with the EM caster dynamics and stability regime changes, can lead to a potential breakout. It is not clear at this time what tolerance in the velocity mismatch is acceptable or how long the mismatch can persist before it is corrected.

5.2 Sensor Development

This section describes the development of sensors that were needed for the head-start and water-model experiments. These sensors are not commercially available.

5.2.1 Wave Detector

A wave detector based on capacitance change was developed for quantifying and characterizing the surface-wave formation caused by a flow of coolant gas over a pool of liquid metal in the head-start experiments. These early experiments were conceived to study the stability of liquid metal when a high-velocity coolant gas flows over it and when a high-frequency magnetic field is applied. The capacitance between the liquid metal surface and a small wire hung above and parallel to the surface (Fig. 5-2a) changes when a wave of liquid propagates underneath the wire. The change in capacitance produces a change of charge on the electrodes if a dc voltage is applied between the electrodes. Figure 5-2b shows a measurement scheme that uses a charge amplifier to convert the charge into a proportional voltage.

Fig. 5-2. Characteristics of Capacitance-Type Wave Detector

Although the measurement principle is straightforward,³ the application requires careful consideration in the design of the wave detector. The electrode width in the direction of the wave propagation must be small (fraction of wavelength) for distortionless reproduction of waves. Choosing the electrode dimensions as in Fig. 5-2a, the expected full-scale change in capacitance is only about 0.03 pF. At this very low capacitance, the signal lead from the top electrode must be shielded properly (a shielded twisted pair) to minimize extraneous pickups from the ambient EM fields and from the 10 kHz applied magnetic field in the head-start experiments. Figure 5-2c gives the response of the wave detector for a typical wave propagation on the surface of liquid tin. The Fourier transform of the signal shows a dominant wave frequency around 11 Hz. The significance of this and other results using the wave detector is presented in Sec. 3.3.1.

5.2.2 Fiber Optic Spectrophotometer

One of the objectives in the design of a tundish is to provide adequate residence time so that the inclusion particles can coalesce and float to the top, thereby minimizing the inclusion content in the flow stream leading to the caster. The residence time as well as fluid flow behavior in the tundish may be analyzed by constructing a physical model with water as the working fluid. A common method of determining the residence time is by injecting a tracer at the tundish inlet and measuring its concentration with time at the outlet using a spectrophotometer.⁴ Briefly, a spectrophotometer consists of a device for producing monochromatic light of known wavelengths and a detector cell which measures the intensity of light falling on it.

Although spectrophotometers are routinely used for quantitative analysis of mixtures and for concentration measurements in liquid chromatography, these instruments require drawing off small samples of test solution for transfer to the detector cell (cuvette) or constructing a flow cell as in liquid chromatography experiments.⁵ This is a serious limitation for on-line measurements, since it is inconvenient to direct part of the flow from the feed stream to the spectrophotometer; furthermore, it may not represent a true sampling of the total flow. Hence, a commercial spectrophotometer (Varian chromatography model) was modified and fitted with fiber optic light guides which transmit light to the tundish outlet and back to the spectrophotometer for on-line measurement of tracer concentration.

The test setup, shown in Fig. 5-3, was used to prove the measurement concept. Using red ink as the tracer, its light absorbance behavior was first determined. The dependence of absorbance with concentration was measured by adding drops of red ink with a syringe into a glass jar containing water (57 cm³). Figure 5-4 shows the absorbance values with respect to wavelength and concentration. The absorbance curve for water includes variation in the absorbance of the light guide as well. The absorbance of the tracer is read with reference to water. As the wavelength approaches that of red light (650 nm), the absorbance of the red ink decreases considerably, as expected. A general linear dependence with concentration is also seen, accounting for variation in drop sizes.

Fig. 5-3. Schematic of Fiber Optic Spectrophotometer Arrangement

To demonstrate the residence time measuring capability, we added a drop of red ink to a 11.4-cm column of water above the light propagation path,

Fig. 5-4.

Light Absorbance Property of
Red Ink

as shown in Fig. 5-3. Choosing a wavelength of 500 nm, the absorbance signal was plotted with respect to time on an X-Y plotter from the time of adding the ink. As shown in Fig. 5-5, the absorbance value shoots up after a time delay corresponding to the time for the dispersion of the red ink to reach the light propagation plane. Additional small peaks in the absorbance curve represent the mixing action in the column of water below the light path.

Fig. 5-5. Absorbance of Tracer with Time

Thus, the fiber optic spectrophotometer is useful for on-line measurement of tracer concentration in water model experiments. Furthermore, it has the potential to measure flow stream parameter variations in the flow and shaping control studies with the water model.

5.3 Process Control Model Development

A comprehensive process control model is necessary to study the process dynamics and to design and develop optimal process control schemes. Detailed models must be developed for each component of the EMCC process and then integrated to provide an overall model. To get an early insight into the general behavior of the process, a simplified mathematical model of the horizontal EMCC process was derived from the underlying physical principles of its various components. As shown in Fig. 5-1, the basic components are the tundish, EM pump, EM caster, and roller drives. The overall model consists of seven variables: tundish head, pump head, strip thickness, vertical strip position, vertical strip velocity, caster magnetic field, and roller speed. The control inputs are the flow rate into the tundish, the EM pump voltage, the magnet-applied voltage, and the roller motor voltage. The differential equations describing the overall model become nonlinear and are linearized about a steady-state operating point for simplifying the analysis.

Table 5-3 lists a tentative set of model parameters pertaining to a bench-scale caster operating at a casting speed of 0.25 m/s. Assuming that the roller motor dynamics are fast relative to the rest of the components and that the solidified strip is drawn at a constant velocity of 0.25 m/s, the model equations are described by six differential equations:

$$\begin{aligned} \frac{d}{dt} (\delta h_t) = & - 0.101 \delta h_t - 1005 \delta h_p + 2.69 \delta q_t \\ & + 5.69 \times 10^{-4} \frac{\delta u_p}{L_1}, \end{aligned} \quad (1)$$

$$\frac{d}{dt} (\delta h_p) = - 1005 \delta h_p + 5.69 \times 10^{-4} \frac{\delta u_p}{L_1}, \quad (2)$$

$$\frac{d}{dt} (\delta T_m) = - 0.25 \delta T_m + 0.25 \delta h_t - 0.25 \delta h_p, \quad (3)$$

$$\frac{d}{dt} (\delta X_1) = \delta X_2, \quad (4)$$

$$\frac{d}{dt} (\delta X_2) = - 59.2 \delta X_1 + 1531 \delta T_m - 592 \delta B_m, \quad (5)$$

$$\frac{d}{dt} (\delta B_m) = - 100 \delta B_m + 6.3 \times 10^{-6} \frac{\delta u_m}{L_2}, \quad (6)$$

where	h_t	=	tundish head
	h_p	=	pump head
	T_m	=	strip thickness
	X_1	=	vertical position of the strip
	X_2	=	vertical velocity of the strip
	B_m	=	applied magnetic field
	q_t	=	flow rate into the tundish
	u_p	=	pump voltage
	u_m	=	magnet voltage
	L_1, L_2	=	inductances in the magnetic circuit of the pump and caster magnet, respectively
	δ	=	change from the steady-state value

Table 5-3. Tentative Set of Model Parameters
for Bench-Scale Caster

Tundish & Nozzle

Area of Tundish	0.61 x 0.61 m ²
Area of Nozzle	0.15 x 0.0064 m ²
Density of Tin	6970 kg/m ³

EM Pump

Length	0.2 m
Frequency	60 Hz
Magnetic Field	580 G
Time Constant	1 ms

Magnet

Length	1 m
Magnetic Field	332 G
Strip Width	0.15 m
Strip Thickness	0.0064 m
Restraining Force	6% change per cm

Steady-State Values

Casting Speed	0.25 m/s
Tundish Input Rate	0.24 x 10 ⁻³ m ³ /s
Tundish Head	0.1032 m
EM Pump Head	0.1 m

The open-loop responses of the model were simulated for a 10% step decrease in the tundish input flow rate. A decrease in the tundish input flow rate results in a decrease in the flow velocity at the inlet of the caster. But, since the solidified strip is drawn out at a constant velocity, the mismatch between the inlet and outlet velocities of the caster produces a reduction in the average thickness of the liquid strip (assuming the width of the strip undergoes no change). Figure 5-6a shows the change in thickness of the strip with time. Because of the reduced strip thickness, the vertical position of the strip moves up under constant magnetic levitation force. However, since the magnet is assumed to exert a restraining force to the vertical movement of the strip (assume 6% change/cm), the change in the vertical strip position approaches a steady-state value as shown in Fig. 5-6b. It is thus evident that the caster magnet must provide a restraining force to ascertain bulk stability of the liquid/solid strip.

Fig. 5-6. Open-Loop Responses for 10% Step Decrease in the Tundish Input Flow Rate

The model developed is useful to study the dynamic interactions among the various components of the EMCC process. It is also useful to calculate the sensitivities of output variables with respect to certain design parameters. Furthermore, it enables one to perform quantitative analyses of sensor, control, and stability requirements.

5.4 Future Direction

As noted in Table 5-1, sensor deficiency exists for determining on-the-fly flow profile, on-the-fly shape fluctuations, position of the onset of solidification, and thickness of solidified skin. Most of these sensors will be needed irrespective of the casting method one adopts, and hence a research program is recommended to develop these sensors. The use of noncontacting techniques such as optical, fiber optic, ultrasonic, laser-generated ultrasound, electromagnetic acoustics, eddy current, and microwaves must be explored.⁶⁻⁹ In the case of the EMCC process, physical constraints (such as enclosed geometry and limited spacing) and environmental parameters (such as high-frequency magnetic field, high-velocity coolant flow, and high temperature) add to the complexity of the sensor design. In the test magnet experiments, it has been found that an instability of some kind occurs locally, leading to the eruption of molten metal. It may be useful to develop a sensor for early detection of these eruptive forces (for example, based on optical speckle pattern contract) and possibly apply local feedback to arrest the instability. Since the time constant of MHD instabilities (magneto-inertial time constant) is in the range of one millisecond, a high-speed data acquisition system capable of handling 10 kHz sampling rate per variable will be needed for process monitoring and control.

The problem of feed system flow and shaping control is generic to any type of near-net-shape continuous casting. Detailed investigation of an EM flow control device with suitable feedback controls must be addressed in the future. In the case of electromagnetic casting, more work is required to ascertain the controllability of the process during startup, ladle change, and programmed setpoint changes. A detailed process control model must be developed based on first principles and validated by experimental data. The questions related to controllability as well as the actual method of controlling the process can be answered using the model.

A distributed/hierarchical approach to process control is recommended, in which the individual components (subsystems) have their own local controllers in the first level.^{10,11} The local controllers would exchange key information about the state of the subsystems to a coordinating or supervisory controller in the second level. Based on process optimization or certain adoptive functions in the higher levels, the supervisory computer may send process loop setpoints or controller-tuning parameters to the local controllers. The distributed control approach provides improved system reliability, which is a critical concern of the steel industries involved in continuous casting. For example, in the event of a malfunction in the supervisory computer, the local controllers can maintain control and steady-state operation in the interim; similarly, if a local controller fails, the supervisory computer can take up its work temporarily. Finally, the control system must be designed to be adaptive with respect to material flow and material grade changes, reliable with respect to modeling uncertainties, and fault tolerant with respect to sensor or component failures.

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APPENDIX A

Summary Report of the Industry/ANL Workshops to Assess the Technical Feasibility of the EMCC Process August 1987

1. Liquid Metal Feed System

The working group identified and discussed in some detail a total of 17 technical issues related to the feed system and the EM caster. Some of these issues were combined because of their interrelationship. These discussions were far ranging and included evaluation and assessment of the impact of the issues on the feasibility of a feed system for a commercial-scale EM caster. The key technical issues related to the successful development of a feed system employing EM flow control and shaping are (1) structural design and materials for large-aspect-ratio shape refractory nozzles and (2) suitable fluid flow control (e.g., rate, shape, thickness, velocity profile, turbulence level).

Satisfactory closed-channel refractory nozzles having large aspect ratios (large width and small depth) are not presently available at the commercial scale. Advances in the state of the art of refractory-nozzle design are obviously required. A refractory nozzle feed system of 17 in. width and 0.30 in. depth has been developed for use in the USX/BSC thin-section casting process. This system does not employ electromagnets for flow control. However, that nozzle utilized internal support ribs, which resulted in the irreversible splitting of the flow into separate streamlets. Relocation of the ribs may alleviate the problem. External supporting structures are an alternative to internal ribs. The support structure could be an integral part of the EM caster design or the linear induction pump (LIP) for the feed system. The design would have to be compatible with the cooling system required for solidification of the levitated steel sheet. Refractory material problems were recognized both in regard to large-aspect-ratio nozzles and small-aspect-ratio conduits to be used to convey liquid steel from the tundish through the coarse EM flow control device and into the EM fine flow control and shaping device. If small-depth closed-channel refractory nozzles would be employed at all, their length should be kept to a minimum. Thin streams also impose constraints on the heat transfer characteristics of the nozzle tip material. Large thermal mass tends to promote freeze off unless some form of precisely controlled preheating can be utilized. It was recommended that a materials subgroup be formed to continue to investigate materials needs, structural designs of refractory components, and design of experiments as required.

The requirements for stable levitation and subsequent solidification of a moving liquid-steel stream in terms of the stream's flow parameters are uncertain at this time. It is expected that the tolerances for fluctuations in stream shape are small (of the order of 1-2%) and that the velocity profile must be uniform to within a similar tolerance. These requirements will have to be better determined through dynamic flow-through/levitation experiments with model fluids and liquid steel.

It is of particular interest to determine if the use of open-channel (or even closed-channel) refractory nozzles used in combination with EM flow and shape control devices can be used to control the liquid-steel-stream parameters. It is also important to determine if such control will be compatible with the requirements for stable levitation. The requirements for stable levitation may be very stringent.

Other technical issues identified and evaluated included (1) freeze-off and clogging of the feed system, (2) start-up, (3) liquid level control in the tundish, (4) EM/fluid flow interactions, (5) instrumentation, sensors, and process control, (6) width, thickness control, and adjustability, and (7) surface roughness. These issues are more appropriately classified as design and engineering problems, since they probably can be solved using existing technology or practices.

In summary, a feed system for a horizontal bench-scale EM caster (6-in. wide strip) was considered feasible, whereas a commercial-scale feed system was considered to require significant R&D to overcome the key technical issues discussed above. This development effort should be initiated in Phase I rather than waiting until Phase II (Laboratory-Scale EM Caster) as currently provided in the Field Work Proposal.

2. Electromagnetic Caster Design/Experimentation

The electromagnetic caster working group, like the other two groups, met three times. A total of 16 technical issues were identified in the first workshops, and subsequently, considerable time was devoted to the evaluation and assessment of these issues relative to the technical feasibility of the EM caster concept. It was reasonable to combine many of the issues because of overlap (i.e., related to the same issue). The key technical feasibility issues related to the EM technology are the ability to obtain stable levitation (horizontal) and containment (vertical).

Designing a system to overcome the magnetohydrodynamic (MHD) instabilities of the solidifying steel sheet is one of the most difficult problems associated with the development of an EM caster in either the horizontal or vertical configurations. No one has ever stably levitated a horizontal liquid sheet or confined a large-aspect-ratio vertical sheet. The technical feasibility of obtaining stability in either configuration is unknown at this time. The initial experiments have not been done yet due to the lack of an appropriate power supply. The specifications for procurement of the power supply have been completed. Delivery is expected in four to six months.

Two major EM casting concepts under investigation are vertical and horizontal configurations. The concept for the horizontal configuration is further advanced; hence, most of the discussions centered on the MHD considerations for horizontal castings. In the horizontal concept, stability is provided by means of inductance stabilization and flux compression. Inductance stabilization provides stability for the sheet as a whole, and flux compression provides stability against local disturbances of the sheet shape. Both stabilization methods have time constants significantly smaller than those associated with instabilities.

Bulk Stabilization. The ANL concept for a horizontal caster uses inductance stabilization for bulk stability because a uniform field, produced by a uniform current sheet, provides no stabilization. In the ANL concept, a constant voltage in a high-Q circuit drives the magnet current so that movements of the steel sheet are automatically compensated by changes in the current. Published analyses that show a lack of stabilization for a uniform field assume a constant current for the levitating magnet.

Local Stabilization. The present concept for horizontal casting achieves local stabilization through flux compression between the solidifying steel sheet and a nearby conducting screen. If the screen is too far from the sheet, it will not provide good stability, particularly against the Rayleigh-Taylor instability. If it is too close, it produces large pressure drops and inefficiencies in the gas cooling system. With the limited design and analysis to date, the feasibility for a successful design that meets all constraints is still an open question.

Surface Wave Instabilities. Other levitational instabilities associated with the interaction with the cooling system also affect feasibility. The production of waves by the passage of a cooling gas parallel to the steel sheet has been investigated in some detail both theoretically and experimentally at ANL and have provided constraints for the maximum gas velocity. In the present horizontal concept, the maximum velocity is about 30 m/s.

Experimental investigation of the MHD instabilities associated with the feasibility of the horizontal casting concept has already been initiated with the Test Magnet Facility at ANL. Planned experiments include both static and flowing tests.

MHD stability is the major technical feasibility issue for the EM caster. It can only be resolved experimentally.

Other technical issues identified and evaluated include (1) frequency for current and magnetic field, (2) current pickup for horizontal caster, (3) edge containment in vertical caster, (4) run-out support, (5) limitations on magnet size, and (6) design concept for low-frequency traveling-field magnet for vertical casting. While these issues are important to the successful development of an EM casting process, they are mostly design and engineering issues that appear solvable using existing technology and practices. Frequency is a troublesome problem from the standpoint that stable levitation appears to require higher frequencies, which increase the EM heating of the strip and add to the coolant requirements.

3. Heat Transfer and Coolant System

Similar to the other working groups, the objectives of the "Heat Transfer Coolant System" working group were to (1) evaluate the technical feasibility of the ANL proposed EMCC coolant system concept at the commercial scale, (2) identify and discuss the critical issues relating to the coolant system, and (3) recommend the needed experiments and analyses to resolve the issues for a commercial-scale operation. During the three workshops, a number of important issues were considered that relate to the technical feasibility of

the coolant system for the EM caster. The key technical feasibility issue reduces to a basic question of the ability to provide sufficient cooling in a reasonable time to achieve an acceptable casting rate and minimize the length of the magnet. Important design considerations related to this basic issue include (1) augmentation of heat transfer, (2) composition and interaction of coolant, (3) coolant operating limits (pressure, velocity), (4) solidification requirements, (5) mechanical support for strip, and (6) radiation cooling. The heat transfer requirements are dependent on the frequency of the magnet (EM heating increases as the frequency increases).

Heat transfer augmentation of the coolant gas is essential for obtaining a reasonable cooling rate. Analysis has shown that simple forced convection (plus radiation) is not adequate. Based on reports in the literature on different methods of heat transfer augmentation, it appears that heat transfer can be augmented to decrease the solidification time. The methods that appear to be appropriate include (1) addition of small water droplets (mist) to the gaseous coolant and (2) use of mechanical devices or turbulence promoters. These methods are known to be very effective at lower temperatures. At this time it is not known how effective they will be at liquid steel temperatures. The effect of turbulence promoters (and design) on levitation stability and augmentation magnitude will require experimental determination.

The composition of the coolant is important from the standpoint of heat transfer and chemical interaction with molten steel. Coolants that have been considered include N_2 , $N_2 + H_2O$ mist, CO_2 , and $CO_2 + H_2O$ mist. Other gases and/or combinations may be possible. The extent of reaction of these gases with liquid steel is known to be dependent on time, temperature, and pressure. Experimental studies will need to be conducted to determine precisely the extent of the chemical reactions under the EM caster operating conditions.

The coolant velocity and pressure are important parameters because they have a direct bearing on the heat transfer. The upper limit of the coolant velocity is related to fluid dynamic interaction between the liquid metal strip and the coolant stream. Experimental studies have indicated a usable velocity of about 30 m/s in the presence of a small magnetic pressure. The maximum allowable coolant pressure is dictated by feed system design and coolant system design. Further investigations are needed to establish these upper limits.

The required degree of solidification of the steel strip within the magnet has not been defined. Again this is an important parameter because it affects the amount of heat that must be removed by the coolant. The options range from a partial liquid core in the strip to some temperature well below the solidus temperature.

A mechanical support system for the steel strip with a partial liquid core would minimize the coolant requirements. The strip will have to be supported at some point. The important question is where and at what temperature. This problem will require investigation based on parameters that control the integrity of the strip (ductility, strain, bulging, sagging, etc.). Providing mechanical support at an early stage appears to be more of a design and engineering issue rather than a feasibility issue.

An emissivity value of 0.4 for liquid steel has been used in the heat transfer analysis to estimate the radiative cooling. It is recognized that this may be a conservative estimate since even a slight contamination of the surface will increase its emissivity significantly and improve the radiative cooling.

Important issues that require experimentation for verification include (1) the extent of chemical interaction of the coolant with liquid steel (coolant composition), (2) the amount of heat transfer augmentation by addition of small water droplets and/or by turbulence promoters, and (3) the effect of coolant velocity, pressure, and turbulence on levitation stability. Analyses have shown that sufficient cooling can be obtained with an augmentation factor of two or three in the heat transfer. The situation is further improved if the strip with a partial liquid core can be mechanically supported.