ENERGY

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RESEARCH OPTIONS FOR THE DEVELOPMENT OF
SENSORS TO MEASURE THE THERMAL STATE
OF SOLID STEEL BODIESBy
T. A. Gaspar
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February 1983

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Battelle Columbus Laboratories
Columbus, Ohio

U. S. DEPARTMENT OF ENERGY

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February 1983

by

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I. SUMMARY

The purpose of the study reported here is to assist Battelle's Pacific Northwest Laboratory (PNL) in planning a research and development program to develop temperature sensors for metal and ceramic industries. This study focuses on sensors to measure internal temperature distributions within bodies of hot steel. A series of literature surveys, interviews, field visits, and meetings with steel-industry organizations was conducted in seeking answers to six questions posed by PNL. These questions, with our responses, are summarized below.

- Does technology exist to allow the development of devices for "measuring" internal temperatures?

Yes, in the context of providing a basis for nondestructively measuring temperature gradients through bodies of hot steel, including bodies with molten centers. The technologies that have been identified for use in internal-temperature measurement stem from four different physical principles: acoustic velocity, thermal expansion, neutron thermalization, and electrical conductivity. Specific techniques involve: ultrasonic transmission, eddy currents, gamma attenuation, dilatometry, and energetic neutrons, among others.

A major problem at this stage of the research is to select from among these physical principles the one or two that seem to offer the most promise for success within a reasonable time, and, from it, to develop a technology for internal temperature-gradient measurements.

- Will the development of these devices allow industry to save significant quantities of energy?

Yes. The identifiable potential energy savings for three major applications in the steel industry (continuous casting, ingot heating and breakdown, and reheat furnaces) is about 90×10^{12} Btu/year (0.09 Quad/year). To this would be added energy savings from other applications in the steel, nonferrous metal, and ceramic industries.

The main driving force promoting implementation by the steel industry might well be perceived benefits resulting from higher quality and higher productivity, rather than energy conservation per se.

- Is anyone developing these devices?

Yes. The development of internal temperature-gradient mapping systems has stimulated entrepreneurial nondestructive testing research. But the extent of real progress that has been made to date is cloudy. A number of investigations seem to have been dropped in midstream. There remains a possibility that someone somewhere may momentarily unveil a practical system adaptable to all steelmaking applications. The likelihood of this happening is judged to be low. However, our open survey carries the risk that we have not identified some proprietary development that might even be the sought-for breakthrough.

- Does industry plan to develop or support the development of this technology?

Yes. The American Iron and Steel Institute (AISI) is co-sponsoring a workshop on Process Control Sensors for the Steel Industry, July, 27-28, 1982. It will feature measurement of thermal state as one of four main research objectives. Although key individuals in AISI and its member organizations see high potential for a successful system, they are constrained by budgets. The potential dollar savings that could result from a successful device is large. But steel companies are faced with an imposing array of alternative uses for funds, some of which are associated with survival rather than improvement. As a result, the extent to which the steel industry will support internal development of new sensors is unclear.

The steel industry is likely to encourage and support specific research programs aimed at industrial applications that offer a high probability for success within the next few years.

- Can a "successful" research program be devised?

Yes, subject to the caveat that "success" needs to be defined. If it means learning more about how to make the desired measurements on a practical and cost-effective basis, the "success" of a program of sufficient scope, time, and funding is likely. If "success" means the attainment of the objective of coming up with a practical and cost-effective device, any program that we can currently visualize must be considered high-risk and long-term.

- Who is capable of conducting an R&D program?

A number of domestic and foreign investigators and organizations have attacked various aspects of the problem. They have provided the background for conducting this Battelle-Columbus study. They have made contributions, some positive, some negative, but each of which contributed to progress. The leaders in the development of sensors include: steel companies, nondestructive-evaluation companies, national and private laboratories, universities, and foreign governments. Additional organizations are capable of conducting research if external support and guidance are provided.

Recommendations

Recommendations include the following:

- Research aimed at measuring the location of the solid/liquid should not be pursued by PNL.
- PNL should not pursue measurement of average internal temperature as an overall objective.
- PNL should pursue measurement of internal temperature distribution in hot steel bodies as its principal research objective.
- If only one technology is to be selected to initiate a sensor development program, it is recommended that research be focused on acoustic mapping techniques, which appear to represent the most generic solution to measurement of internal temperature distributions.
- The most appropriate level of activity for the next phase of this study combines focused technical analysis with preliminary laboratory investigations.

II. INTRODUCTION

This study was authorized in December 1981 and initiated in January 1982 on the basis of a subcontract from the Pacific Northwest Laboratory (PNL) to Battelle's Columbus Laboratories (BCL).

The objective of the PNL project is to support the Department of Energy's research and development program to improve the energy efficiency in the metals and ceramics industries. As part of the project, PNL will select and manage a research team qualified to identify sensing methods that could be used to determine the thermal state of hot solids; for example, metal ingots, slabs, blooms, and plates, as well as ceramic products. A second phase of the PNL project, assuming a successful first phase, would be the development and testing of practical sensors that could be used on a production basis; that is, measuring temperature profiles during industrial operations such as continuous casting; ingot production; soaking of ingots; reheating of slabs, blooms, and billets; hot rolling; and heat treatment.

The BCL subcontract represented by this report is in support of the PNL project. More specifically, the BCL subcontract is oriented toward sensors that measure the average temperature and/or temperature gradients within a body of hot steel.

The subcontract provides for BCL to aid PNL in planning the PNL program on high-temperature sensing by collecting and evaluating opinions on a number of questions. These questions are:

- Does technology exist to allow the development of devices for "measuring" internal temperatures?
- Will the development of these devices allow industry to save significant quantities of energy?
- Is anyone developing these devices?
- Does industry plan to develop or support the development of this technology?
- Can a "successful" research program be devised?
- Who is capable of conducting an R&D program?

Early in the BCL study, attention was given to the fact that Task Group 5-4 of the American Iron and Steel Institute (AISI) has independently begun study of the potential and problems of high-temperature sensors. A decision had to be made about the degree of interaction between the two studies (BCL and AISI). This was facilitated by a meeting in February 1982 involving individuals representing Battelle, PNL, Task Group 5-4, AISI staff, and The DOE Office of Industrial Programs (OIP). A high degree of rapport was established, and was maintained throughout the remainder of the BCL study, both in meetings and in individual discussions. The decision was to exchange information, data, and opinions freely on an informal basis, but to maintain the independence of the BCL and AISI studies, recognizing that the two studies might result in different recommendations and actions.

One of the inherent differences between the BCL and AISI studies is in the time frame. The BCL study was scheduled to result in a draft report, including recommendations to PNL, following the fifth month of work (May 1982). The AISI study is following a more extended time schedule, so that its recommendations may not be forthcoming for some additional months.

One of the similarities that has evolved in both the BCL and AISI studies is agreement on the desirability of developing a technique to measure temperature gradients through bodies of hot steel. Although this appears to be the most desirable and most useful end result, investigators involved in both studies recognize that because gradient-mapping presents formidable technical problems, alternatives involving lesser degrees of difficulty may be developed as stepping stones to the ultimate objective of gradient-mapping.

The sensors under consideration in this BCL study are devices and systems for the real-time measurement of temperature. As such, they are different from "models" that infer or predict temperatures based mostly on mathematical analysis. Modeling of casting and hot-working processes is being practiced, largely because of the lack of suitable and practical technology to measure temperature gradients. In the long run, modeling and direct measurement will probably coexist, with each being used in particular situations. Indeed, one of the useful applications of direct measurement would be to confirm and to calibrate models.

III. RESEARCH PROCEDURE

The results of this study were obtained from the following sources:

- Literature surveys of Engineering Information, Metals Abstracts, Alloys Index, and Information Service in Mechanical Engineering were conducted for temperature measurement of hot solid steel. In addition, a search of Soviet patent and technical literature was conducted, as well as a survey of Science Abstracts for possible experimental techniques.
- A series of telephone interviews was conducted with individuals from industry, academia, and government to survey the need for measurement of the thermal state of solids and the extent to which such measurements are practically obtainable. The telephone-conversation flow-chart presented in Appendix A illustrates the format followed during these conversations.
- Field trips were made to major steel companies, including mill visits and group discussions.
- Meetings were held with the American Iron and Steel Institute (AISI) Task Group 5-4 on Sensors to Measure Temperature Profile of Hot Solid Steel Bodies, and with a consultant to the Canadian Steel Industry Research Association (CSIRA) who is evaluating quality-control sensors for the Canadian steel industry.
- Discussions and interviews were held with Battelle scientists involved in physical and optical systems, nondestructive evaluation, and laser processing of materials.

A listing of individuals who were contacted during the course of this study is given in Appendix B.

IV. CURRENT PRACTICES

Currently, thermocouples and pyrometers are the most widely used devices to measure temperatures in the steel industry. These devices measure an object's surface temperature by radiation or contact. These techniques will be discussed, along with attempts to calculate thermal state by numerical modeling. Finally, experimental verifications of numerical models are surveyed.

Surface-Temperature Measurements

Thermocouples and pyrometers are used extensively to measure surface temperatures of solid steel. Thermocouples generally consist of joined wires of two dissimilar metals. The junction is used as a temperature probe. An electromotive force created at the junction is proportional to the difference between the temperature at the junction and a reference temperature.

Pyrometers measure the changes in radiant energy of a heated object. Two types of detectors are used: photoelectric detectors, which produce electrons as the radiant energy excites their surface, and photoresistive detectors, which change their electrical resistivity when irradiated. Commercial pyrometers typically measure total radiation, a single waveband of radiation, or two wavelengths (two-color ratio pyrometers).

In practice, surface-temperature measurements of steel made with pyrometers may deviate from the true value by 100 C or more. Factors contributing to measuring errors include, but are not limited to: changes in emissivity due to scale, surface defects, water and steam; reflected radiation from furnace walls, heat tubes, and flames; and improper maintenance.

Systems are available to compensate for some measurement errors. One device combines a de-scaler with an optical pyrometer to measure the surface temperature of continuously cast strands.^{(1)*} A second technique incorporates dual pyrometers to compensate for errors caused by reflected radiation.⁽²⁾ One of the pyrometers measures the steel surface temperature, while the other measures either the furnace-wall temperature (Figure IV-1) or the temperature of a referenced plate (Figure IV-2) or closed tube. Both of these systems are used industrially.

Infrared thermography is another technique that is used in steel mills for surface-temperature measurement.⁽³⁾ Infrared thermography uses a thermal-imaging camera to produce TV-type images in which different surface temperatures are represented by different colors. Sumitomo Metal Industries, Ltd. has reported the use of the system on a continuous caster to observe uneven cooling at the corner of slabs during continuous casting

* List of references on pp 55-58.

FIGURE IV-1. DUAL PYROMETER SYSTEM USING FURNACE WALL AS REFERENCE (2)

FIGURE IV-2. DUAL PYROMETER SYSTEM USING COOLED PLATE AS REFERENCE (2)

at the Kashima Steel Works.⁽⁴⁾ The camera is mounted 8.5 meters (about 28 feet) from the meniscus and monitors temperatures in the range of 750-800 C (1380-1470 F).

The infrared scanning radiometer has been combined with numerical models for predicting internal cavities in steel from surface isotherms.⁽⁵⁾ Although these tests were performed at comparatively low temperatures (about 35 C), it has been suggested that unsteady thermotopography and numerical modeling would be combined to predict internal temperature gradients at higher temperatures. Measurements up to 2000 C are obtainable by infrared thermography.

Modeling

Numerical solutions for calculating internal temperature profiles in hot solid or solidifying steel are beginning to be used for real-time monitoring of continuous casting, ingot solidification, soaking pits, reheat furnaces, annealing furnaces, and rolling operations. Variables that are used as inputs to computer models include: Chemical composition, dimensions, geometry, casting temperature, time from onset of solidification, heat-transfer coefficient, surface temperature, spray pressure or water consumption, furnace heating cycle, furnace conditions, furnace tonnage, and others. Each of these variables must be measured or estimated and entered as data into the control computer. Therefore, the precision of the numerical solution is limited by the precision of the measured input data. Accuracy may be further diminished by the underlying assumption of the model, which may not predict periods of fluctuation in operating conditions.

Numerical modeling is a powerful tool for process control. Despite the existence of models that can predict the heat content or internal temperature profile of a body of hot steel, they do not replace the need for an accurate real-time measurement.

Experimental Verification of Temperature-Profile Models

Most numerical models of internal temperature gradients are compared to experimentally measured values. The experimental techniques employed

to monitor solidification kinetics include: the pour-out method, radio-isotope tracers, and horizontal probing. For temperature gradients in both solid and solidifying steel, embedded thermocouples are widely used. With the exception of horizontal probing, each of these techniques is destructive.

In the pour-out method, molten metal is allowed to cool in a mold for a measured period of time, and then the remaining liquid is poured out. This may be accomplished by inverting the mold or tapping the bottom of the ingot. Results of the pour-out technique are difficult to reproduce, except with pure metals, and are relatively inaccurate.

The tracer method involves periodic injection of radioactive⁽⁶⁾ isotopes into the liquid steel in either ingots or continuous castings⁽⁷⁾. The radioactivity becomes uniformly distributed throughout the remaining liquid. If the same isotope is used throughout, equal additions are made at regular intervals, resulting in solidified zones of progressively higher activity. The piece is usually sectioned and a photographic exposure made of the surface in a process called autoradiography. Alternatively, different isotopes could be used with each subsequent addition and the differences in their radioactive properties measured.

Horizontal probing is a nondestructive technique for nondestructively measuring the thickness of the solidified shell in ingots. The technique, as illustrated in Figure IV-3, uses simple geometry to convert the mechanical measurement into shell thickness. The maximum error is reported to be about 6 percent, although degradation of the probe and possible contamination of the melt are not mentioned.⁽⁸⁾

Embedded thermocouples can be used to monitor either solidification or the temperature of solids. For monitoring solidification, thermocouples are inserted at various points in the mold cavity, and the duration of thermal arrest is measured. However, the motion of the solidification front is difficult to reconstruct from a few points.

A new embedded-thermocouple system for use in slab-reheat furnaces is being sold commercially by Fedesco⁽⁹⁾. The system consists of embedded NiCr-Ni thermocouples that are connected to an electronic monitor sealed in a specially designed insulating box that rides on top of the slab (Figure IV-4). The monitor is capable of storing up to 255 measurements

in each of six channels during its voyage through the reheat furnace. After transit through the furnace, the monitor is removed. The monitor is then connected to a strip-chart recorder that prints out the data. Bethlehem Steel, Inland Steel, Republic Steel, and Ford Motor Company have already purchased these systems. (10)

FIGURE IV-3. SCHEMATIC DIAGRAM OF HORIZONTAL PROBING TECHNIQUE (8)

FIGURE IV-4. PHOTOGRAPH OF FEDESCO'S EMBEDDED THERMOCOUPLE SYSTEM MOUNTED ON A STEEL SLAB (9)

V. INTERNAL-TEMPERATURE MEASUREMENT

Up to this point, the terms "thermal state", "temperature profile", and "temperature measurement" have been used loosely and interchangeably. Before proceeding to evaluate nondestructive testing methods, the objectives of a sensor-development program to measure internal temperatures in hot steel bodies need to be described in greater detail.

One can envision at least three categories of systems (presented in probable order of increasing difficulty):

(1) Real-time measurement and location of the liquid/internal solid interface during solidification. Solidification of steel proceeds with cellular or dendritic extensions of the solid into the liquid, giving rise to a zone comprised of both states. This is called the "mushy" zone (Figure V-1). Measuring the location of the mushy zone involves the measurement of a finite temperature range (solidus to liquidus).

(2) Real-time measurement of the average internal temperature or heat capacity of bulk solids. This might involve a temperature measurement integrated over the thickness at a single point, over a particular cross section, or over the entire volume of the solid. The magnitude of the temperature variation is not reflected by an average temperature measurement.

(3) Real-time measurement of internal-temperature distributions. This is the ultimate target and would be of greatest utility in steel production. The measured temperature distribution could be one, two, or three dimensional.

FIGURE V-1. SCHEMATIC OF "MUSHY ZONE" DURING STEEL SOLIDIFICATION (32)

Nondestructive Tests

Measurement of the internal temperatures of hot solid steel bodies will require some method of nondestructive testing. A successful nondestructive test exhibits a number of fundamental characteristics. These include:

- A Probing Medium. A nondestructive test requires a probing medium. Usually this is some type of energy, be it electromagnetic radiations, sound energy, electrical, or mechanical. But it must be capable of transmission to the area of interest. In this case, to the center of the body of hot steel. Therefore, an energy transmission source is required.
- Modulation of the Probing Medium. The characteristic to be measured must alter or modulate the probing medium in some manner. This altered or changed probing medium must then be capable of exiting the inspected part with the information.
- Detection of the Modulated Probing Medium. In order to be able to record or otherwise measure the modulated signal, some detection method must be capable of recording the modulated signal. This signal may be amplified, or processed in other ways.
- Interpretation. The detected signal must be interpretable. This interpretation must be reliable to the extent that decisions can be made and acceptance/rejection criteria established.

Note that "nondestructive" is not synonymous with "noncontact". A nondestructive contact system could be acceptable if it were capable of performing real-time measurement. In general, however, contacting probes are susceptible to high-temperature wear and erosion. For this reason, noncontacting systems are preferred.

Identification of Possible Nondestructive Test Methods

Many nondestructive tests do not directly measure the desired physical characteristics. Rather, measurement of some related phenomena is often used to obtain a result. For example, the internal temperature gradients of a body of hot steel can be measured directly with embedded thermocouples, but by sacrificing the piece being evaluated. A nonintrusive

alternative might be a measurement of the temperature-dependent velocity of an acoustic wave in the solid. The velocity measurement would be translated to an internal temperature value by calibration. The velocity of sound in a solid is one of four temperature-dependent physical principles that have been identified for possible adaptation to internal temperature measurement. The other three include thermal expansion, neutron thermalization, and electrical conductivity.

Velocity of Sound

The velocity of acoustic waves in materials is a function of temperature. Conversely, the internal temperature of a material can be determined by measurement of the velocity of an internally transmitted acoustic wave. The relationship between acoustic velocity and temperature has been measured for several different steels (Figure V-2), cast iron (Figure V-3), and nonferrous pure metals (Figure V-4). The attenuation of a 0.5 MHz signal with temperature from 0.47 percent carbon steel is shown in Figure V-5.

If the temperature of a specimen is uniform, a single measurement of velocity is sufficient to obtain an internal temperature measurement. In steelmaking applications, temperature gradients do exist. Therefore, a single measurement of ultrasonic velocity would yield an average (integrated) temperature. To establish the internal-temperature depth profile, a complex series of velocity measurements must be made. The technique is called ultrasonic tomography. Ultrasonic tomography has been used in steels to map residual stresses⁽¹⁵⁾. But, to our knowledge, it has not been applied to temperature-gradient mapping.

Ultrasonic techniques are being developed to measure the solid/liquid interface of steel during solidification. Nippon Steel has developed a system using noncontacting electromagnetic ultrasonic transducers (EMAT) for both transmission and retrieval of longitudinal ultrasonic waves^(16,17). The EMATS were installed roughly 6 meters away from the mold on a continuous caster at Nippon's Yawata Works, as shown schematically in Figure V-6. The position of the ultrasonically measured solidification front was within 2 to 3 mm of a directly (destructively) measured value (Figure V-7). According to Nippon representatives, their shell-thickness system is experimental, but Nippon does use an ultrasonic system in production to detect porosity in continuously cast slabs⁽¹⁸⁾.

FIGURE V-2. LONGITUDINAL ULTRASONIC WAVE VELOCITY AS A FUNCTION OF TEMPERATURE FOR DIFFERENT STEELS (12)

$\square$, uninoculated; $\square$, inoculated; Δ , alloyed

Cast iron		Chemical composition, %									
Num- ber	Type	C	Si	Mn	P	S	Cr	Ni	Mo	Mg _{res.}	Ce _{res.}
1	uninocu- lated	3.64	0.58	0.84	0.053	0.024	0	0	0	0	0
2		3.54	1.26	0.55	0.041	0.014	0	0	0	0	0
3		3.93	2.36	0.66	0.042	0.024	0	0	0	0	0
4	inocu- lated	3.90	0.71	0.68	0.034	0.018	0	0	0	0.049	0
5		3.82	0.76	0.69	0.033	0.024	0	0	0	0	0.210
6		3.57	1.97	0.65	0.04	0.014	0	0	0	0.031	0
7		4.08	2.34	0.69	0.043	0.016	0	0	0	0.033	0
8	alloyed	3.74	0.50	0.88	0.042	0.014	6.18	0	0	0	0
9		3.78	0.87	0.96	0.054	0.023	7.80	0.20	0.56	0	0.093
10		3.14	0.53	0.72	0.040	0.024	1.34	0.46	0	0	0

FIGURE V-3. ULTRASONIC VELOCITY AS A FUNCTION OF TEMPERATURE FOR DIFFERENT CAST IRONS (11)

FIGURE V-4. VELOCITY OF LONGITUDINAL ULTRASONIC WAVES IN NON-FERROUS PURE METALS AS A FUNCTION OF TEMPERATURE (13)

FIGURE V-5. ATTENUATION OF 0.5 MHz ULTRASONIC SIGNAL WITH TEMPERATURE FOR 0.47% CARBON STEEL (14)

FIGURE V-6. SCHEMATIC OF NIPPON STEEL SYSTEM TO MEASURE SOLIDIFICATION SHELL THICKNESS IN CONTINUOUSLY CAST STEEL STRANDS (17)

FIGURE V-7. SOLIDIFICATION SHELL THICKNESS AND OTHER EXPERIMENTAL PARAMETERS MEASURED WITH NIPPON STEEL SYSTEM (17)

Krautkramer GmbH in Cologne, West Germany, is developing laser-induced ultrasound to locate the solidification shell in continuously cast steel. The system will be installed and field-tested in German mills before it will be available commercially. A detailed description of the system or its capabilities has not been found in the published literature.

In the early 1970's, work was conducted at the Timken Company in Canton, Ohio, investigating a momentary-contact conventional ultrasonic transducer that was developed at Panametrics, Inc. in Waltham, Massachusetts^(19,20). More recently, it has been rumored that Timken is developing a proprietary contacting ultrasonic technique for measuring the solidification-shell thickness of continuously cast steel. Attempts to obtain a confirmation or denial of this rumor from Timken were unsuccessful.

Alternatives to time-of-flight ultrasonic measurements have been suggested. If a quasi-continuous ultrasonic wave were used, the phase shift of the continuous wave might be used to monitor the internal temperature of the specimen. Another suggested approach is time-lapse measurement of the resonance of a solid specimen. The rimming action of steels during solidification has been characterized by acoustic measurements⁽²¹⁾.

Thermal Expansion/Density

Metals expand when heated and contract during cooling. For example, the coefficient of linear expansion for steels is 6.7 in./in./°F. Thermal expansion can be determined directly by time-lapse measurements of dimensional changes during heating or cooling. Such measurements are affected by internal-temperature fluctuations. This technique is called dilatometry. It has been applied to measurement of the average temperature of steel billets and their enthalpy by researchers in the Soviet Union⁽²²⁾. It is not known whether the Soviet dilatometric method for monitoring the temperature of steel in furnaces has been used industrially.

Laser-optic systems have been developed to be capable of dimensional measurements of distances as small as a fraction of a wavelength of light. An advantage of laser-optic systems compared to mechanical systems in dilatometric measurement is that no physical contact with the sample is required. Laser-optic systems can also scan large surface areas rapidly,

suggesting the possibility of mapping the expansion of the surfaces in three dimensions. The internal-temperature profiles might be reconstructed from the surface-expansion profiles.

As the dimensions of a steel body increases during heating, the density decreases accordingly. Rather than measuring dimensional charges to determine internal temperatures, the density changes of the body could be measured. To this end, radiography has been used to penetrate steels of thicknesses of a foot or more. The absorption of radiation by matter is dependent on both density and thickness: measurement of one of the two parameters can be used to determine the other.

The Soviets have developed a radiographic system called FAZA-2 to measure the location of the solid/liquid interface in a continuously cast steel strand⁽²³⁻²⁵⁾. The different densities of solid steel and of molten steel are measured experimentally (7.8 g/cm^3 and 7.2 g/cm^3 , respectively). By fixing the densities, the solid-shell thickness can be calculated from radiographic measurements.

The FAZA-2 system consists of a cesium source of gamma radiation that is placed next to the continuous cast strand. Because the shell thickness may not be uniform on both sides of the strand, the transmitted and backscattered radiation flux are measured separately by two cesium detectors (Figure V-8). The solid-shell thickness on each side of the strand can be calculated, with the aid of a computer.

The FAZA-2 device has been used on a 70 mm x 300 mm continuous casting machine at the Azovstal Steel Works in Zhdanov, USSR. During operation, the mean square error does not exceed 0.7 to 0.8 mm. At casting rates of 1.5 to 2.5 m/min, the time lag for the system is reported to be less than 0.4 second. It is reported that breakouts are avoided and billet quality is improved as a direct result of measurements taken by the FAZA-2 system.

Scientific Measurements Systems (SMS), Austin, Texas, is developing gamma tomographic systems to detect slag inclusions, delaminations, and to determine internal-temperature profiles in hot steel billets with liquid centers. The systems will be sold commercially to private steel companies. A complex series of gamma transmission measurements at differing orientations with respect to the billet are fed into a computer. The computer uses an algorithm to reconstruct the interior structural density of the billet. With

1, unit for preliminary analysis of discrete information; 2, unit for analysing analog information; 3, N-327/3 recording unit; 4, unit for controlling withdrawal mechanism; 5, withdrawal speed regulator; for other explanations, see text

FIGURE V-8. SCHEMATIC OF SOVIET FAZA-2 SYSTEM FOR MEASURING SOLIDIFICATION SHELL THICKNESS (25)

calibration, the density profile can be converted to an internal-temperature profile plotted at 20 C intervals and projected in a television-like image.

Neutron Thermalization

Energetic neutrons injected into a material collide with the surrounding atoms as they propagate through the specimen. These collisions reduce the kinetic energy of the neutrons until they reach thermal equilibrium with the atoms in the specimen. Some of the neutrons are absorbed, but many more will be transmitted. The energy distribution of transmitted neutrons can be measured and can be related to the energy of the atoms that make up the sample. The energy of the atoms is, in turn, directly related to the temperature of the specimens. With calibration, it is possible to obtain a weighted average internal-temperature measurement.

The absorption of neutrons in a given sample depends on the chemical composition of the material. The neutron-capture cross section is a measure of absorption (in barns) which varies irregularly with the atomic weight of the element.

A prototype neutron-thermalization system was developed at IRT Corporation in San Diego, California, under DOE sponsorship^(26,27). The neutron sensor was intended to be used for geothermal-well logging, but might be used to measure the internal temperature of steel. A Californium-252 source of fast neutrons is placed next to the specimen. The emitted neutrons enter the specimen and transfer their energy during collisions with the neutrons in the material. The thermalized neutrons emerge from the specimen and are counted by detectors that are sensitive to different energy ranges. The average temperature of the specimen is reconstructed from the measured energy of the thermalized neutrons.

Electrical Conductivity

The electrical conductivity/resistivity of a conductor varies with temperature. The relationship between resistivity and temperature for an iron standard is shown in Figure V-9. By measurement of the conductivity

FIGURE V-9. RESISTIVITY AND FIRST DERIVATIVE $d\rho/dT$ OF AN IRON STANDARD WITH TEMPERATURE (28)

or resistivity of a hot steel body at various depths, the temperature gradients might be reconstructed.

Iron and steels are ferromagnetic, with a Curie point at roughly 1420 F for pure iron. Magnetic permeability might affect conductivity measurements taken below the Curie point in steels. Permeability varies with temperature below the Curie point. Permeability measurements might be used in place of or in addition to conductivity measurements to reconstruct internal-temperature profiles below the Curie point.

Several different eddy-current techniques for temperature measurement have been described in the literature. Most examine surface temperatures, although researchers have applied eddy-current methods to monitor solidification^(29,30) and internal-temperature gradients in nonmagnetic metals⁽³¹⁾. These techniques might be adapted to monitor the solidification and internal temperatures of steel above the Curie point.

Since 1970, researchers at the University of Minnesota have been characterizing materials at elevated temperatures using eddy-current techniques. They have developed systematic techniques for interpreting eddy-current data and producing profiles of electrical conductivity. From a conductivity profile, internal-temperature profiles can be determined, internal flaws detected, and solidifying regions located and characterized^(32,33).

An eddy-current inspection system was installed on a billet caster at North Star Steel in Saint Paul, Minnesota (Figure V-10). The strand was stopped and allowed to cool. The cooling of the strand and mold could be detected, as well as the ferromagnetic transformation of the strand skin. During casting, a breakout was detected from eddy-current signals. The average mold temperature was determined by calibration from laboratory measurements with an empty mold. Because the coils were placed around the mold, the mold became a factor in the measurements. Measurements taken below the mold might yield more information about solidification.

A new business enterprise, called Castings Analysis, Inc., will be formed in June 1982 to adapt the eddy-current techniques developed at the University of Minnesota to industrial problems. Castings Analysis will be a subsidiary of Magnetic Analysis, Inc. of Mount Vernon, New York, and will be staffed by researchers from the University of Minnesota. Information concerning Castings Analysis' products and services was unavailable before

FIGURE V-10. SCHEMATIC OF COIL PLACEMENT IN MOLD OF
CONTINUOUS CASTING MACHINE AT NORTH STAR STEEL (33)

the date of publication of this report. However, they are discussing temperature-gradient mapping systems with aluminum and steel company executives.

VI. UTILITY OF THERMAL-PROFILE SENSOR IN EXISTING FACILITIES

If a thermal-profile sensor were developed, it would have immediate application in existing steelmaking facilities. This was established without question by the practically unanimous opinion of knowledgeable management and operating personnel in the steel industry, and by their encouragement and involvement in efforts to develop such a sensor.

In terms of total energy consumption, the three most energy-intensive operations to which the sensor might be applied are:

- Continuous casting
- Ingot production and breakdown
- Reheat furnaces.

As will be shown, the potential savings to be expected from wide implementation of a thermal-profile sensor are about as follows:

	<u>Continuous Casting</u>	<u>Ingot Production and Breakdown</u>	<u>Reheat Furnaces</u>	<u>Total</u>
Tonnage basis, 10^6 tons/yr	41.2	116.6	120.0	---
Potential Savings:				
Total, 10^{12} Btu/yr	19.2	22.8	35.1	77.1
Specific, 10^6 Btu/ton	0.5	0.2	0.3	---
\$ Millions/yr	\$ 77	\$91	\$140	\$308.

There are many other steelmaking operations that stand to benefit from internal temperature-profile measurement. These include, but are not limited to, castings, batch annealing furnaces, and furnaces used in the production of forgings, tubular products, structural products, and coated products. Non-steelmaking applications might include measurement of internal temperature during metal extrusion, ceramics production, operation of fluidized beds, power generation, and other industrial applications.

It is possible, but improbable, that one universal nonintrusive sensor might be developed to satisfy the diversity of needs for knowledge of the internal temperature profile of a solid or semi-solid body. Therefore, the ultimate development is likely to consist of a family of sensors, perhaps all based on one general principle. Although the potential applications may be varied and diverse, this discussion will focus on the three potential applications in steelmaking judged to have the highest energy-saving opportunities.

Continuous Casting

The high melting point, low thermal conductivity, and high specific heat of steel serve to limit heat transfer during continuous casting. This contributes to retention of molten steel in the interior of the continuously cast strand for some distance beyond the mold. During continuous casting, solidification of steel occurs over a much greater distance beyond the mold than with aluminum (Figure VI-1).

In the mold, if the solidified shell does not have sufficient strength to contain the molten metal, a rupture will occur, resulting in a "breakout". Similarly, molten steel present during cutting of a strand results in a "runout". In vertical-bending types of casters, a molten steel center in the bending region may lead to centerline cracking. Measurement of the thermal gradients in the continuously cast strand would provide additional means to alleviate these problems.

Computer control of continuous casters is difficult to implement because the casting rate changes frequently and secondary cooling rates also vary. Real-time measurement of the temperature profile would make possible a significant advancement toward computer control of continuous casting. Therefore, it is not surprising that most of the nondestructive techniques identified in the previous section are being field-tested first on casters.

Surface-temperature measurements aside, many efforts are underway to measure internal phenomena. In an attempt to locate the solidification front, Nippon Steel, Tokyo, Japan, is developing an ultrasonic system using noncontacting EMAT's. Krautkramer of Cologne, West Germany, is developing a laser-induced ultrasonic system. There are unverified rumors that Timken Company, Canton, Ohio, USA, is developing contacting ultrasonic systems.

FIGURE VI-1. SCHEMATIC OF SOLIDIFICATION OF STEEL AND ALUMINUM DURING CONTINUOUS CASTING (12)

The Soviets claim to have developed a gamma-attenuation technique to locate the solidification front. A new company called Castings Analysis, Mount Vernon, New York, will design and build eddy-current systems to monitor solidification and possibly to construct internal-temperature profiles of steel and nonferrous metals during solidification. Scientific Measurement Systems, Austin, Texas, claims to be building a tomographic system, using gamma-transmission measurements that can determine internal temperature gradients and project them in a TV-type image.

The environment to which these measurement devices will be subjected is severe. Surface temperatures range from 1200 to 2600 F on the strand. A real-time measurement may involve a few minutes, but a measurement on the order of seconds is preferable. Internally, there may be porosity, chemical segregation, and molten steel. Externally, an oxide scale exists along with water and steam.

Let's assume that a suitable device becomes available for all types of continuous casters. How much energy could be saved following industry-wide adoption of a temperature-gradient mapping system? Both direct and indirect energy savings can be identified.

Knowledge of the internal temperature profile would allow casters to be operated at higher rates. Presently, casters are operated conservatively to avoid breakout and runout. Measurement of the thermal state would allow casting speeds to be increased by an estimated 10 percent. This represents additional continuous casting capacity of 4.2 million tons annually at a saving of about 1.4×10^6 Btu/ton when compared with ingot practice. Therefore, a total potential energy savings from increased capacity of existing continuous casters is estimated to be about 5.8×10^{12} Btu/yr.

As previously mentioned, the problems of breakout, runout, and centerline cracking could be alleviated through measurement of internal temperature gradients. It is estimated that yield improvements of up to 1.5 percent are possible, with corresponding increases in overall energy efficiency. The total potential energy saving from yield improvements is estimated at 13.4×10^{12} Btu/yr.

When combined, the potential direct and indirect energy savings total 19.2×10^{12} Btu/year (0.5×10^6 Btu/ton) for temperature-distribution mapping during continuous casting (Table VI-1). In addition, measurement of temperature distributions could be used to control solidification and solid-state cooling. The potential results is higher metallurgical quality with greater freedom to continuously cast steels that are currently considered too difficult to cast. The impact that the sensing device might have on continuous casting technology in the future will be discussed in Section VII.

The estimates of potential energy savings as presented in Table VI-1 are based on industry-wide adoption of measured temperature distributions. In reality, how might the steel industry respond? This is examined in four different categories related to the capacity of the casters currently in use.

First, consider the case of casters that produce billets and rounds. Nation-wide, about 80 billet casters are installed or committed.⁽³⁴⁾ The number of strands per caster varies from one to six. The capacity ranges from 33,000 tons/strand/year to 188,000 tons/strand/year. The mean capacity is roughly 75,000 tons/strand/year.

It has been estimated (Table VI-1) that the total potential energy saving attributable to temperature-distribution mapping averages about 0.5×10^6 Btu/ton/year for continuously cast products. This represents a saving of 38×10^9 Btu/year for a single strand operating at 75,000 ton/year. With current energy costs averaging roughly \$4 per million Btu, the benefit of a temperature-distribution measurement from energy savings alone is about \$152,000/year for an average billet strand. These calculations are given in Table VI-2.

Similarly, the benefit of real-time temperature-distribution measurements can be estimated for slab and bloom casters. The annual average capacities per strand vary much more for slab casters than for billet casters. Consequently, slab casters are classified into three categories: (1) less than 500,000 tons per year per strand, (2) more than 500,000 but less than 1 million tons per year per strand, and (3) more than 1 million tons per year per strand. This system of classification reduces the variance in the average potential energy saving per strand. The results are compiled in Table VI-3.

The average benefit of temperature-distribution measurement in slab casters is estimated to range from \$500,000 per strand per year to \$3 million per strand per year. As the benefit increases, the number of facilities that

TABLE VI-1. ANNUAL POTENTIAL ENERGY SAVINGS FROM MEASUREMENT
OF THERMAL STATE IN CONTINUOUS CASTERS

	<u>Type of Steel Plant</u>			
	<u>Integrated</u>	<u>Scrap Based</u>	<u>Specialty</u>	<u>Total</u>
Installed/committed C.C. capacity, 10^6 tons/yr (34)	22.7	16.0	2.5	41.2
Potential increase in C.C. capacity, 10^6 tons/yr	2.3	1.6	0.3	4.2
Potential energy savings from increased C.C. capacity, 10^{12} Btu/yr (35)	3.2	2.2	0.4	5.8
Potential Capacity, 10^6 tons/yr	25.0	17.6	2.8	45.4
Estimated energy consumption, 10^{12} Btu/yr	495.0	348.0	55.0	898.0
Potential energy savings through yield improvements from measured temperature profile, 10^{12} Btu/yr				
$\epsilon^* = 0.015$	7.4	5.2	0.8	13.4
Total potential annual savings, 10^{12} Btu	10.6	7.4	1.2	19.2
Specific potential energy saying per unit capacity, 10^6 Btu/ton				0.5

* ϵ = estimated potential energy savings based on steel industry operating data

TABLE VI-2. CONTINUOUSLY CAST ROUNDS AND BILLETS

Average annual capacity (per strand)	75,000 tpy
Number of casting machines	80
Number of strands	263
Potential average energy saving per strand	
$(75,000) (0.5 \times 10^6) = 38 \times 10^9 \text{ Btu/strand/year}$	
Average benefit*	
$(38 \times 10^9) (4 \times 10^{-6}) = \$152,000/\text{strand/year.}$	

* Based on average cost of \$4 per million Btu.

TABLE VI-3. CONTINUOUSLY CAST BLOOMS AND SLABS,
ANNUAL CAPACITY RANGE (C in tons per year)

	<u>C < 500,000</u>	<u>500,000 < C < 1,000,000</u>	<u>C > 1,000,000</u>
Average capacity per strand, tons/year	250,000	750,000	1,500,000
Number of casting machines	14	7	3
Number of strands	22	9	3
Average energy saving per strand, 10^{12} Btu/year	0.13	0.38	0.75
Average benefit, per strand/year*	\$500,000	\$1,500,000	\$3,000,000

* Based on average cost of \$4 per million Btu.

could afford a gradient-mapping system diminishes. However, even the short-range benefits are considered large enough to justify a substantial development program.

Ingot Production and Breakdown

There has been less interest in developing sensors to monitor internal temperatures during ingot production and breakdown than during continuous casting. In fact, only one study involving ingot solidification was found. The investigators developed an acoustic technique to monitor the rimming action⁽²¹⁾.

Measurement of their internal-temperature profiles would allow ingots to be optimally stripped and charged hotter to soaking pits. Because the heating of the ingots in the soaking pits could be optimized, fuel consumption would decrease accordingly. This would result in ingots of more uniform temperature during breakdown. It is anticipated that the soaking time could be shortened, leading to reductions in fuel consumption, the operation of fewer furnaces, and extended furnace life. Optimization of ingot soaking would minimize formation of excess scale, thereby increasing yield.

The yield during ingot breakdown is also anticipated to be capable of improvement because of measurements of the internal-temperature profile. Temperature and pressure are the two major variables during deformation. Internal-temperature measurement would allow more precise calculation of deformation parameters. As a result, it is anticipated that roll wear and roll breakage would be significantly reduced and overall yield improved.

It is estimated that up to 15 percent of the fuel consumed in soaking pits could be conserved by knowledge of the thermal state of solid ingots during charging. Most ingots are hot charged. But the quantity of heat contained therein may vary greatly, depending on the time elapsed from teeming and stripping. Measurement of the thermal state would lead to optimization of soaking-pit heating cycles for the worst-case ingot in the lot. The total potential energy saving from reduced fuel consumption in soaking pits is estimated to be about 19×10^6 million Btu per year (Table VI-4).

TABLE VI-4. POTENTIAL ENERGY SAVING FROM MEASUREMENT OF
THERMAL STATE IN SOAKING PITS AND BREAKDOWN MILL

Total

Soaking pits:

Charging temp, °F (36)	77	1400	1600	
Annual production, 10 ⁶ tons/year (36)	11.7	46.6	58.3	116.6
Annual energy required, 10 ¹² Btu/year (36)	42.28	75.52	67.34	182.10

Estimated potential energy savings
from reduced fuel consumption in
soaking pit furnaces,
10¹² Btu/year*

$\epsilon^{**} = 0.05$	0.2	0.4	0.3	
$\epsilon = 0.10$	3.0	5.1	4.7	
$\epsilon = 0.15$	1.3	2.2	2.0	
Subtotals	4.5	7.7	7.0	19.2

Potential energy savings from
yield improvements,
10¹² Btu/year*

$\epsilon^{**} = 0.01$	.1	.1	.1	
$\epsilon = 0.02$	.5	.9	.8	
$\epsilon = 0.03$	.3	.4	.4	
	.9	1.4	1.3	3.6

Total potential energy savings,
10¹² Btu 22.8

Specific potential energy savings,
10⁶ Btu/ton/year 0.2

* Based on frequency distribution of estimated potential energy savings

** ϵ = individual estimates of potential energy savings

Optimization of the reheating of ingots and measurement of their thermal state before hot breakdown is estimated to result in up to 3 percent improvement in yield during hot breakdown. Yield improvements arise from elimination of excessive scale, improved quality, and greater dimensional control. In addition, roll life and productivity would also be extended. The total potential energy saving from yield improvements is estimated to be 3.6×10^{12} Btu/year.

The total potential energy saving from measurement of the internal temperature gradient is estimated to be 22.8×10^{12} Btu/year for ingot production and breakdown. This represents an average saving of 0.2 million Btu per ton of charged product. (Table VI-4.)

It has been estimated that there are more than 2,500 soaking pit furnaces in the United States with a total reheat capacity of 185 million tons annually⁽³⁷⁾. Therefore, the average capacity for a single soaking pit is 74,000 tons per year. The estimated potential energy saving per soaking pit is roughly 15×10^9 Btu/year, based on our estimate of a savings of 0.2×10^6 per ton of annual capacity. Assuming that energy costs \$4 per million Btu, the estimated benefit of internal-temperature profile measurement on a single soaking pit furnace is roughly \$60,000 per year. In modern integrated steel mills, the average soaking pit capacity is in the 150,000 tpy to 200,000 tpy range, representing a utility of \$120,000 to \$160,000 per furnace.

Reheat Furnaces

There are many different types and sizes of furnaces for heating billets, rounds, slabs, forgings, etc. This discussion will focus primarily on slab-reheat furnaces used in hot-strip mills and plate mills. Slab-reheat furnaces are among the largest energy consumers in an integrated mill, consuming up to about 3 million Btu per ton of steel.

Slab-reheat furnaces operate in several different stages, including preheat, heating, and soaking. The rolling mill's productive capacity is usually limited by either heating capacity or rolling capacity for the product size rolled. Furnace control and scheduling are, therefore, essential to increase the energy efficiency of the mill.

There have been many attempts to model the heating of billets and slabs in reheat furnaces. With a good model, it is possible to reduce fuel consumption and maintain hot steel ready while increasing yield. For model verification, Fedesco's embedded-thermocouple system is beginning to be used

for both model verification and regular monitoring of reheat furnaces in several major American mills.

A model, no matter how sophisticated, does not take the place of an accurate measurement of internal-temperature profile. Models must be updated regularly to take into account changing furnace conditions. A measurement of internal-temperature gradient reduces uncertainty, allowing tighter control.

Lowering of fuel consumption by up to 15 percent is estimated to be possible because of measurement of the thermal state of pieces in reheating furnaces. Direct energy savings through reductions in fuel consumption would be supplemented by indirect energy savings because of increased furnace life, reduced furnace maintenance, and shorter cycle time. Potential energy saving from lower fuel consumption in reheating furnaces is estimated to total about 29.4×10^{12} Btu/year. See Table VI-5.

There is also a potential energy saving through increased yield of plate and strip mills. It is estimated that yield improvements of up to 3 percent could result from measurement of internal temperature gradients. The potential energy saving from yield improvements is estimated to amount to 5.7 million Btu/year.

The total potential energy saving from nation-wide application of temperature-gradient measurements to reheat furnaces and associated rolling operations is estimated as about 35×10^{12} Btu per year. The total potential energy saving appears to be greater for reheat furnaces than for continuous casters. However, note that the average potential energy saving per ton of rated capacity is higher for continuous casting than for reheat furnaces.

The relative utility of internal temperature-gradient measurements might be estimated from the costs of existing commercial systems. Equipment for Fedesco's system of embedded thermocouples costs between roughly \$20,000 and \$40,000 as of May 1982, depending on the options selected. The cost of the measurement is actually much higher because of costs associated with preparing and scrapping the test slab.

Alternatively, the utility of an internal temperature-gradient measurement can be estimated from the average potential energy saving found in Table VI-5. A large slab reheat furnace has a capacity of roughly 300 tons per hour. One eight-hour turn represents 2,400 tons. Multiplying that by the average potential energy saving of 0.3 million Btu/ton yields a saving of 720 million Btu per turn or \$2,900 per turn, assuming an energy cost of \$4/million Btu.

TABLE VI-5. POTENTIAL ENERGY SAVINGS FROM MEASURED THERMAL STATE IN REHEAT FURNACES AND ROLLING OPERATIONS

Charging temperature, °F (36)	77
Annual production, 10 ⁶ tons/year (36)	120
Annual energy required, 10 ¹² Btu/year (36)	280
Potential energy saving through reduced fuel consumption,* 10 ¹² Btu/year	
$\epsilon^{**} = 0.05$	1.4
$\epsilon = 0.10$	19.6
$\epsilon = 0.15$	<u>8.4</u>
Total	29.4
Potential energy saving through improved yield,* 10 ¹² Btu/year	
$\epsilon^{**} = 0.01$	0.6
$\epsilon = 0.02$	3.4
$\epsilon = 0.02$	<u>1.7</u>
Total	5.7
Total potential energy saving, 10 ¹² Btu/year	35.1
Specific potential energy saving, 10 ⁶ Btu/ton/year	0.3

* Based on frequency distribution of estimated potential energy savings

** ϵ = individual estimates of potential energy savings

If operating at high rate, e.g., 18 turns per week, 50 weeks per year, the total annual energy saving for a 300-ton-per-hour reheat furnace is estimated to be 0.65×10^{12} Btu/year; worth roughly \$2.6 million/year. This figure serves as an upper bound because relatively few reheat furnaces are in the 300-ton-per-hour class.

Average throughput for reheat furnaces is probably closer to 100 tons per hour. Multiplying the annual energy saving estimated above by one-third yields an annual energy savings per furnace of 0.22×10^{12} Btu/year valued at \$870,000 per year.

The editors of 33 Metals Producing magazine surveyed the United States steel industry in 1978. Responses indicated there are about 103 reheat furnaces in hot rolling mills and 56 reheat furnaces in hot plate mills. The number of no-responses is roughly compensated by plant closings since 1978. Multiplying the number of slab reheating furnaces (~160) by the average energy saving per furnace (0.22×10^{12} Btu per year) yields 35.2×10^{12} Btu/year, which checks with the total potential energy saving of 35.1×10^{12} Btu/year, as calculated in Table VI-5.

VII. PROSPECTS IN NEW FACILITIES

The implications of real-time measurement of the internal temperature profile of steel bodies are far-reaching. It may be too early realistically to assess the total impact that internal temperature measurements would have on steel production. However, the development of an internal-temperature sensor is expected to spur more widespread utilization of new energy-saving technologies. This discussion will focus on four technologies in particular:

- Direct rolling
- Liquid-Center Charging and Rolling
- Hot Charging
- Controlled Solidification.

Direct Rolling

The principle of direct rolling is straightforward: the hot slabs produced by either continuous casting or ingot breakdown are rolled immediately in the hot mill without reheating (CC-DR and IC-DR in Figure VII-1). This eliminates the use of reheat furnaces. In North America, direct rolling has been adopted by a few "mini mills" and one integrated producer.

Real-time measurement of internal temperature would encourage greater use of direct rolling. The deformation of the steel during hot rolling could be controlled with greater certainty. Sorting based on the heat content of slabs could be used to avoid rolling slabs that have not retained sufficient heat.

The lack of internal temperature measurements does not represent the sole barrier of adopting direct-rolling technology. In many existing mills, the melt shop and hot mill are not in close proximity. In addition, surface-inspection techniques for detecting flaws in hot slabs and billets require further development.

The average energy consumption during slab reheating is estimated to vary from 1.5 million Btu/ton to 4 million Btu/ton. Therefore, this approximates the potential energy saving attainable from direct rolling. A typical reheat furnace (100 tons per hour) operating at full capacity (18 turns, 50 weeks) is estimated to use between 1.1×10^{12} Btu and 2.9×10^{12} Btu/year, costing an estimated \$4 million to \$12 million annually. Most hot strip mills are supplied from 2 to 5 reheat furnaces. Therefore, the total potential energy saving because of eliminating reheat furnaces by direct rolling is estimated to range from 2.2×10^{12} to 14.5×10^{12} Btu per year for a single hot mill.

Liquid-Center Charging and Rolling

Some steel plants are saving energy by charging rimmed steel ingots into the soaking pits before the ingots are completely solidified. This practice is not new. However, Cook et al have refined the practice at ARMC0's Middletown (Ohio) Works, by the use of mathematical modeling, to a point where energy saving may have approached its potential maximum⁽⁴⁰⁾.

FIGURE VII-1. SCHEMATIC OF FLOW OF HOT-CHARGED DIRECT-ROLLING SYSTEMS (39)

The model operates on a real-time basis as part of an integrated control system, and provides the basis for the ready-to-roll decision. The system takes into consideration the following variables:

- Time of teem of first and last ingot in a heat
- Pouring temperature
- Mold temperature
- Holding time in molds, which is based on the percentage of metal solidified
- Time required to strip ingots and charge to pits
- Soaking-pit temperature and time charged
- Breakdown-mill schedule.

Ingots can be charged while up to 50 percent of the ingot is still liquid. Such ingots require little or no additional heat from the pit. Thus, the pit is used more as a temperature-equalizing furnace than as a heating furnace. Cook has found that there are optimum combinations in the multiplicity of stripping and charging times. If ingots are charged early enough, a delayed firing practice can be used which provides additional energy benefits and easier scheduling.

ARMCO's Middletown Works has adopted the practice of rolling rimmed ingots while their centers are still about 5 to 10 percent liquid. More than this amount causes the ingots to bulge during rolling.

The following advantages have accrued from the liquid-center charging and rolling development:

- The energy consumed in the soaking pit is 15% of that required during normal hot practice.
- Pit time has been shortened from 8 to 9 hours to 1.5 to 3 hours.
- Mold life has been increased because of the shortened time that the ingots are left in the molds.
- Soaking-pit furnace linings last longer.
- Breakdown-mill roll life has been extended.
- Breakdown-mill yield on ingots has been increased.
- Breakdown-mill energy consumption has been decreased.
- Metallurgical quality improves.

Possible Improvement by Use of Temperature-Profile Sensor

The computerized system developed by Cook et al reduces their urgency for developing a sensor that actually measures the temperature of an ingot throughout its cross section. Nevertheless, such a system would still be useful and contribute to further saving of energy. Thus, refinements probably could be made in Cook's computerized system if precise information could be obtained on (1) the amount of liquid metal in an ingot, (2) the average temperature of the ingots, and (3) the temperature profile through the ingot. While it might not be necessary to have such information on every ingot, it would be desirable to check one or two ingots, perhaps the first and last poured, from every heat.

Furthermore, liquid charging and rolling has been applied only to rimming grades. The process has also been applied to semi-killed grades, but it may not be expedient to apply it to killed steels due to metallurgical limitations. Thus, a temperature-sensing system that would determine the precise moment at which killed steel ingots are sufficiently cool to be stripped would be desirable to establish metallurgical hold time and to confirm model projections.

Hot Charging

Hot charging refers to the practice of rapidly dispatching steel slabs to the hot strip mill reheating furnace as soon as possible after they have been produced by the continuous casting process or from ingots in the slabbing mill. This is illustrated as flows CC-HCR and IC-HCR in Figure VIII-1. Hot charging differs from direct rolling in that direct rolling bypasses the reheating furnace.

In contrast, plants that do not use hot charging or direct rolling are obliged to charge into their reheating furnaces slabs that have been stored at room or outdoor temperature. This requires much more energy in the reheating furnace.

It was estimated earlier that direct rolling could save between 2.2×10^{12} and 14.5×10^{12} Btu/year for a single hot rolling mill, depending on whether the mill used 2 or 5 reheat furnaces. With hot charging, less energy could be saved because the reheat furnaces are retained. The amount

of energy saved by hot charging depends on the temperature and on the distribution of temperature of the slab when it is charged. A reasonable assumption is that about half as much energy could be saved in hot charging as in direct rolling, namely between 1.1×10^{12} and 7.5×10^{12} Btu/year for a single furnace.

Continuous Casting - Continuous Rolling Concept for Future Steel Plants

A limiting factor for energy saving when hot charging slabs from a continuous caster to a reheat furnace is the need to prevent runouts. The slab must be completely solidified before it is cut off from the rest of the strand. By the time the center has frozen, the outside surfaces of the slab, particularly the corners, are relatively cool.

A steel plant of advanced design can be visualized in which the cast strand enters an equalizing furnace while the center of the strand is still partly molten. Solidification is completed in the furnace. The residual heat in the strand makes it unnecessary to add much, if any, heat from the furnace. The strand is not cut into slabs until it leaves the equalizing furnace, at which point the slab enters directly into the hot strip mill.

In order to fill the capacity of the strip mill, several strands would be fed into one or more equalizing furnaces, all serving the strip mill.

Internal temperature-gradient measurements would greatly facilitate the connection of the continuously cast strands to the hot rolling mill. The measurements could be used in control of the continuous casting machine, equalizing furnaces, slab cutting, and hot rolling mill operation. Elimination of defects and hot inspection of cast slabs will also be essential to any future continuous casting-continuous rolling plant.

Controlled Solidification

Real-time measurement of internal temperature gradients of steel during solidification may lead to revolutionary advances in process control. Continuous-casting technology, in particular, can be expected to benefit

greatly. Continuous casters are controlled by metering the flow of molten steel through a tundish. If the internal temperature gradient were measured continuously, the caster could be controlled by continuous real-time monitoring of the solidification and secondary cooling of the strand. A higher level of control of microstructure would be a beneficial result.

Continuous measurement of internal temperature gradients would allow the solidification growth rate to be monitored. The solidification rate could be controlled by varying the casting speed or by application of localized stirring. Not only could the quality of current continuously cast alloys be improved, but it might be possible to continuously cast a greater variety of alloys. Continuous casting might be extended to include alloys that are not now continuously cast because of segregation problems.

If the variety of steels that can be continuously cast is increased, this will encourage greater use of continuous casting over ingot metallurgy. Continuous casting saves an estimated 1.4 million Btu per ton compared to ingot practice. In addition, yield improvements and better quality control offer further energy-saving potential.

VIII. RESEARCH RECOMMENDATIONS

Before recommending specific research from a group of alternatives, it is appropriate to organize the results discussed in the previous sections of this report.

Three different categories of parameters have been identified. They are:

1. Measurement Goals

- Real-time measurement and location of the solid/liquid interface of steel during solidification
- Real-time measurement of the average internal temperature of hot solid steel
- Real-time measurement of internal temperature distributions in bodies of hot steel.

2. Production Applications

- Continuous casting
- Ingot production and breakdown
- Reheat furnaces.

3. Temperature-Dependent Physical Principles

- Thermal expansion/Density
- Acoustic velocity
- Electrical conductivity
- Neutron thermalization.

A series of three matrices was prepared in which each parameter in each category was analyzed in combination with each parameter in each of the other two categories. Each element in each matrix (a total of 33 elements in the three matrices) was assigned one of four judgments as follows:

- (A) The combination of the two parameters is reported to have been attempted.
- (P) The combination of the two parameters may have potential, but has not reported to have been attempted.
- (N) The two parameters are not related.
- (D) The combination of the two parameters is reported to be under development.

The three matrices presented in Figures VIII-1 to VIII-3 show the nature of the relationships between applications and goals, between physical principles and applications, and between physical principles and goals. This system, however, does not take into account the magnitude of each activity. This will be discussed, specific to each measurement goal, in the recommendations to follow.

The following decision criteria were used to evaluate each of the measurement goals: "Any government-financed research and development activities will concentrate on long-term, high-risk, high potential payoff projects with the best chance for wide generic application to materials problems and increased productivity." (National Materials and Minerals Program Plan and Report to Congress, April 5, 1982)

Measurement Goals Steel Industry Applications	Measure Solid/Liquid Interface	Measure Average Internal Temperature	Internal Temperature Distribution Mapping
Continuous Casting	A	P	D
Ingot Production and Breakdown	P	P	P
Reheat Furnaces	N	D	P

FIGURE VIII-1. RESEARCH MATRIX COMBINING MEASUREMENT GOALS WITH STEELMAKING APPLICATIONS

Physical Principles Steelmaking Applications	Acoustic Velocity	Thermal Expansion	Neutron Thermalization	Electrical Conductivity
Continuous Casting	A	A	P	A
Ingot Production and Breakdown	A	P	P	P
Reheat Furnaces	P	P	P	P

FIGURE VIII-2. RESEARCH MATRIX COMBINING PHYSICAL PRINCIPLES WITH STEELMAKING APPLICATIONS

Physical Principles Measurement Goals	Acoustic Velocity	Thermal Expansion	Neutron Thermalization	Electrical Conductivity
Measure Solid/Liquid Interface	A	A	P	D
Measure Average Internal Temperature	P	D	A	D
Internal Temperature Distribution Mapping	P	D	P	D

FIGURE VIII-3. RESEARCH MATRIX COMBINING PHYSICAL PRINCIPLES WITH MEASUREMENT GOALS

Futhermore, it is helpful to identify several different research and development alternatives. These include:

- No further research
- Literature search
- Technical evaluation
- Laboratory research and development
- Field testing
- Use in production.

Armed with a set of matrices describing current activities, decision criteria, and an outline of possible research alternatives, it is possible to make specific research recommendations concerning each of the three different measurement goals.

Real-Time Measurement of the Location of the Solid/Liquid Interface

Most of the R&D activity identified during this study involves measurement of the location of the solidification front during continuous casting. This observation indicates that prevention of breakouts and runouts is of primary concern to the steel industry. The tree diagram presented in Figure VIII-4 illustrates the different paths that have been tested. The dashed lines indicate that the techniques are thought to be under development, yet have not been reported in the scientific literature.

Clearly, the extent of research activity suggested by Figure VIII-4 indicates that almost any research undertaken by PNL might duplicate either current or past efforts to measure the solid/liquid interface. The risk involved in conducting research on such measurements is considered relatively low, because several of the systems are reported to have been successfully field tested. Finally, it is anticipated that commercial systems to detect the location of the solidification front may emerge in the near future.

Based on these arguments, it is recommended that PNL not pursue research aimed at measuring the location of the solid/liquid interface.

FIGURE VIII-4. TREE DIAGRAM OF EXISTING RESEARCH ALTERNATIVES TO MEASURE THE LOCATION OF THE SOLID/LIQUID INTERFACE OF STEEL DURING SOLIDIFICATION

Real-Time Measurement of the Average
Internal Temperature of Hot Steel Bodies

The tree diagram in Figure VIII-5 illustrates the research alternatives that have been suggested to measure the average internal temperature of hot steel bodies. Relatively little research activity was discovered concerning average internal temperature measurement. Therefore, duplication of research efforts is not considered likely.

There are two technologies that appear to be fairly well developed. The first is dilatometry, which the Soviets have been investigating in recent years. The Soviets reported successes on the laboratory scale in 1980. Whether the unit has been field tested or is in production is not known. Secondly, IRT Corporation has developed a prototype neutron thermalization sensor under DOE sponsorship. To our knowledge, however, extensive tests with steel have not been conducted.

Both the risk and the benefits associated with an average internal-temperature measurement appear moderate. One reason is that an average bulk-temperature measurement alone is not particularly useful in continuous casting where knowledge of the position of the solidification front is more important. This greatly diminishes the potential for widespread generic application. In furnaces, information about the magnitude of the temperature distribution may be of greater benefit than the average temperature. In short, measurement of the average internal temperature would be an improvement upon existing industrial temperature measurement, yet falls short of many process-control needs.

It is recommended that PNL not pursue average internal-temperature measurements as an overall objective, because the long-term benefits are considered too small to justify a major development program.

FIGURE VIII-5. TREE DIAGRAM OF RESEARCH ALTERNATIVES TO MEASURE AVERAGE INTERNAL TEMPERATURE OF HOT STEEL BODIES

—— Possible techniques for measuring average internal temperature

Real-Time Measurement of Internal-Temperature Distributions of Hot Steel Bodies

Measurement of internal temperature distributions has the widest generic application of the three proposed measurement goals. The location of the solid/liquid interface, the average internal temperature, and internal temperature gradients can each be derived from measurements of the internal temperature distribution. Therefore, internal temperature distribution mapping is at least as useful as the alternatives combined.

Although commercial systems for measuring internal temperature distributions in steel are being developed for specific applications, no generic device is currently available nor known to be under development. It is possible that a single generic solution does not exist. On the other hand, if a generic device were developed, its use in the steel industry represents a potential energy savings estimated at 0.8 quad per year.

It is recommended that PNL pursue measurement of internal temperature distributions in hot steel bodies as its principal research objective.

The tree diagram in Figure VIII-6 shows the research alternatives for measuring internal temperature distributions in hot steel. The solid lines represent systems in current use. The dashed lines represent systems thought to be in development. The alternating dash-dot lines represent untested alternatives.

The most readily available commercial system is Fedesco's STOR thermocouple system for monitoring the internal temperature distribution of slabs in reheating furnaces. However, embedded thermocouples are intrusive and therefore do not satisfy the requirements for a continuous real-time nondestructive measurement.

Electrical conductivity and magnetic permeability might be used to determine internal temperature distributions in steel. Castings Analysis is exploring these techniques in attempting to develop systems for monitoring internal temperature distributions and solidification for the aluminum and steel industries. No commercial systems yet exist.

Castings Analysis uses eddy current measurements and mathematical conversion techniques pioneered by geophysicists to construct a model of the electrical conductivity profile of the spectrum. The inversion techniques may yield more than one solution, requiring additional data interpretation.

FIGURE VIII-6. TREE DIAGRAM OF RESEARCH ALTERNATIVES TO MEASURE INTERNAL TEMPERATURE DISTRIBUTIONS OF HOT STEEL BODIES

— Existing
 - - - Under Development
 . . . Potential

Below the magnetic Curie point, the mathematical analysis becomes more difficult and requires measurement of permeability variations in addition to conductivity.

Tomographic systems using gamma attenuation measurements are being developed by the SMS Corporation for industrial applications in the steel industry. Their systems are capable of reconstructing internal temperature distributions in tubular products and billets. The sensitivity of x-rays and gamma to density changes is expected to require increasingly higher flux densities to obtain the desired degree of resolution, especially for large specimens.

Neutron thermalization techniques might be used to measure internal temperature distributions in steel. A single neutron transmission measurement yields an integrated average temperature weighted more heavily toward the surface. A series of neutron transmission measurements might be used to reconstruct internal temperature distributions. During this survey, we did not encounter any suggestions that neutron thermalization techniques be applied to perform temperature distribution mapping.

Similarly, it has been suggested that a series of acoustic velocity measurements be used to reconstruct the internal temperature distributions. The temperature dependence of acoustic velocity, as shown in Figures V-2 to V-4, can be determined experimentally with small samples of uniform temperature. Real-time measurement during steel production involves large volumes of steel, with the temperature nonuniformly distributed throughout the volume. A complex series of acoustic velocity measurements would be required to reconstruct the internal temperature distributions.

Acoustic velocity measurements are currently being developed for determining the location of the solid/liquid interface during steel solidification. No one was found to be pursuing average (integrated) temperature measurement or temperature distribution mapping using acoustic velocity techniques. However, the experience and hardware under development for measuring the location of the solidification front in steel provides a good starting point for attempting temperature-distribution mapping. Advances in the development of electromagnetic acoustic transducers (EMATs) and laser-induced ultrasound exhibit a strong potential for remote sensing. Remote sensing may be necessary for widespread generic application of the technology.

Acoustic velocity is not dependent solely upon temperature. Other factors, including chemical composition, microstructure, internal stresses, and variation of modulus can affect the velocity. The extent to which these physical characteristics of the steel affect acoustic velocity is not known at this time. If these interdependencies were sorted out, it may be possible to simultaneously measure variations in modulus, internal stresses, and internal temperature distributions. A substantial research and development effort would be needed to arrive at such a system.

A combination of physical principals may be required to measure the internal temperature distribution. However, limited resources are available. If only one technology is to be selected to initiate a sensor development program, it is recommended that research be focused on acoustic mapping techniques, which appear to represent the most generic solution to measurement of internal temperature distribution for all of the steel applications considered. The alternatives, ranked in order of decreasing preferences, are perceived to be: electrical conductivity; gamma tomography and neutron thermalization.

The real-time measurement of internal temperature distributions in bodies of hot steel is a difficult assignment. Step-by-step evolutionary research can be expected to be time-consuming and expensive. There is a substantial risk that even a large investment in research and development might not yield a practical solution within a reasonable period of time. What is really needed is innovation and a flash of genius. These resist scheduling and programming. However, a program of evolutionary research can establish conditions that encourage innovation.

The level of activity required in the next phase of a sensor development program probably combines focused technical analysis with preliminary laboratory investigations. Several basic questions need to be addressed. Among these are:

- Would systems combining measurements based on different physical principals be more effective than systems relying on a single temperature-dependent physical phenomenon?
- Can the temperature dependence of the acoustic velocity be isolated from non-temperature-related phenomena that also effect acoustic velocity?
- What type of acoustic measurement, whether it be phase shift, time of flight, or some other, would be adequately sensitive to temperature?

- Does the hardware exist for transmitting and receiving acoustic waves in hot steel bodies?

What further developments are necessary?

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APPENDIX A

Survey Guide and Flowchart

GUIDE FOR INTERVIEWS

1. Current practices

(a) Where do you measure and control temperatures? (stripping yard, soaking pits, blooming/slabbing mill, bar mills, strip mill, concast machine)

(b) What instruments are now used?
(Optical pyrometer, radiation pyrometer, etc.)

(c) Continuous observation, intermittent, etc.

(d) Manual, automated, or computer control?

2. What are the problems or deficiencies with current practices?

3. How could improvements conserve energy?

4. What developments, if any, are in progress to overcome current problems or deficiencies?

5. What would you recommend for R&D to improve present situation?

6. In what other areas are improved sensors needed?

7. What, if any, R&D is in progress to develop them?

8. Who do you suggest we contact for information on other areas?

TELEPHONE SURVEY FLOWCHART

APPENDIX B

List of
Individuals Contacted
During the Study

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Mr. Robert D. Jeffress

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