METHOD OF CONTINUOUSLY CASTING STEEL

Original Filed Oct. 8, 1964 4 Sheets-Sheet 1

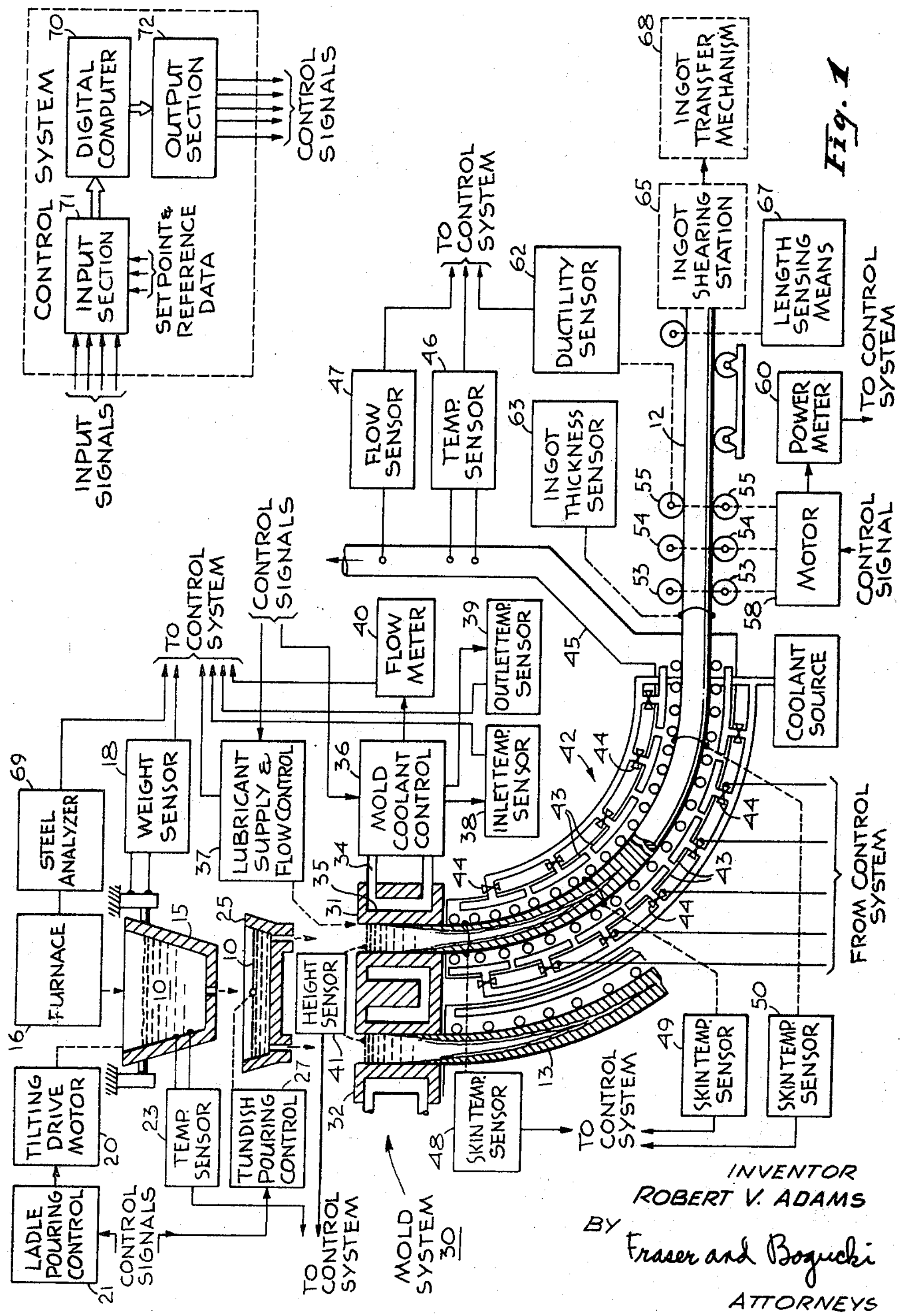

Fig. 1

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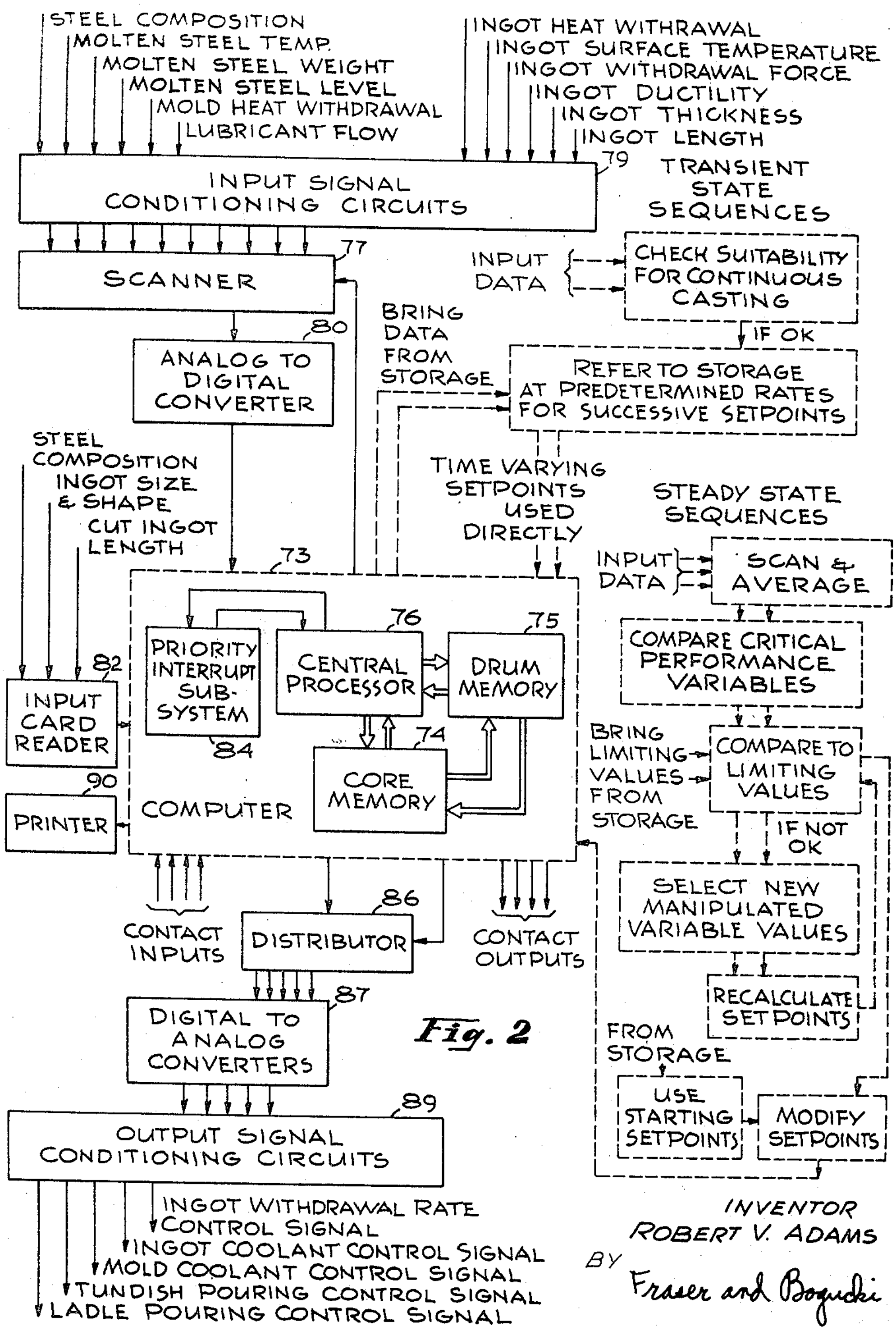

Fig. 2

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Fig. 3

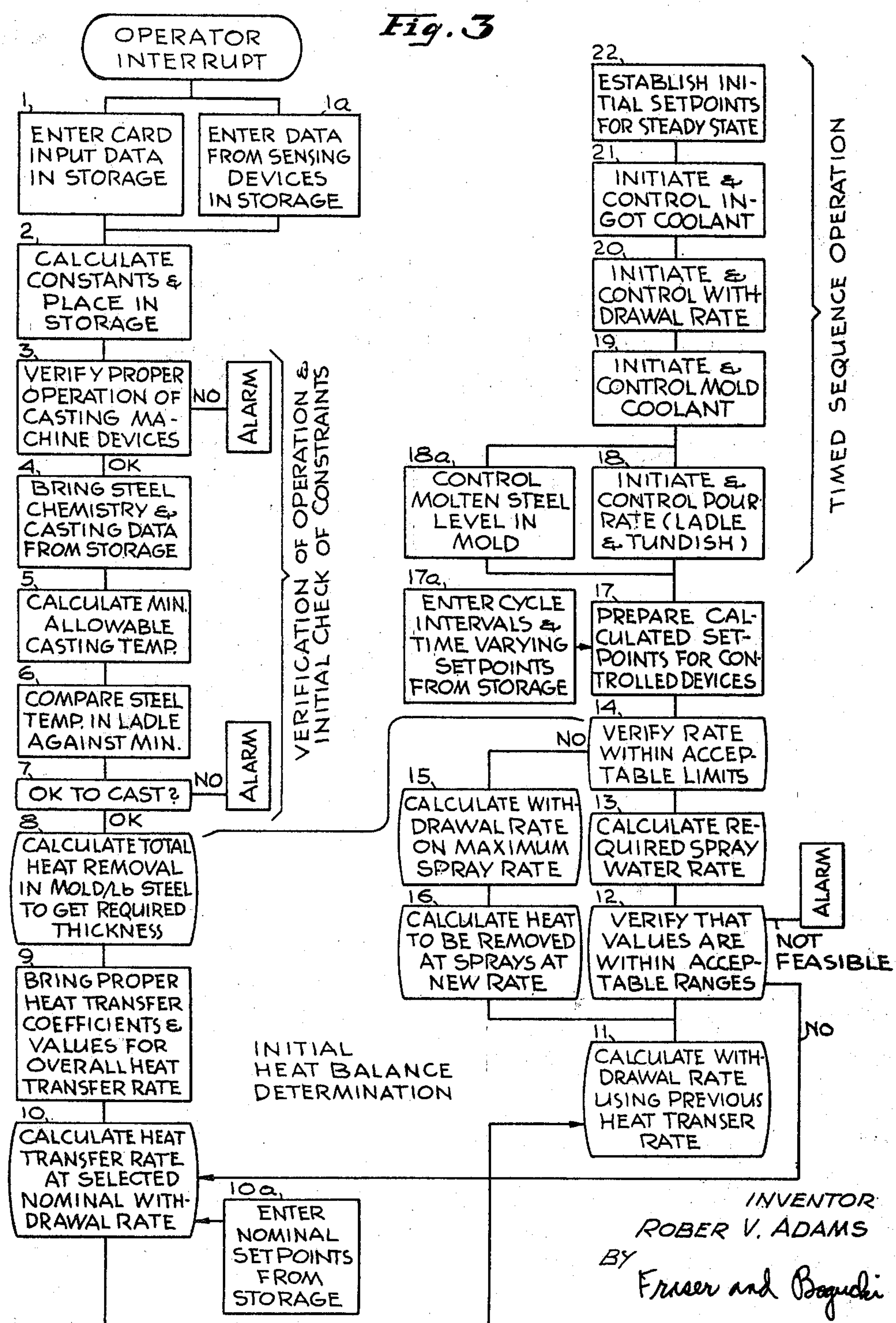

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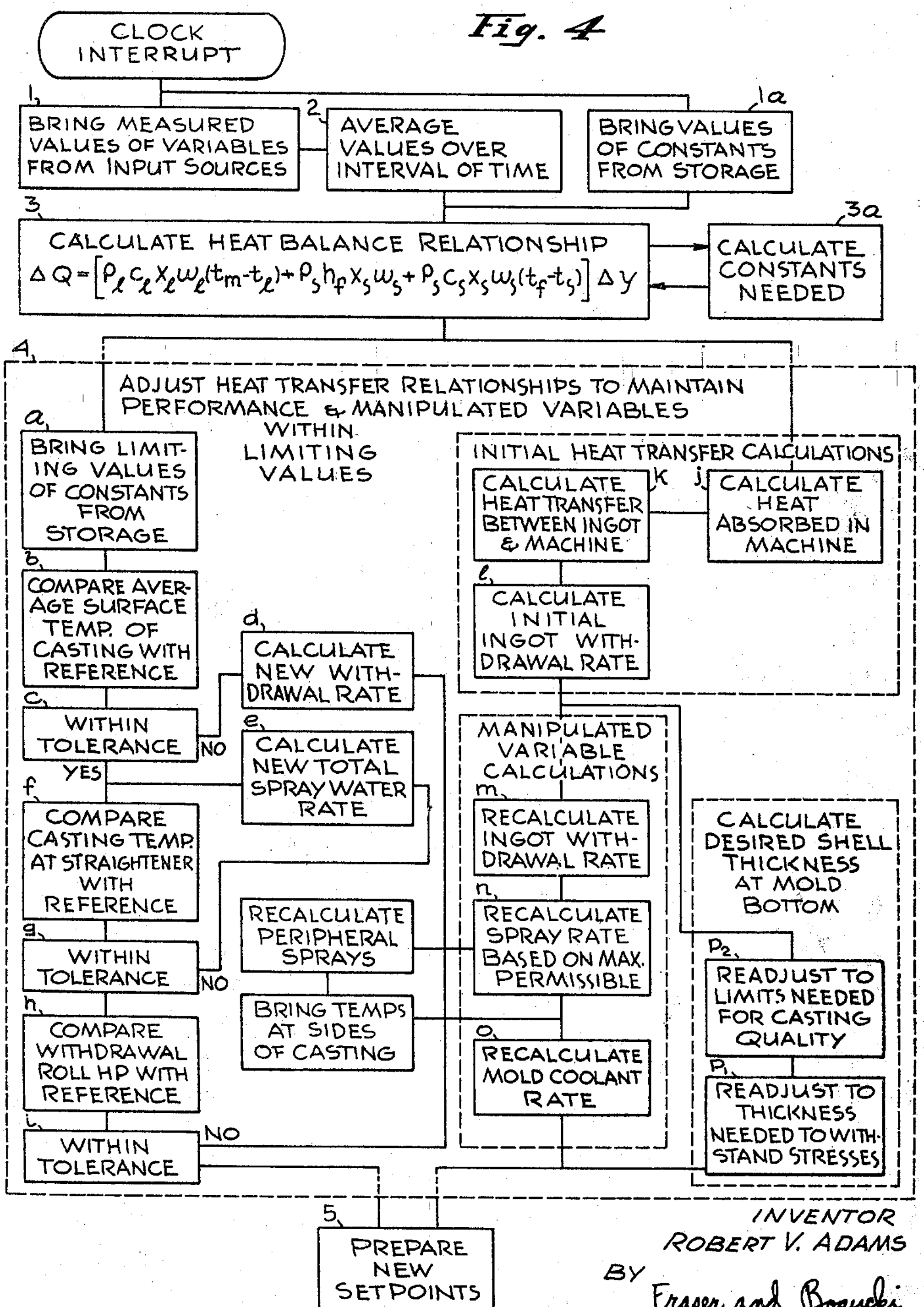
Fig. 4



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3,478,808
METHOD OF CONTINUOUSLY CASTING STEEL

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Original application Oct. 8, 1964, Ser. No. 402,440, now Patent No. 3,358,743, dated Dec. 19, 1967. Divided and this application July 21, 1967, Ser. No. 677,809
Int. Cl. B22d 11/14
U.S. Cl. 164—4 17 Claims

ABSTRACT OF THE DISCLOSURE

Methods for continuous casting, such as the continuous casting of steel, adjust operating setpoints by sensing particular variables computing indirect variables, and adjusting stored operating setpoints referenced to average or typical conditions so as to tend to maintain the indirect variables within selected limits.

This application is a division of previously filed application Ser. No. 402,440, filed Oct. 8, 1964, now Patent No. 3,358,743, entitled "Continuous Casting System."

This invention relates to systems for continuous metal casting, and more particularly to methods and apparatus for the controlled automatic casting of steel.

In the basic metal producing industries, such as the steel, copper and aluminum industries, the term "continuous casting" has been applied to processes by which semifinished products are derived directly from molten metal in a single solidification and forming step. Usually, the molten metal is fed through an open mold having an interior configuration defining the exterior shape of the cast product, and heat is withdrawn from the metal rapidly, so that it solidifies at its outer periphery while passing through the mold. Although the process is now truly continuous only for a given pour or heat of molten metal, it is not inherently so limited. Continuous casting is to be contrasted with conventional casting practices, in which molten metal is formed into separate ingots which are then successively reduced in one or more rolling mills to obtain bars, slabs or billets equivalent to those obtained in one step by the continuous casting process.

The advantages of continuous casting are numerous, in terms of lowered capital investment and operating costs for the machines and improved quality of the manufactured product. Although the process has been under study for many years, substantial numbers of commercial installations have been erected only relatively recently. Although simple in concept, continuous casting is in fact intricate in application, and involves many factors which are not even now fully understood. The characteristics of different steels vary widely and the material being handled undergoes complex temperature, physical and metallurgical transformations before the final solidified product is obtained. Because extremely high temperatures and product weights are involved, and because high production rates are required, it is extremely difficult to concentrate on optimization of product quality. The use of a high casting rate is of no particular benefit if excessive "down time" is consumed in setting up and initiating runs, or in correcting equipment failures. In either event, machine throughput is further effectively reduced to the extent that the product is of unacceptable quality. The primary defects encountered in continuously cast steels are surface tears and pinholes, internal tears, and butt end scrap. The catastrophic failures which occur in continuous metal casting operations demonstrate the complexity of this casting technique. With a given level of molten metal in the mold, solidification starts by the formation of an outer shell and the continued inward growth of this shell as the solidified billet or slab is withdrawn from the open bottom of the mold. Large quantities of liquid coolant are passed in contact with the mold, in order to maintain the rate of heat withdrawal within certain limits, as well as above a certain minimum. If the cooling gradient is discontinuous or excessive, the outer shell of the metal billet or slab may adhere to the surface of the mold, and then tear away, either leaving an imperfection in the surface or causing a metal breakout. If the cooling rate is inadequate, the shell may not be of sufficient thickness and may open under stress upon leaving the mold. The molten interior of the billet or slab also may not be solidified at the time of reaching the withdrawal rolls and the product may be substantially deformed. In the event that catastrophic failure does occur, in the form of breakout, the entire content of molten metal in the mold, as well as in the interior of the billet or slab, is discharged onto associated equipment. It is of course not desirable to restrict operating rates in order to maintain better control, because the throughput of the casting machine is correspondingly reduced while costs are increased.

Catastrophic failures develop predictably following certain events. For example, a weakened shell wall may result in the bulging of the ingot preliminary to breakout. When this occurs, corrective measures to prevent breakout must be undertaken as quickly as possible. Similarly, other failures are preceded by sudden and irregular changes in operating conditions, such as the failure of a mechanism or an erroneous switching action. Constant monitoring of all operative conditions, and appropriate action or indication, are needed to provide maximum throughput and yield.

Typical prior continuous casting installations employ individual operators who visually observe particular operating conditions and make necessary adjustments in accordance with predetermined criteria. Thus, the flow of metal from a tundish into the top of the mold may be monitored by an observer who notes the level sensed by a molten level indicator system and adjusts the flow so as to maintain the molten metal level substantially constant. The flow of coolant and the ingot withdrawal rate may be regulated by an operator who observes surface quality and various temperatures, and attempts to maintain desired absolute temperatures as well as particular relative temperature gradients along the path of metal flow.

The controllable factors in a system of this nature include in part the metal flow rate, the heat withdrawal rate in the mold and spray cooling regions, the withdrawal tension and the withdrawal pressure. These factors are not, however, directly related to more critical operating factors which can seldom be directly measured, such as the thickness of the shell at the bottom of the mold, the rate at which the shell is solidifying and the point at which the product is completely solidified, and the temperature gradient along the casting. Proper control of the process requires proper solidification of the exterior shell within the mold, followed by uniform internal solidification to a point ahead of the withdrawal rolls, at which the entire interior of the billet or slab is solidified. To maintain these conditions under high speed operation, the withdrawal rate, the molten metal flow, and the rate of heat withdrawal within the mold and within the spray, as well as the temperature gradient along the length of the casting must all be properly interrelated.

Stated in another way, necessary corrective action must be undertaken on the basis of slightly changing observed variables because the critical factors cannot themselves be directly measured. Operators working on these present systems can learn through experience how to maximize throughput for limited times but they cannot respond sufficiently rapidly, or with adequate precision, to slight but meaningful changes in operating characteristics. Furthermore, increasingly stringent demands on continuous casting machine no longer permit reliance on operator techniques to overcome the many and varied conditions which are apt to be encountered in typical high rate production runs. As is well known, the metallurgy and temperature characteristics of different grades and alloys of steel differ widely. For certain special kinds of steel used in high volume, entirely different factors must be monitored and controlled. Rimming steels, for example, require the maintenance of a rimming action but the avoidance of excessive turbulence and oxidation. Other special considerations further complicate the continuous casting problem. The casting system characteristics themselves change because of the temperatures and masses involved. Account must always be taken of the wear of the tundish, the nozzle and the mold walls. Further, the size and shape of the casting may materially affect the casting procedure.

There are in addition a number of modern developments in continuous casting which further complicate problems of control. To minimize capital costs, a technique has been devised for casting from a curved mold, with the formed billet or slab thereafter being straightened. To have proper straightening action, the cast product must have proper ductility on reaching the straightening rolls. Furthermore, continuous casting machines are now being used to feed continuous rolling processors directly, thus forming the basis for a completely integrated high speed metal refining, forming and fabricating facility. Control of the multiple factors involved in such an installation is essentially dependent upon obtaining both the necessary quality and throughput from the continuous casting machine.

Coordination of a continuous casting machine with associated steel melting and rolling facilities especially dictates high production rates and yields and minimum downtime. These requirements in turn tend to impose the use of multistrand machines, as to which minimization of butt end scrap becomes a significant problem. Adjustment of strand lengths and cut lengths can be employed to provide minimum butt end scrap, but this requires computations which are extremely difficult for an operator. Similarly, it is also difficult for an operator to log data as to production variables, or to prepare business records. Performance of such functions, however, is highly desirable because of the insights which can be gained into the continuous casting process and because cost, inventory, shipping and billing data can thereafter be handled largely by automatic data processing machinery.

Various automatic control techniques have been proposed for limited parts of a continuous casting system, based mainly upon mechanical mechanisms. These techniques, however, provide relatively simple closed loop systems for control of those variables which can directly be measured, such as metal level and coolant temperature, and do not control the more significant variables within the process, either directly or indirectly.

It is therefore an object of the present invention to provide a novel system for the control of a continuous casting machine.

Another object of the present invention is to provide an improved method for the continuous casting of steel.

A further object of the present invention is to provide an improved continuous casting system which enables higher throughput to be maintained with superior quality.

Another object of the present invention is to provide an improved system for continuous casting and forming of metal billets and slabs.

Yet another object of the present invention is to provide an improved casting system which operates substantially continuously over prolonged intervals to provide improved casting quality and substantially optimum throughput.

Systems in accordance with the invention are characterized by unified and simultaneous control of many variables in a continuous casting machine through use of stored information and virtually simultaneous sensing of a number of variables. Sensing devices measure the values of a number of independent variables, which may be at least partially redundant and which are largely different from the variables that can be controlled. A number of values are derived that are representative of the status of critical performance variables in the process. From the performance variables further calculations are made, after comparison to stored values, for each of the controlled mechanisms, such that all critical parameters are maintained within selected limits. The system controls given variables which cannot be directly measured by calculations based on the observed surface temperature of the casting, which are then maintained within selected limits. Process conditions are also modified so as to optimize throughput while maintaining quality. Particular setpoints are established for controllable variables, but only after significant constraints on product strength and quality have been observed.

A feature of systems in accordance with the invention is the unification of a digital system with a continuous casting machine to provide a novel casting system. The digital system receives data from the various sensors at high scanning rates, and from this data derives setpoints for manipulated variables in accordance with known control functions and limiting values for critical performance. As a result of the ability of the digital system to interrelate the control functions with data received at high rates of speed, a number of further and particular advantages are derived. The results of previous casting operations may be recorded and utilized as general setpoints for a particular operation. Even though no direct experience may have been had with a particular type of product, extrapolated values may be derived for use as initial setpoints. Thereafter, disturbances in the process which result in inability to maintain the setpoints and proper operating conditions result in appropriate adjustment of the setpoint.

Another aspect of the invention relates to the control of both discontinuous and truly continuous phases of a steel making cycle. In the discontinuous (e.g., start and stop) phases the control functions are carried out in timed cycles leading to the establishment of operating setpoints derived from stored values. In the continuous phase, the operating setpoints are changed periodically or substantially continuously in order to assure that constraining values are maintained within selected limits. The operating setpoints may further be modified, in accordance with desired quality, to give maximum permissible throughput. Thus the system may operate in an open loop fashion for transient conditions and in closed loop fashion for steady state conditions.

Another feature of the present invention resides in the organization and operation of the system such that relatively inexpensive sensors may be employed as the sources of information. By high speed scanning of these sensors, and by interrelating the values which they present, a substantially accurate and comprehensive model of the state of the process may be derived without the use of complex instrumentation. Further, the rate of change of variables, and not merely the value of the variables themselves, may constitute important input information to the process. By the use of such information, minute changes which result in substantial variations may be anticipated and corrected by feed-forward techniques. Further, abnormal changes or conditions may be quickly identified and an appropriate alarm given. A significant change of this kind is that which occurs in casting thickness when a bulge occurs prior to breakout.

Another feature of systems in accordance with the invention is the capability of such systems to monitor and control a number of simultaneous casting operations, and also to adapt to additional or changed input and output requirements. The multiple simultaneous control capability is employed in casting multiple strands using like or different size molds. By this means, product yield may be maximized through manipulation of cutting lengths so as to reduce butt end scrap. The capability to modify input and output relationships is of particular importance, because of continual changes in instrumentation and control mechanisms, and the resultant desirability of adding or substituting new equipment. Further, the system is inherently capable of incorporating additional features, such as data logging for use in analysis of information and in establishing reference setpoints, and preparing production and inventory records.

A better understanding of the invention may be had by reference to the following description, taken in conjunction with the accompanying drawings, in which:

FIGURE 1 is a combined block diagram and side view, materially simplified and partially in section, of a continuous casting system in accordance with the present invention;

FIG. 2 is a block diagram representation of principal functional units employed in a digital system for use in a continuous casting machine in accordance with the invention;

FIG. 3 is a block diagram of successive steps performed by a system in accordance with the invention when operating in a transient mode; and

FIG. 4 is a block diagram of successive steps performed by a system in accordance with the invention when operating in a steady state mode.

An automatically controlled continuous casting system is illustrated in functional schematic and diagrammatic form in FIG. 1. Molten steel **10** for casting into the form of ingots, billets or slabs **12**, **13** is disposed in a ladle **15** after pouring from a furnace **16** as a single melt. The mechanisms for handling molten steel may be of any conventional form, but the ladle **15** includes certain associated instrumentation mounted within the ladle or on the supporting elements of the ladle transport and tilting mechanism (not shown in detail). Alternately the transfer ladle may utilize a stopper rod for bottom pouring. A weight sensing unit **18**, such as a strain gauge mechanism, is mounted on the ladle **15** support. The drive motor **20** for tilting the ladle **15** may be controlled manually by an operator in conventional fashion, but the motor **20** may also be controlled in servo fashion by signals received from the processing system through a pouring control **21**. If a stopper rod were used, the servo control mechanism would determine rod position to control the flow rate. The ladle **15** is also equipped with an associated temperature sensing means **23** which may comprise one or more optical pyrometer devices or bimetallic elements capable of withstanding the temperature of molten steel. The temperature sensor **23** provides a continual indication of the temperature of the molten steel within the ladle **15**.

In conventional fashion, steel is poured from the ladle **15** into a tundish **25** for controlled, non-turbulent flow into the casting machine itself. Inasmuch as a multiple mold system may be utilized, it is common practice to use an appropriate multiple-outlet tundish. Here, a two mold system is illustrated, and the tundish **25** is additionally centrally pivoted under the control of a tundish pouring control system **27**, so that in predictable fashion a known disproportion can be maintained between the flows into each of the two molds. The flow relationship is governed by the signal applied from the control system to the tundish pouring control **27**. As pointed out above in conjunction with the transfer ladle, the flow rate from the tundish and into the mold could be determined and governed by a stopper rod mechanism.

The continuous casting mold system **30** includes a pair of adjacent molds **31**, **32**, only the first of which will be described in detail, inasmuch as they may be in all other respects identical. It will be recognized, however, that the various sensors and controls are utilized in conjunction with each of the parallel molds, and that they are appropriately controlled concurrently. In accordance with continuous steel casting processes, the mold **31** may be of the curved, oscillating type, in that the central longitudinal axis of the mold **31** is curved from the vertical toward the horizontal, with the mold oscillating in conventional fashion along this arcuate central axis. This construction enables a curved ingot **12** to be formed and diverted into a horizontal path within a relatively short vertical distance. This arrangement greatly reduces the size and cost of the casting structure and the building in which it is mounted. It is to be expressly understood, however, that the invention may be practiced with any type of mold system.

FIG. 1 very generally illustrates the manner in which the casting proceeds, in that a coolant **34** passed at a high rate of flow about the periphery of the mold **31** withdraws heat from the molten steel **10** at the top of the mold through a heat conductive (such as copper) material which defines the inner wall of the mold **31**. A solidified shell begins to form on the outer surface or periphery of the molten steel **10**, immediately below the meniscus. As a solid outer wall develops from this shell, the ingot **12** is withdrawn out of the bottom of the mold **31**, and further cooled until, at some point along its path, a point of complete solidification is reached. The initial cooling rates within the mold and immediately adjacent the mold, are of critical importance, inasmuch as breakouts caused from excessively thin walls, or adhesion to the sides of the mold **31** due to various factors, can cause severe difficulty. The coolant **34** flowing through the coolant chambers **35** about the mold **31** is shown as regulated in at least one property by a mold coolant control **36**, which may be a valve system electrically operated by control signals. The mold coolant flow rate is extremely high and may not be chosen to be regulated in some systems. It is feasible, however, to vary the mold coolant pressure, so as to avoid partial boiling at the mold coolant interface, and modify the heat withdrawal rate to a limited degree. Input and output temperature sensors **38**, **39** in the path of flow of the coolant **34** before and after the mold **31** provide temperature differential measurements from which heat withdrawal rates may be calculated. The rate of mold coolant flow is measured by a flow meter **40**, and the temperature and flow rate measurements are provided in signal form to the control systems to enable determination of the heat withdrawal in the mold.

It is desirable, for most applications, to measure the height of the meniscus within the mold **31**. This measurement may be taken by a height sensor **41** of the radiant energy type having an X-ray source disposed on one side of the mold and an array of sensor devices at various heights on the opposite side of mold **31**, from the readings of which the height of the molten steel meniscus within the mold **31** is accurately indicated in analog or digital form. A lubricant supply and flow control **37** is included in the mold system **30**, and is operable from the control system. The amount of lubricant used has a direct bearing on both the ingot friction and ingot surface quality.

Immediately upon leaving the mold **31**, the internally molten ingot **12** passes into an ingot or spray cooling region defined by a spray chamber **42**. A number of high velocity spray heads **43** having rate control valves **44** are mounted along the path of the ingot, and at spaced points about the circumference of the ingot **12**. The flow rates are governed by signals applied to the different valves **44** from the control system. The spray is withdrawn from the region of the ingot **12** at the downstream end of the spray heads **43** through a conduit system **45**, in which are positioned temperature sensors **46** and flow sensors **47**. These sensor elements **46**, **47** provide the means for determining the amount of heat withdrawn from the ingot in the spray cooling region. Additionally, if greater precision is desired as to this determination, means (not shown) may be mounted in the conduit system for determining the amount and temperature of vaporized coolant in the exhaust.

A plurality of ingot skin temperature sensors **48**, **49**, **50** are mounted at successive points along the path of the ingot in the region of solidification. Although only three sensors **48**, **49**, **50** are shown in block form for simplicity, these represent sensing stations at which temperatures are taken at a number of points about the periphery of the ingot. While accurate temperature readings at individual points can be obtained only with difficulty, because of the presence of spray and steam, systems in accordance with the invention appropriately utilize this information in determining the temperature gradients along and around the ingot **12**, the solidification profile, and the point of complete solidification within the ingot. The skin temperature sensor **48** closest to or within the mold **31** itself may comprise an electrical signal generating elecent, such as a bimetallic member, whereas the sensors **49**, **50** within the ingot cooling region may comprise a pair of shielded optical pyrometer devices or bimetallic elements. Sensors (not shown) may also be employed for detecting the temperatures of the mold and tundish walls.

Subsequent to the ingot cooling zone, the ingot **12** passes through a series of withdrawal roll pairs **53**, **54**, **55** disposed along a horizontal plane. The three withdrawal roll pairs **53–55** also serve as straighteners for the ingot **12**, which at this region must be sufficiently ductile to permit straightening, but yet completely solidified internally. The roll pairs **53–55** are driven separately, if desired, but in the present example are driven by a single motor **58** that is operated at a speed determined by the control system. One measurement at the withdrawal roll system is derived from a power meter **60** or similar measuring device, and representing the power required for the motor to withdraw the ingot **12** at the selected rate. During the casting operation, the ingot may adhere to the sides of the mold, so that the amount of power required to withdraw the ingot may vary widely. The second measurement is therefore a measurement of the ductility of the ingot **12** itself, derived from the resistance to compression presented by the ingot in a direction transverse to its length. The measuring device **62** for this purpose may comprise a strain gauge or other sensor mounted on the common coupling of one pair of withdrawal rolls **53–55**. An ingot thickness sensor **63** is also disposed prior to or in conjunction with the withdrawal rolls **53–55**. The sensor **63** may comprise mechanical, optical or magnetic means in operative relation to the sides of the ingot **31**, or coupled to a pair of rolls **53–55** to provide a signal representative of a selected transverse dimension of the ingot **31**. The thickness sensor **63** may be positioned within the spray cooling region, the position chosen being one in which a significant bulge is discernible while corrective measures can still be effective.

It will be appreciated that although the curved and multiple mold types of continuous casting machines provide particularly good examples of such systems because of their increasingly wide use and advantages, systems in accordance with the invention need not use these principles or arrangements. Similarly, while the illustrated system is shown as applied to the casting of slabs, continuous casting machines in practice may cast rounds, squares and other shapes as required. Casting conditions of course vary dependent on the shapes being cast, as well as the steel that is utilized.

Subsequent to the withdrawal and straightener rolls **53–55**, the ingot **12** passes ingot shearing station **65**, which may be a conventional torch cutter type of system which moves with the ingot **12** during the cutting operation. Adjacent the shearing station **65** is disposed a length sensing means **67**, here a calibrated roller (not shown in detail) in engagement with the ingot **12**, and a suitable analog or digital signal generator. More conventionally, the length sensing device for actuating the shearing station **65** may be a bar or other member interposed at a selectable position in the path of the extending end of the ingot **12**, and arranged to operate the cutter mechanism when the ingot has reached a specific length. As previously described, similar cooling, straightening and shearing sections are utilized for each of the two parallel casting stands operating from a given melt of steel. Both may then feed the sheared ingot lengths to the associated cooling tables or ingot transfer mechanisms **68**, which are not shown in detail.

Not illustrated in FIG. 1 is a starter bar arrangement such as is conventionally used for filling the mold **31** when the initial supply of molten metal **10** is fed from the ladle-tundish system. Reference will hereafter be made to the transient phases of system operation, which include the start-up and shut-down sequences, and emergency sequences. The mechanics of the start-up and shut-down functions remain the same as in conventional systems, but the manner in which they are controlled in accordance with the invention is substantially different. It is important to note, however, that from the economic standpoint speed is almost as important during transient phases as during steady state phases. The casting of a given melt, say 100 tons, will take approximately 1 hour, whereas an approximate half hour may be required before the next casting operation can begin. Drastic reductions in the time needed for the accomplishment of transient phases can therefore materially improve the economics of the casting machine.

Additionally, a steel composition analyzer **69**, such as a spectrophotometer, is connected to the furnace **16** to provide data as to the actual composition of the steel melt to the control system. The steel analyzer **69** may include a digital conversion system, or the control system may include predetermined subroutines for converting analog input data to percentage values for different elements.

The casting process may properly be spoken of as "continuous," even if only the steady state phase of the operation is considered. Nevertheless, it must be recognized that the discontinuous phases of the operation are of great importance, not only to the economics of this method of casting metals, but also to the control problem which is presented. The novel control systems in accordance with the invention, therefore, include the control system elements illustrated in very general form in FIG. 1 integrally with the sensing and control elements on the casting machine. A digital computer **70** continuously receives signals representative of the directly sensed variables at an input section **71**, and provides signals to operate the various controllable elements, principally for entirely different variables, at an output section **72**.

The data provided to the input section **71** includes setpoint information from previous heats, stored in the computer **70** memory, as well as particular instructions pertaining to the heat in question, inserted by a card, tape input, or panel device. Further data is stored as to limiting values for certain critical performance variables, such as temperature gradients, points of complete solidification, withdrawal rates, and mold and spray coolant flow rates and heat withdrawal rates. The digital computer **70** is also provided with and stores time-varying setpoint information for the control of time varying actuator movements which are required during transient state conditions. These time varying setpoint instructions stored in the memory for the transient phases may comprise sequences of setting values for the directly controllable variables in the casting machine. The setpoints used during steady state operation represent both values of directly controllable variables and computed reference values which are useful in the operation of the system.

In this system, the digital computer **70** is arranged and used to compute certain critical parameters related to the heat transfer conditions applicable to the ingot being cast. These variables, which need not and in most cases cannot be directly measured, include the temperature gradients along and about the ingot, surface and internal stresses along the ingot, the profile of the solidified part of the casting and the point of complete solidification within the ingot. While setpoint information, typically derived from the histories of past castings, may be suitable for controlling an entire casting sequence, this is unlikely, inasmuch as both adequate quality and maximized throughput must be maintained over a range of conditions. The system therefore adjusts setpoints in indirect relation to the input and output variables but on the basis of the most significant factors pertaining to the successful operation of the casting machine. It must also be borne in mind that, even though it is likely that further advances in the art will result in a substantial reduction of down time between castings, transient conditions and discontinuities cannot be avoided because of the inevitability of intermittent failures, the necessity of equipment repair and the need for producing different grades of steel and different shapes and sizes of ingot.

COMPUTER AND CONTROL SYSTEM

It is preferred to employ a process control type of computer system, preferably one having specific features and subsystems. The various sensors and control devices operating in conjunction with the casting machine provide the necessary data inputs to the input section of the computer, and are operated in response to the signals derived from the output section of the computer. A conventional closed loop control or a direct process control system is not fully suitable for this application, for a number of reasons. One reason is that the variables which are sensed are not directly related to the controllable devices. Another reason is that the most significant casting variables cannot be directly measured, or controlled. Thirdly, the transient or discontinuous portions of the overall process are substantially different from steady state operation, and consume substantial amounts of time. The process is further complicated in that there are wide variations in the heat transfer and physical characteristics of the starting material and the ultimate product. Therefore, a computer and control system such as is shown in FIG. 2 is preferred. The following is a brief description of the signals provided to and derived from the computer and control system, and its general mode of operation.

For the computer itself, it is preferred to employ a control computer **73** of the type having a core memory **74**, a drum memory **75**, and a central processor **76** for its principal storage, arithmetic and processing units. In addition, it is desirable to utilize an input-output unit which includes means for receiving a considerable number of input signals and means for providing a considerable number of output control signals. Systems in accordance with the invention therefore employ a scanner **77** that receives the signals from input signal conditioning circuits **79** that are coupled to the various sensors (not shown in FIG. 2). The conditioning circuits **79**, which may be conventional, provide the necessary amplification of generated signals with freedom from noise and drift. The scanner **77** successively couples the separate input terminals to a single output terminal, to which is also coupled an analog to digital converter **80**. Under commands from the computer **73** to the scanner **77** the various sensors provide analog signals successively to the system. These analog signals may change slowly, in accordance with relatively slow changes in the variable being measured, but may also have substantially higher frequency transient or noise variations which average to zero. In the present system, the input signals are repeatedly scanned at a relatively high rate of speed, while utilizing the computer **73** to average the signals so as to effectively cancel the noise components.

The input signals applied to the computer **73** through the analog to digital converter **80** are derived from the various signal generating devices described in detail in conjunction with the casting machine of FIG. 1. For simplicity, these may be characterized more generally as follows:

(1) Steel composition (derived from the analyzer **69** associated with the furnace **16**).

(2) Molten steel temperature (derived from the ladle temperature sensor **23**).

(3) Molten steel weight (derived from the ladle weight sensor **18**).

(4) Molten steel level in the mold (derived from the sensor **40** at the mold).

(5) Mold heat withdrawal (derived from the temperature sensors **38, 39** and coolant flow meter **40** at the mold).

(6) Spray heat withdrawal (derived from the temperature sensors **46** and the flow sensor **47** in the spray cooling region).

(7) Ingot surface temperatures (derived from the temperature sensors **48–50** along the ingot path).

(8) Lubricant flow rate (derived from the lubricant supply and flow control **37**).

(9) Ingot thickness (derived from the ingot thickness sensor **63**).

(10) Ingot withdrawal force (from the power meter **60**).

(11) Ingot ductility (from the ductility sensor **62** coupled to the withdrwal rolls).

(12) Ingot length (derived from the length sensor **67**).

Other input data of a digital nature is provided directly to the computer. The use of conventional switching circuits, timers and the like to assure that various operating elements of this system are in position and properly operating when starting will be understood and therefore has not been illustrated in detail. Thus, separate switch-in signals may be provided to denote that the starter bar is in position, that the starter bar withdrawal has begun, and that the starter bar has been fully withdrawn. All control signals of this nature are classified and grouped together as contact inputs. These input signals are essentially merely switching signals and are applied directly to the computer **73**. Also applied directly to the computer **73** are external program inputs, supplied through a card reader **82**, or other conventional device such as a paper tape reader or operator communication panel. For each heat, one or more cards are prepared with appropriate input data pertaining to specified steel composition, ingot size and shape, and cut ingot length, including upper and lower acceptable length limits. In order to provide further output information, the input data may also include accounting data, but performance and use of accounting and record keeping function will not be described herein.

It is also preferred that the computer **73** include a priority interrupt subsystem **84**, for enabling the main program sequence to be interrupted on a selective priority basis to respond to process emergencies, perform critical measurements or calculations, accept or deliver data, and respond to, leave, and return to other on-and-off line tasks. In this manner, routines may be retained until completion of other routines of higher priority.

The output section of the system comprises a group of digital to analog converters **87** coupled to the computer **73** through a distributor **86**, although they may also be directely coupled if desired. The distributor **86**, under timing control from the computer **73**, applies aproprlate signals in turn to the digital to analog converters **87**. Each converter **78** controls a different one of a group of output signal conditioning circuits **89** of conventional form which operate the individual controllable devices (not shown in FIG. 2) in the casting machine of FIG. 1. Among the signals that are generated are the ladle pouring control signal, the tundish pouring control signal, the lubricant flow control signal, the mold coolant control signal, the spray coolant control signal, the ingot withdrawal rate control signal, and alarm signals generated for any of a number of reasons. A wide variety of additional output devices may be utilized, but the only one shown in FIG. 2 is a printer **90**, which may be used to record setpoints, times and operating conditions for future reference and analysis. It should be noted, however, that the computer **73** may also be used to initiate shipping and inventory records for the steel as it is being cast. In adidtion, for various control and emergency functions, the computer **73** provides a number of on-off or switching control signals that are grouped together under the designation "contact output."

An important aspect of the organization of this system relates to the fact that the effective input information includes internally retained information within the storage of the computer. The general plan of use of this stored data, and the functional subroutines within the computer **73** are indicated broadly in FIG. 2. Reference should also be made to FIG. 1 for the various signal sources, FIG. 2 illustrates in generalized form that under transient conditions the control system operates essentially in an open loop mode, whereas under steady state conditions it operates in a closed loop mode which, however, may have hybrid characteristics. The setpoints themselves are not, as previously noted, directly determinative of the variations in the sensed variables. Accordingly, the computer undertakes routines in which it utilizes the input information to compute critical performance variables and to compare these to desired standards other than the setpoints. In accordance with these computations and comparisons, the setpoints are appropriately revised in the steady state mode.

The considerations involved in the operation of the control system and casting machine are discussed in substantially greater detail in conjunction with FIGS. 3 and 4, but are briefly reviewed here. In the multiple ladle type of casting system, a melt of steel of a given desired composition is poured from the furnace **16** into the ladle **15**, then the ladle is moved into pouring position relative to the casting machine. Prior to the pouring from the ladle, the program input data is provided to the computer **73** (FIG. 2) through the input card reader **82**, and a precise determination of actual steel composition is made by the analyzer **69** (FIG. 1). The starter bar (not shown in FIG. 1) is in position in each of the molds, and the computer **73** established the starting setpoints for each of the controlled elements. The system then proceeds through start, continuous run and shutdown sequences for the particular heat of steel, responding to emergency conditions as they occur.

The input data obtained from the card reader **82** identifies the steel type and the finished product specifications, so that the computer **73** may make reference to stored start sequence data appropriate for the specified steel and product. Input data pertaining to steel specification may not be required from the input card reader **82** if the steel analyzer data is accurate and substantially complete. Usually, however, there are special considerations applicable to the properties of the steel or the casting of the steel which require that the operator-prepared program input data also be used. Thus, if the steel being cast is a rimming steel, this fact may require certain additional data in order to control the addition of deoxidant agents during the casting process.

With a starter bar in position for each of the molds, the mold coolant control **36** and the spray coolant control valves **44** are operated to provide minimum heat withdrawal until ingot formation has commenced. The pouring control system **27** operates the tundish **25** to insure initially equal delivery of steel into the two molds. At this point or previously, the computer program makes an initial verification that the heat may be cast successfully. The program uses the molten steel temperature in the ladle as the basis for a computation as to whether the molten steel temperature is within an appropriate range to permit satisfactory completion of the casting by the continuous casting method. If the necessary conditions are met as determined by the actual temperature and the likely final temperature, the steel is then poured at a controlled rate into the tundish **25**, and therefrom into the molds. A launder mechanism may also be operated to separate slag and other impurities from the flow. This event initiates a time-varying control cycle, governed by the computer **73**, during which the reference is made to the computer storage for setpoint data and the following events transpire:

A. The motor **58** for the withdrawal roll pairs **53, 54, 55** is brought up to and maintained at a selected speed.

B. The lubricant supply and flow control **37** is actuated and kept in operation.

C. The mold coolant control **36** is operated to allow heat withdrawal in the mold as the ingot forms and begins to be withdrawn with the starter bars from the mold.

D. The spray coolant controls **44** are varied substantially linearly with time from a time prior to the initial appearance of the formed ingot from the bottom of the mold.

E. The predetermined setpoints for these controls are used directly until the starter bar has passed the withdrawal rolls **53** to **55** and the operation is substantially on a continuous basis.

The above steps may also be controlled by an operator, in which case the control system may be used to scan the controlled devices to insure that they are actuated in the proper order and time sequence. As the system starts running continuously, the pouring rate, mold heat withdrawal rate, ingot heat withdrawal rate and ingot speed are first held at computed setpoints for the given steel composition and ingot characteristics. In the steady state mode, the various analog imputs are continuously scanned and averaged, to provide more accurate values for the subsequent computations. Computations are then made of the critical variables which cannot be directly measured, namely the thickness of solidified casting at the exit end of the mold, the profile of the solidified portion, and the point of complete solidification within the ingot. These variables are largely determinative of production rate and ingot quality, although ingot ductility at the withdrawal rolls is another significant factor. The principal information used for this purpose is derived from the various ingot skin temperature readings. If it is determined that the temperature gradient along the ingot cross-section is too high, for example, transverse tears and other billet defects are apt to be introduced, leading to a reduction of surface quality if not a breakout of molten steel. Obviously, if a correction is needed it can be effected by adjustment of one or more of the controllable varables, but the adjustment which is made inevitably changes the total heat balance and effects the other critical variables. If the temperature gradient is too high, for example, it may be reduced by increasing the ingot withdrawal rate, or by decreasing the rate of heat withdrawal at the mold or in the spray zones. Integrated adjustment of these various factors is carried out in an optimum fashion by iterative techniques using new calculations based upon selected acceptable values for the variables. Once the setpoint values are all modified to provide fully acceptable conditions, the setpoints then existing are modified to the new values. The overall system then comprises a closed loop system, which seeks to maintain the withdrawal force, temperature gradients, ingot stresses and point of complete solidification within particular limiting values maintained in the storage. The manipulated variables are not, except in a few instances, operated in individual closed servo loops, but are adjusted in interrelated fashion in accordance with the critical performance variables.

Concurrently with the casting and withdrawal of the ingot, the computer performs a separate subroutine in which the relationship of the length of ingot cast from each mold is related to the cut length for the particular order in order to maximize yield. This is further related to the amount of steel left in the ladle **15**, so that an appropriate imbalance between the steel fed into the two molds is introduced by control of the pouring control system **27**. The total wastage in butt end scrap at the shearing station **65** is thereby kept to a minimum. The continuous run sequence then continues until the molten steel level of the remaining operative mold begins to drop and no further steel is available in the ladle **15**.

As the termination of the cast is approached, care must be taken to assure that the trailing end of the ingot does not cool irregularly. Thus the system again shifts from the use of selected setpoints to the use of time-varying setpoints obtained from computer storage and used without modification. The mold and spray coolant may be shut off abruptly as the trailing end of the ingot passes the mold and spray regions respectively. For a greater degree of control, the setpoints may be changed so as to gradually decrease the mold coolant flow until the ingot has exited, and thereafter reduce the mold coolant flow at a rapid rate in order to permit gradual cooling of the mold walls. The spray coolant may also be systematically reduced in rate as the trailing edge of the ingot is passed toward the withdrawal rolls. Excessive cooling at this point might abruptly decrease the ductility of the trailing end of the ingot, and cause damage to both the ingot and the withdrawal rolls.

As longer wearing tundishes and mold walls are developed, it is feasible to operate the continuous run sequence for substantially longer than present casting systems operate, by supplying a new ladle of steel as the previously used one is emptied. With such systems, erosion of operating units becomes a significant factor which may require data to be supplied to the computer. The time-varying start-up and shut-down sequences must be used, however, whenever steel types are changed and whenever erosion becomes significant. Automatic control of the shut-down sequence is of particular significance in enabling the shut-down time to be minimized.

The computer continuously receives signals representative of important variables, and may utilize separate subroutines to insure that either or both the absolute values and rates of change of these variables are within acceptable limits. Thus, significant degradations in the functioning of the system may be detected and alarm indications provided. Substantially all of the measurements described in FIG. 1 will be used in such checks, although rates of changes will typically not be observed as to mold and spray coolant rates and temperatures, and lubricant flow rates.

The data logging and record keeping functions are subsidiary to the casting operation, but provide further extensions of the capability of the digital system. As desired by an operator, the values of important variables may be noted sequentially during a cast, for use in detailed analysis of thermodynamic factors, and for calculation of future setpoints. Additionally, basic business records useful in shipping, billing and maintaining inventory of the fabricated product may be initiated concurrently with the casting operation.

PROCESS STEPS AND OPERATIONAL CONTROLS

The computer program and its relation to the various input signals derived from the casting machine and the output control signals provided to the casting machine will now be described. At the outset, the computer storage contains start-up and shut-down cycle data, setpoint data for normal operating conditions for specific steel grades, and the necessary interpolation subroutines for modifying setpoints in accordance with steel characteristics. Further, the storage contains data as to the limiting values or operating constraints for manipulated as well as performance variables. The computer program determines scanning rates and signal averaging, and the computer system includes facility for priority interrupt. The performance of these individual functions for a given cast will be discussed in detail, in the sequence in which they are performed.

Start-up sequence.—The successive operating steps in starting are shown in FIG. 3. After operator interruption of the existing program, input data is entered (step 1) as the operator inserts a punched card or other storage member in the input reader of the computer, with information as to the melt size, ingot size and shape, the desired cutting length range and the specifications called for in the heat of steel. These are entered in the computer storage. As the ladle is brought to the pouring position, information is also entered into the storage (step 1*a*) from the various measuring devices of the casting machine, to provide information as to the actual steel analysis, the temperature of the steel in the ladle, and any significant data as to the molds, tundish and nozzle characteristics. The system then calculates, in step 2, the proper constants for various factors used in the heat transfer equations, including constants for the mold, tundish, nozzle, and heat grade. Where actual steel chemistry varies from that specified or the grade is unlike previously known grades, new constants may be interpolated in accordance with known functions.

The start-up phase then continues with initial determinations of whether the casting machine is functioning properly and can properly operate under the specified conditions. Although the calculations and comparisons which are used may be extensive, they are performed so rapidly that they are substantially instantaneous, relative to the handling of the steel in the ladle.

At or before the time the ladle is brought to the pouring position, a separate verification is made of the proper operation of the different controllable devices and sensing devices on the casting machine. These various input and output devices are merely scanned to insure that they are properly operating (step 3). Thus, it is insured that the starter bar is in position, the lubricating, mold coolant, spray coolant and any other mechanisms which affect the heat balance equation are properly operative, that the withdrawal roll motors and instruments are in operation, that the ingot length sensor is properly operating and that the mold oscillation mechanism is properly functioning. As the comparison is made an alarm indication is provided if any of the operative checks reveals a malfunction. The computer prolgram is also set to return at longer intervals, of the order of one minute, to verify proper operation of these.

With the actual steel chemistry and steel temperature data at hand, a check is then made (steps 4, 5, 6 and 7) of whether the steel temperature in the ladle is high enough to permit satisfactory completion of the cast. Because of the variables in melting and casting, and because delays occur before the ladle can be brought to the pouring position, the steel temperature in the ladle may drop below a point at which the casting can be satisfactorily completed. The predicted temperatures can be calculated separately to a first order of magnitude for given casting conditions, without considering the various adjustments which can be made in achieving the proper heat balance relationship. Thus, if the first order indication is that the temperature is below the minimum required for satisfactory completion of the cast, the check is made at step 7 and the alarm is sounded.

An initial calculation of heat balance relationships is then made, in order to determine, on the basis of the actual steel grade, steel temperature, and ingot specifications, the initial operating setpoints. This initial calculation includes a determination that all of the operating factors are within allowable operating limits for the casting conditions required. The heat balance equation is discussed in detail below, in conjunction with the steady state operating phase. Essentially, however, it must be ascertained that the rate of heat withdrawal required is within achievable limits considering the variations in mold coolant and spray coolant heat transfer rates which can be achieved. In addition, it must be ascertained that, given these satisfactory heat transfer rates, the ingot withdrawal rate is also within acceptable limits. Thus the start-up phase provides an initial calculation of setpoints for the steady state phase, even though stored setpoints may alternatively be utilized in initially setting up the system.

Limiting values for the mold cooling heat transfer rate, the spray cooling heat transfer rate and the ingot withdrawal rate for the casting machine are known, and maintained in the computer storage. Steps 8 through 16 represent in general form the heat balance determinations which are utilized in accomplishing step 17, the calculation of initial setpoints for the steady state operation. The first steps of this sequence may be used to to verify that operating constraints will not be exceeded. In step 8, the computer calculates the total heat required to be removed in the mold per pound of steel to obtain the required minimum thickness of ingot leaving the mold. The other needed values (step 9) constitute the heat transfer coefficients and various constants which are disclosed in detail in the specific discussion of the heat balance equations below. These various input values are then used to make an initial calculation (step 10) of the heat transfer rate at a selected nominal withdrawal rate, obtained (step 10*a*) from storage with other nominal setpoint values.

The calculated heat transfer rate will most likely differ from actual heat transfer rates derived or calculated from previous heats. Thus it is desirable to also calculate (step 11) the withdrawal rate using previous heat transfer rates. Using the results of steps 10 and 11, a further calculation may be made based upon whether either or both of the results are within limits (step 12). If not, the computer program calls for a return to step 10, and the calculation of a heat transfer rate using a different selected nominal withdrawal rate. In both steps 10 and 11, the calculated withdrawal and heat transfer rates are compared to predetermined maximums and minimums, and an alarm may be sounded if the program cannot be completed after a given range of adjustments has been attempted.

After the initial determination, terminating with step 12, of the fact that calculated heat transfer rates and withdrawal rates will provide the desired steel thickness at the exit of the mold, and that these rates are within acceptable limits, the required spray water rate is calculated (step 13) to solidify the ingot as required without exceeding previously determined limits on temperature gradient across the ingot cross section. This water rate is then checked against the maximum available rate (step 14), and if the calculated spray water rate is not allowable, a new withdrwal rate (step 15) is calculated based upon the maximum spray rate available. The heat to be removed by the sprays is then calculated at the new rate (step 16) and the newly calculated withdrawal rate is then returned to the system to verify that the rates are within acceptable limits (step 12).

When this sequence has been carried out to a point at which the heat transfer rate, the withdrawal rate and the spray water rate are all within acceptable limits, the figures thus attained are the calculated setpoints for the controlled devices (step 17) At this time also (step 17) the cycle intervals and the time varying setpoints are brought from the storage.

With all of the operating figures within acceptable limits, the casting operation may be commenced by initiating flow from the ladle into the tundish, using a launder mechanism if desired, and from the tundish into the one or more molds to be utilized. At this point the time sequences of operation of the various controllable devices at the casting machine are initiated. Inasmuch as the various devices may be operated substantially concurrently, and are also varied concurrently until they reach the calculated or predetermined setpoints, it should be borne in mind that steps 18 through 21 do not represent a time sequence.

The ladle is first operated to initiate pouring into the tundish, with the provision being made for automatic disposal of surface slag if desired. The pouring rate is brought up to the predetermined setpoint in a timed cycle, drawn from the computer storage, and thereafter the molten steel level in the mold is sensed by the appropriate device of the casting machine, and returned to the computer to be used as a reference for thereafter controlling the pour rate (step 18*a*).

As molten metal reaches the mold, and initially solidifies at the starter bar, the mold coolant rate or pressure is brought from a starting level to the calculated setpoint level in synchronism with the buildup of the level of molten steel in the mold (step 19). If cooling water is permitted to flow into the mold prematurely, condensation water might form on the inside of the mold. The entry of molten metal produces steam which might damage the mold lining or the ingot surface or both. Similarly, mold lubricant and spray water must be turned on at the proper time to avoid damage to the machine. The withdrawal action is begun within a very short time, inasmuch as the newly formed ingot base adheres to the starter bar and the mold shell develops initially very rapidly. Consequently (step 20), the starter bar withdrawal is begun and the withdrawal rate is brought up to the calculated setpoint again within a predetermined length of time. Heat transfer in the spray region is brought from an initial starting level (step 21) to the calculated setpoint level at a slower rate, inasmuch as normal heat withdrawal at the ingot is not required until a substantial length of the ingot has been drawn from the mold. The calculated setpoints may be maintained for a predetermined length of time after the starter bar has exited from the withdrawal rolls, and substantially constant operation has been achieved (step 22).

If it is preferred to use the operator to perform the bulk of the start-up function, the computer may be used simply to check the various units in turn and to actuate an alarm whenever a unit is not turned on at the proper time. In one sense, a closed loop exists between an individual-controlled device and the machine, but the casting machine operation itself is open loop.

Thus it may be seen that the start-up phase involves an initial determination of constraints and verification of the safety of the operation, as well as calculation of the initial setpoints and control of the variable start-up timing cycles. This degree of control insures greater reliability and more immediate achievement of a quality product, but only parts of these various controls need be utilized if desired. On the other hand, the calculation and data transfer rates of the computer are sufficiently high so that considerably more complex and detailed calculations can be undertaken at each phase, in order to insure even greater control. The starting cycle is completed within perhaps 10 minutes in a particular cast, within which time a computer can make some of the initial calculations of wall thickness and surface and internal stresses described below in conjunction with steady state operation, making appropriate adjustments to the various operative elements.

Steady state phase.—Satisfactory performance of the control functions requires that the interrelation of a great many operating variables, both independent and dependent, be considered. The independent variables may be classified as both manipulated variables, or those which may be directly controlled, and disturbance variables, or those which are ordinarily determined by system conditions. The manipulated variables may be listed as follows: (1) ingot withdrawal speed, (2) mold water pressure, (3) spray water rate, (4) lubricant rate, (5) mold water rate.

Of these, the mold water rate will often be kept invariant in the steady state phase of the system, because of the difficulties of adjusting the flow rate at the high levels which are required.

The disturbance variables may be listed as follows: (1) hot metal temperature, (2) hot metal chemistry, (3) cooling water entry temperature, (4) mold and tundish characteristics.

The mold and tundish characteristics relate to the size and degree of wear of the mechanism. The amount of pinch force exerted by the withdrawal rolls may also be independently varied by the operator, and might accordingly be listed as a separate independent variable. More typically, however, the variations in the pinch force with which the control system are concerned result from the actual dimensions of the ingot because the pinch rolls are preset in position and the steel ductility at the withdrawal rolls, so that this is more properly treated as a dependent variable.

The dependent variables are divided into two major groups, a first of which may be termed performance variables. These are the variables which directly and indirectly relate to the economic use of the casting machine in terms of the quality and amount of the product produced. Various performance variables may be listed, not necessarily in the order of their importance, as follows: (1) casting speed, (2) casting quality, (3) casting thickness at mold bottom, (4) casting temperature at straightener rolls.

Items 3 and 4 above might be classified as a part of casting quality, but are of such importance that they are listed separately. The various constraints on operation discussed below in connection with the specific example of FIG. 4 are also indirectly but significantly determinative of casting quality.

The other dependent variables are what might be termed intermediate variables, which are directly related to performance characteristics or to the constraints, and are significantly affected by operating conditions. The major intermediate variables may be identified as: (1) casting surface temperature, (2) cooling water temperature differential, (3) withdrawal roll motor horsepower, (4) withdrawal pinch force.

The principal operative sequences which are used in the steady state phase are represented in generalized diagrammatic form in FIG. 4. It will be recalled that the initial operating setpoints are brought from the storage for and used at the termination of the start-up state phase, with or without adjustments for steel temperature and composition. The computer system also scans the storage to derive program control sequences for the various calculations which are performed as described below, and brings the measured values derived at the sensing devices (step 1). Concurrently, reference is made to the storage for the values of constants utilized in the equations, as well as for the limiting values, or constraints, which are imposed upon certain of the operating variables (step 1*a*). Input signals derived from the various input sources of the system are scanned at high speed and averaged in the computer system during operation (step 2). These of course represent a number of the manipulated and disturbance variables previously mentioned.

Given the availability of the various constants and input variables, therefore, the control system proceeds through successive calculations and readjustments of the operating setpoints. The heat balance relationship between the casting itself and the casting machine, including the mold and spray cooling regions, must be calculated in order to establish a standard by which the amount of heat to be removed in order to establish a given depth of solidified shell in the casting can be determined (step 3). A straightforward thermal expression for this heat balance relationship is:

$$Q_{out}=Q_{in}$$

where Q_{out}=heat removed from the casting (B.t.u.), and Q_{in}=heat absorbed by the cooling water and casting equipment (B.t.u.). The expansion of these simple terms into a practical empirical formula involves the consideration of many factors, including the loss of heat of the steel as a liquid and a solid, and the loss of heat in solidification. Considering these factors, Equation 1 illustrates the heat loss for an increment of distance along the axis of the strand, in going from the liquid state to a given thickness of solid steel.

$$\Delta Q=[\rho_l c_l x_l \omega_l (t_{in}-t_l)+\rho_s h_f x_s + \rho_s c_l x_s{}_s (t_f-t_s)]\Delta y \quad (1)$$

ρ_l=density of molten steel (lb./ft.^{3})
c_l=specific heat of molten steel (B.t.u./lb.)
x_l=thickness of molten steel (heat)
ω_l=width of molten steel (heat)
t_{in}=temperature of steel into mold (° F.)
t_l=average temperature of molten steel (° F.)
ρ_s=density of solid steel (lb./ft.^{3})
h_f=heat of fusion (B.t.u./lb.)
x_s=thickness of solid steel (ft.)
ω_s=width of solid steel (ft.)
c_s=specific heat of solid steel (B.t.u./lb.-° F.)
t_f=fusion temperature of steel (° F.)
t_s=average temperature of solid steel (° F.)
Δy=length of ingot in incrementally selected section (ft.)

For a given height of steel (y) in the mold, the above expression may be modified to give the heat balance around the mold as follows:

$$\rho_\omega c_\omega V_\omega (t_{in}-t_{out})=[\rho_l c_l \omega_l (t_m-t_l) + \rho_s h_f x_s{}_s + \rho_s c_s x_s{}_s (t_f-t_s)]y \quad (1a)$$

where
ρ_ω=density of water (lb./ft.^{3})
c_ω=specific heat of water (B.t.u./lb.-° F.)
V_ω=volume of water through mold (ft.^{3})
t_{in}=temperature of water into the mold (° F.)
t_{out}=temperature of water out of the mold mold (° F.)

Unidirectional heat transfer may be assumed, so that the temperature of the molten steel will be a result only of the heat transferred from the outer wall. The temperature at the strand axis will then be dependent on the amount of cooling done in the previous incremental length along the strand axis. Of the remaining variables, only those which require some elucidation will be discussed in detail hereafter. Standard factors such as the density of water are brought from the computer storage, whereas the temperature of the water in and out of the mold (t_{in} and t_{out}) and other values such as V_ω and t_m are derived from the input sensors.

Of the above variables, ρ_ω, ρ_l, ρ_s, c_l, c_s, c_ω, h_f, and t_f have known values for specific steel chemistry and temperature. For example, the fusion temperature of steel is variable, dependent upon the chemical composition of the steel. A formula may be utilized, as set forth at page 32 of the handbook "Basic Open Hearth Steel-Making," published by the A.I.M.E. This formula adjusts a standard fusion temperature in accordance with the percentages of the most common elements used in steel compositions, the straightforward calculation being made by reference to the nominal steel specification for the melt derived from the card input data, or from the actual steel analysis.

The specific heat of the molten steel and the specific heat of solid steel may be used as constants, or appropriate values may be computed depending on the particular steel condition. Thus, the specific heat of the molten steel may be taken as a constant whereas the specific heat of the solid steel may be calculated in accordance with the somewhat discontinuous curve shown on page 545 of the handbook "Basic Open Hearth Steel-Making."

The heat of fusion of steel is generally taken as approximately 117 B.t.u./lb. with no allowance made for variations in chemical composition.

The remaining variables, x_l, $_{\omega l}$, x_s, $_{\omega s}$, t_l, and t_s are all related to the shape of the liquidus-solidus curve or the temperature within the casting itself. Thus they are all related to the distribution of the heat loss from the casting. The thicknesses of molten and solid steel may be established by using a polynominal of the following form:

$$x=a+by+cy^2+dy^3$$

where

x=thickness of solid steel
y=distance from the mold steel surface
a, b, c, d=empirical coefficients

The various empirical coefficients are affected by a number of factors, and the position of the boundary surface is preferably obtained by using an overall heat balance as described below.

The liquid steel temperature may be averaged in accordance with a differential equation which considers the thermal conductivity of the steel, the specific heat of the steel, and the steel density, and assumes two-dimensional heat flow in a homogeneous, isotropic medium. The solid steel temperature is of less significance, because of the lesser volume of solid steel in the mold, and because the skin temperature is known and the temperature profile can be assumed to correspond generally to the solidus-liquidus line.

Obviously, the computing system is also capable of performing the intermediate calculations as necessary (step 3*a*) in order to determine unknown values in the above heat balance equation, as well as to specifically identify the effects of changes in particular conditions, as in grades of steel. The computer may calculate values based on either different values or on the particular variable measured at different times. Through the use of the production logging facility of the computing system, a body of information may be assembled which enables particular constants to be established with greater precision, and enables the empirical equations to be defined more precisely.

As previously mentioned, the steady state phase may be considered as a hybrid closed loop operation, in that it involves certain separate closed loops, as illustrated in steps *b* through *i* within step 4. In step 4, the heat transfer relationships are adjusted to maintain the different variables within limiting values, after bringing the limiting values from storage (step 4a). Substeps *b* through *i* deal with the adjustment of certain controllable variables which have substantially direct relation to measured variables. In this conjunction, the system operates in what may be regarded as an "immediate mode," providing direct feedback control. Thus (substeps *b*, *c*, *d* and *e*), the average surface temperature or the surface temperature gradient of the casting may be straightforwardly computed from the measured surface temperatures and compared to reference values. New withdrawal and spray water rates may be computed if the surface temperatures or the surface temperature gradients are not within tolerance. Viewed differently, the surface temperatures are used to determine approximations of the liquidus-solidus profile, and to adjust the profile as needed. The known thermal conductivities of the steel being cast and the surface temperatures on the casting can be used to identify the casting thickness. A steady-state transfer of heat may be assumed over small periods of time at one point along the strand axis. Making these assumptions the actual thickness may be estimated. From this determination, necessary corrections in heat withdrawal rates can be made.

The casting temperature at the straightener (substep *f*) and the withdrawal roll horsepower (substep *h*) may be compared to reference values and new withdrawal and spray water rates calculated if the values are not within tolerance (substeps *d* and *i*). Other direct control loops of this nature may be used, to effect operation of manipulatable factors so as to tend to keep within predetermined tolerances. In all of these calculations, standard feed-forward techniques may be used to anticipate needed changes.

Other significant relationships are determined by using the heat transfer relationships in the mold and spray cooling regions to calculate variations from average values of critical operating variables and to find optimum operating setpoints for manipulated variables. To determine optimum setpoints, consideration must be given to the important variables which affect heat input to the casting machine, physical limitations on casting, and the rate at which heat can be removed. Understanding of these factors permits creation of a model of the formation of the casting, and interrelated adjustment of the manipulated variables. The withdrawal of heat from the solidifying casting involves a highly complex transformation, for which neither average values or linear rates of change are satisfactory for control. The physical limitations imposed are generally related to the shell thickness at the mold bottom.

In order to provide initial withdrawal rate figures from which subsequent adjustments may be made, the heat absorbed by the casting machine (Q_{in}) and the heat given up by the casting are determined (substeps *j* and *k*). From these the withdrawal rate may be calculated (substep *l*). The constraints on operation are then applied, and used as bases for modifying the setpoints. The heat absorbed by the casting machine (Q_{in}) comprises the heat absorbed by the cooling water, the heat absorbed by the casting machine and surrounding members, and the heat radiated to the atmosphere. By far the most significant of these three types of heat loss is the loss to the cooling water, which can be divided into the two primary cooling zones of the mold and the sprays. Heat loss to the mold cooling water can be expressed by the following relationship:

$$Q_{in}\ (\text{mold cooling water})=\rho_\omega V_\omega(t_{in}-t_{out}) \qquad (2)$$

where:

ρ_ω=density of water (lb./ft.^{3})
V_ω=volume of water through the mold (ft.^{3})
t_{in}=temperature of water into mold (° F.).
t_{out}=temperature of water out of mold (° F.).

All of the above factors are either constant, or provided from the input measuring equipment.

The heat absorbed by the casting machine itself and its surrounding members can be assumed to be constant, in view of the predominant effect of the cooling water. If greater precision is desired in this respect, temperature sensors about the casting machine can provide measurements upon which a more precise calculation of the heat conducted from the molten steel through the casting machine can be calculated. The heat radiated from the casting through the atmosphere may also for practical purposes be taken as a constant, although measurements and calculations of specific values can again be made. Adding together these three sources of loss, they must be equal to

$$\sum \Delta Q_{out}$$

for the length along the strand axis.

The heat loss to the cooling sprays can be expressed as follows:

$$\Delta Q_{in}\ (\text{spray})=\rho_\omega V_{\omega\text{return}}(t_{in}-t_{out})+\rho_\omega V_{\omega\text{lost}}h_e \qquad (3)$$

where:

ρ=density of water (lb./ft.^{3})
$V_{\omega\text{return}}$=volume of water returned to system (ft.^{3})
t_{in}=temperature of spray cooling water (° F.)
t_{out}=temperature of return spray cooling water (° F.)
$V_{\omega\text{lost}}$=volume of water lost due to evaporation (ft.^{3})
h_e=heat of evaporation of water (B.t.u./lb.)

All of these values are either directly measured or directly available from storage, assuming that a measurement is made of the amount and temperature of vapor carried from the exhaust stack. Substantial vaporization occurs, of course, when the spray water impinges upon the surface of the casting, and this vaporization and the subsequent superheating of the steam must be accounted for in determining the total heat taken out in the spray region. With certain types of spray systems, an estimate can be made based upon the proportion of water converted into steam, as determined by a comparison of the volume of output water to the volume of input water in the spray region.

The actual rate of heat transfer between the steel casting and the machine, including the mold and spray cooling regions, is determined by the transfer of heat from the molten steel through the solidified portion of the casting and to the associated mold or spray regions as the steel is continually moving. Because the heat transfer mechanisms are substantially different for these two regions, they will again be considered separately.

In the mold region, the heat in the molten steel must pass through the solidified portion of the casting, through a gap between the casting and the mold, through the mold wall and through the boundary between the mold wall and the cooling water. The rate at which heat can be transferred must be established. The heat transfer relationship can be expressed as follows:

$$U=\frac{1}{1/k_1+t_c/k_c+1/k_3+t_m/k_m+1/k_4} \qquad (4)$$

U=overall heat transfer coefficient (B.t.u./hr.-ft.^{2}-° F.)
k_1=heat transfer coefficient between molten steel and solid casting (B.t.u./hr.-ft.^{2}-° F.)
t_c=thickness of solid casting (ft.)
k_c=thermal conductivity of steel casting (B.t.u./hr.-ft.^{2}-° F.)
k_3=heat transfer coefficient in mold air gap (B.t.u./hr.-ft.^{2}-° F.)
t_m=mold thickness (ft.)
k_m=thermal conductivity of copper mold (B.t.u./hr.-ft.^{2}-° F.)
k_4=heat transfer coefficient between mold and cooling water (B.t.u./hr.-ft.^{2}-° F.)

The above complex relationship is required because of the discontinuous cross-section presented between the molten steel and the cooling water. Note that the casting-mold-water interface is expressed in terms of a number of heat transfer coefficients k_1, k_c, k_3, k_m, and k_4. The heat transfer coefficient of the molten steel and solid casting (k_1), of the casting (k_c), of the copper mold (k_m) and of the water and the mold (k_4) may be experimentally determined or represent known functions, given temperature and flow conditions. The heat transfer coefficient of the mold-air gap, however, is assumed here to be based upon a coating of lubricant between the casting and the mold, and is expressed as follows:

$$k_3=\frac{1}{1/k_5+x_r/k_r(P_{\text{burn}})} \qquad (5)$$

where:

k_5=heat transfenr coefficient for molten steel (B.t.u./hr.-ft.^{2}-° F.
x_r=thickness of lubricant coating (ft.)
k_r=thermal conductivity of lubricant (B.t.u./hr.-ft.^{2}-° F.)
P_{burn}=(factor to account for percentage of lubricant burned)

The value k_5 is understood by those skilled in the art to be derived from one of several published empirical formulas which take account of turbulent flow and laminar flow considerations, only general discussion of which is provided here.

As one alternative, direct metal-to-metal contact can be assumed, in which the coefficient k_3 equals an appropriate film coefficient (k_r). As a second alternative, a different empirical known expression may be utilized which assumes the presence of an air gap between the casting and the mold.

The heat transfer coefficient (k_4) between the mold wall and the cooling water may follow a different function if partial boiling of the cooling water is found to occur. Again, reference may be made to published data for this function. The mold conductivity is essentially a constant, because a small change is likely in the temperature of the mold. The thermal conductivity of the casting, however, is dependnet upon the thermal conductivity of the liquid casting, and therefore its temperature, as well as the thermal conductivity and thickness of the solidified portion.

With the heat balance relationship and the heat transfer relationship computed, in terms of Q(B.t.u./lb.) and q' (B.t.u./lb.) the casting speed r (feet/min.) may then be determined in substep l, as follows:

$$Q/q'=r \qquad (6)$$

The rate r is the nominal withdrawal rate that will yield a thickness of solid steel as designated in the initial calculations for q which in turn is heat transfer rate based on metal mass rather than surface area. Any rate greater than this will result in a thinner wall casting, tending toward a danger of breakout, and any lesser rate will result in a thicker solidified casting, and consequently a reduction in the production rate of the casting machine. The initial withdrawal rate is based upon an assumed value for the thickness of steel casting at the mold, and is used (substeps m, n, and o) to establish properly related values for the spray cooling and mold cooling rates. The heat transfer required from the spray zones must observe the limitations on the heat capacity of those zones. The overall heat coefficient of the spray zones may be expressed as:

$$U=\frac{1}{1/k_1+t_c/k_c+1/k_2} \qquad (7)$$

where:

U=overall heat transfer coefficient (B.t.u./hr.–ft.^{2}–° F.)
k_1=heat transfer coefficient between molten steel (B.t.u./hr.–ft.^{2}–° F.)
t_c=thickness of solid casting (ft.)
k_c=thermal conductivity of steel casting
k_2=heat transfer coefficient between casting and cooling water (B.t.u./hr.–ft.^{2}–° F.)

The only coefficient different from those in Equation 5 above is k_2, the coefficient between the casting and the cooling water. This is affected by the casting surface temperature, the spray pressure and flow rate, and the spray nozzle design.

Such values do not take into account many effects which lead to molten steel breakout, poor steel quality or low throughput. Accordingly, an extensive series of recomputations of each of the manipulated variables and the operating setpoints may also be undertaken in the light of certain constraints on operation. The speed of the computing system and its facility for providing stored subprograms are used to insure that a final set of operating setpoints is established which are both feasible and which place the critical performance variables within appropriate limits. The constraints on operation are each related in some manner to the thickness of the shell at the exit end of the mold.

In this step (substep p) the constraints are computed on the basis of shell strength, or resistance to breakout (substep p_1), and on the basis of casting quality (substep p_2). The shell strength must be adequate to withstand both mechanical and thermal stresses. The tensile stress is due to the longitudinal force or bending moment introduced by the ferrostatic pressure of the liquid column, whereas the thermal stress is distributed over the entire casting face due to a temperature difference between the molten steel and the outside casting surface.

The shell thickness may initially be computed as in Equation 1a above. The stresses, however, must also be computed and compared to acceptable limits, and readjustments made until the total tensile stress is below the allowable yield stress by a selected factor of safety. The bending moment for a slab casting is as follows:

$$M_b=\left(\frac{\gamma_{liq}.h_m}{12}\right)\left(\frac{b^2+a^2}{1+\phi}\right)\phi+\left(\frac{\gamma_{liq}.h_m b^2}{8}\right) \quad (8)$$

where:

λ_{liq}=density of the molten steel
a=narrow dimension of casting
b=wide dimension of casting
$\phi=(k_2^3/k_1^3)\ (a/b)$ coefficient to allow for mold shape
k_1, k_2=coefficients to allow for differences in solidification at mold corners
h_m=height of molten steel column

The stress then is:

$$\sigma_b=\frac{M_b}{\dfrac{x_s^2(h_m-h_1)}{b}}$$

where h_1=height of column of molten steel with no solid shell.

The thermal tensile stress is as follows:

$$\sigma_{therm}=0.95\beta E\Delta t \quad (9)$$

where:

β=coefficient of linear expansion
E=modulus of elasticity
Δt=temperautre drop in the solidifying shell=t_m-t_{surf}
t_m—fusion temperaturs of cast steel
t_{surf}=temperature of strand surface

The total tensile stress is the algebraic sum of these two stresses ($\sigma_{tot}=\sigma_b=\sigma_{therm}$). The two stresses are somewhat opposite in effect, inasmuch as increasing shell thickness to provide greater strength necessarily increases the slope of the temperature gradient and the thermal stress. It is necessary to trade these factors off against each other until a satisfactory compromise is reached.

The shell thickness at the mold bottom, and the liquidus-solidus profile, determine the point of complete solidification within the casting. This point is required to be somewhat upstream of the withdrawal rolls, but should preferably be close to the withdrawal rolls, in order to assure a less steep temperature gradient along the casting, and to assure greater ductility at the straightening and withdrawal rolls and maximize production rate. Obviously, if the location of the point of complete solidification can be directly identified, as by the use of a high energy beam of radiant energy in conjunction with an appropriate detector, this value can be fed directly into the computer as another input signal. In the present state of the art, however, it is preferred to compute the position of the point of complete solidification from the signals provided from the steel temperature detector, the various casting surface temperature detectors, and the ductility sensor. This computed value may then be compared against a desired range of values held in the storage.

The second class of constraints on shell thickness (substep p_2) is imposed by casting quality considerations. The principal defects involved are longitudinal surface cracks due to transverse stresses, resulting from the forces described immediately above, and an additional stress due to friction provided by the casting attempting to shrink. This force is expressed in the following terms:

$$F_{fr}=\mu N A_{fr} \quad (10)$$

where:

F_{fr}=force due to friction in mold
μ=coefficient of friction between casting and mold
N=normal specific pressure on the face of the mold under direct contact of the casting $\gamma_{liq}(h_1+\frac{1}{2}\Delta h)$
A_{fr}=direct contact surface between the casting and the mold wall (=hb, where h=height of column of solid steel shell in direct contrast with mold b=width of mold)

The stress due to the above frictional force will then be:

$$fr=\frac{\mu\gamma_{liq}b(h_1+\frac{1}{2}\Delta h)}{\epsilon_{mean}} \quad (11)$$

where ϵ_{mean}=mean shell thickness for the above Δh.

Transverse surface stresses are also encountered, but there are considerably smaller in magnitude, and may be regarded as negligible except in the event of sticking in the mold wall, an event which is largely avoided by the use of the oscillating mold. In the event of sticking in the mold wall, there is a substantial increase in the power requirement at the withdrawal rolls. This condition may trigger an appropriate device, such as a meter relay to initiate a corrective cycle, such as the supply of additional lubricant or a reversal of the oscillating mold direction.

Surface quality is also affected by conditions which lead to transverse internal tears within the billet, introduced in the spray cooling zone. Internal cracks appear, in a transverse direction and at right angles to the axes of the withdrawal rolls, if the thermal stress introduced by spray cooling and the mechanical stress due to roll pressure exceed the tensile strength of the billet. The thermal stresses may be calculated in accordance with Equation 9 above. The stress contributed by the gripping load introduced by the pinch rolls can be expressed by the following equation:

$$S_m=P/A \quad (12)$$

where:

P=total load on the pinch rolls (lbs.)
A=area of contact between the pinch rolls and the casting (ft.^{2})

This total stress should not exceed the tensile strength of the cast billet. For this determination, data may be brought from storage relative to the tensile strength of the billet for its given metallurgy, and an appropriate subroutine may be utilized to correct this tensile strength in accordance with the actual temperature of the billet at the withdrawal rolls.

A different type of control loop is also maintained, as shown in substeps r and s in FIG. 4. An uneven temperature contour may exist around the periphery of the casting at a given longitudinal position. With a number of temperature sensors disposed about the periphery at each longitudinal position, the computing system need only compare the successive readings for each longitudinal position to determine whether uneven cooling which is likely to give rise to rupture of the casting exists. The peripheral temperature gradient is controlled differently than the other variables, however, inasmuch as the total heat withdrawn in this region remains the same. Therefore control of the cooling in the separate peripheral regions is adjusted only relative to the adjacent regions, and not relative to the withdrawal rate or the total temperature gradient in the spray cooling region.

Shut-down phase.—The shut-down phase is initiated when the molten steel level in the mold begins to drop and there is no further supply available in the tundish to correct the level. Prior systems have simply shut off mold and spray coolants upon passage of the butt end of the casting, and it remains feasible to do so if normal downtimes are acceptable. If accelerated or brief shut-down phases are desired, they may proceed in a timed sequence which is substantially the reverse of the start-up cycle, in that the mold coolant is first gradually brought to a mold level followed substantially immediately by a slower rate of decrease of the spray water coolant, and followed by shut-down of the withdrawal rolls or the start of a new casting.

Additional features.—It has previously been suggested that any given characteristic of a casting operation can be optimized, so as to insure better quality at a lower rate of operation, or to accept greater risks at a higher speed of operation. It should also be understood that the economic value of this system is enhanced by the facility which it provides for predicting the characteristics of new types of steel or unique casting conditions. The system down-time is greatly decreased, not only because of the increased reliability and protection against catastrophic failure which quality control provides, but also because of the timed transient cycles which enable changeovers to be made between heats with minimum lost time.

Important aspects of the invention relate to the emergency procedures and alarm indications which are feasible. If the ingot thickness sensor provides signals which indicate either in magnitude or rate of change that the ingot is bulging excessively, an alarm may be indicated and all spray water applied to the casting. Similarly, if a major or minor breakout occurs, drastic emergency measures may be undertaken. The system will typically monitor the sensors at a rate of the order of 100 points per second, so that variations in other variables are also constantly being monitored, and any faulty conditions indicated. Inasmuch as most breakouts are due to insufficient solid thickness, foreign inclusions in the casting or laps and seams due to improper variation of the withdrawal rate, all of which conditions can be ascertained and largely controlled, systems in accordance with the invention provide increased levels of throughput as well as improved quality.

A further important feature is the facility of this system for cooperation in a completely integrated continuous steel fabricating plant, and for automatic retention of data pertaining to production information as well as casting information. During control of a cast, heat reports can be typed out for operating personnel, performance information can be logged, and if deired housing and shipping data can be prepared for later use. Such features become extremely important if the casting operation is tied directly to a continuous rolling facility.

Other important aspects of the inevntion relate to the versatility which such systems provide. Although multiple inputs are accommodated and multiple output devices are controlled, the system is fully amenable to accepting additional or different input data and utilizing it in the same unified system for both transient and steady state control of the operating processes. The ability of the system to relate many partially redundant factors, and to compute on the basis of these factors includes the ability to program the input functions so as to ignore erroneous readings, and to utilize the most likely readings where different ones of a number of input signals are in conflict. Such systems inherently have an ability to anticipate changes on the basis of the use of rates of change of input variables, or rates of change of computer variables. Thus the safety aspects of the system are further enhanced.

While there have been described above and illustrated in the drawings various forms of automatic control systems for the continuous casting of metals, it will be appreciated that the invention is not limited thereto, so that all alternative forms, variations and modifications falling within the scope of the appended claims should be considered to be part of the invention.

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows.

I claim:

1. The method of continuously casting steel in a system having particular controllable variables adjustable to operating setpoints including the steps of:
- storing operating setpoints for the particular variables from successful casts for known steels;
- sensing during a cast the value of variables, other than the particular variables, relating to the physical characteristics of the steel being cast;
- computing the solidification profile and stress along the casting from the sensed variables;
- comparing the computed solidification profile and the stress to selected standards; and
- concurrently modifying the setpoints in accordance with the results of the comparison.

2. The method of continuously casting steel through use of controlled mechanisms adjustable to operating setpoints which includes the steps of:
- deriving setpoints for controlled mechanisms with respect to average conditions for the steel being cast;
- measuring predetermined ones of the actual physical conditions existing during casting for the steel being cast;
- computing adjusted setpoints based on the measured actual conditions for the steel being cast;
- concurrently computing the profile of the solidified portion of the casting and determining casting strength and quality constraints from the computed profile;
- modifying the adjusted setpoints in accordance with the determined constraints to establish casting strength and quality within selected limits;
- determining required surface temperatures for the modified setpoints; and
- controlling the cooling of the casting to tend to maintain the required surface temperatures.

3. The method of continuously casting steel using the values of controllable variables and sensed variables as to the physical characteristics of the steel being cast including the steps of:
- presenting stored setpoint data for particular controllable variables;
- sensing a plurality of variables during the casting sequence;
- controlling the controllable variables in accordance with the stored setpoints;
- computing indirect variables as to the status of the steel being cast from the sensed variables; and
- modifying the operating setpoints in accordance with desired conditions for the indirect variables.

4. The method of controlling a continuous state transformation process to provide a solidified casting from a molten supply comprising:
- continuously forming a moving casting from a molten supply;
- continuously withdrawing heat from the casting exterior;
- measuring the temperature of the casting exterior;
- computing the rate of heat withdrawal from the casting from at least the measured temperature;
- measuring the rate of movement of the casting; and
- maintaining the profile of the solidified portion of the casting within selected limits.

5. The method of controlling a continuous state transformation process to provide a solidified casting from a molten supply including the steps of:
- continuously withdrawing heat from the casting exterior to form an initial solidified shell;
- forcefully withdrawing the casting;
- monitoring selected variables as to the physical status of the casting during heat withdrawal;
- computing the rate of heat withdrawal from the casting from the monitored variables;
- varying the heat withdrawal rate and the casting withdrawal rate to maintain a selected profile for the liquidus-solidus boundary;
- monitoring the casting thickness; and
- interrupting casting withdrawal upon identification of excessive change in the casting thickness.

6. The method of controlling a continuous casting oper-

ation by varying the heat withdrawal rate and the rate of casting which includes the steps of:

continuously computing the heat transfer rate required for the ingot being cast;

continuously monitoring the temperature of the ingot being cast at at least two points therealong;

determining the value of at least two nonmeasured variables representative of the transformation state of the ingot being cast from the monitored temperatures; and

continuously varying the heat withdrawal rate and the rate of casting to maintain the values of the nonmeasured variables within selected limits while maintaining the required heat transfer rate.

7. The method of controlling a continuous casting operation employing a mold, a mold cooling region and a spray cooling region, which includes the steps of:

monitoring the surface temperature of an ingot being cast at at least two points along the mold and spray cooling regions;

monitoring the heat transferred to a cooling medium from the ingot;

determining the thickness of the solidified portion of the ingot being cast as it leaves the mold;

determining the point of minimum acceptable deforming temperature along the ingot from the monitored surface temperature, the monitored heat transfer, and the thickness determination; and

controlling the cooling of the ingot from the monitored surface temperature, the monitored heat transfer, and the thickness determination to maintain the point of minimum acceptable deforming temperature in advance of a selected region and to maintain a predetermined minimum thickness in the solidified portion of the ingot as it leaves the mold.

8. The method of controlling a continuous casting operation employing a curved mold which includes the steps of:

continuously monitoring the surface temperature of an ingot being cast at at least two points along the path of the ingot;

continuously monitoring the heat transferred to a cooling medium from the ingot;

computing the thickness of the solidified portion of the ingot as it leaves the mold from the monitored surface temperatures and heat transfer;

computing the approximate point of complete solidification within the ingot being cast from the monitored surface temperatures and heat transfer;

computing the point of minimum deforming temperature at which the ingot may be straightened; and

concurrently controlling the withdrawal of heat from the ingot and the ingot withdrawal rate to maintain the point of minimum deforming temperature at a region subsequent to the straightened region, to maintain the point of complete solidification at a region prior to the straightening region, and to maintain the thickness of the solidified portion of the ingot as it leaves the mold in excess of a predetermined minimum.

9. The method of controlling a continuous transformation process for producing steel castings from molten metal including the steps of:

passing the molten metal through a casting region;

withdrawing heat from the casting region;

measuring the heat withdrawn from the casting region;

passing the casting through a spray cooling region;

measuring heat withdrawn in the spray cooling region;

sensing the surface temperature at points on the periphery of the casting;

computing the solidification profile of the casting from the withdrawn heat measurements and the sensed temperatures;

computing the stresses on the solidified portion of the casting as it leaves the casting region from the withdrawn heat measurements and the sensed temperatures; and

controlling the rate of movement and the rate of heat withdrawal to maintain the point of complete solidification in a selected region, and to maintain the stresses on the casting as it leaves the casting region between selected limits.

10. The method as set forth in claim 9 above, including in addition the steps of:

passing the formed casting through a straightening system;

computing the minimum acceptable deforming point along the length of the casting from the computed stresses;

computing the allowable rate of heat withdrawal from the casting from the computed stresses; and

concurrently adjusting the rate of casting movement and the rate of heat withdrawal to maintain the point of complete solidification in a selected region prior to the straightening system, and the point of minimum deforming temperature in a selected region subsequent to the straightening system.

11. The method of controlling a steel casting operation, through use of a plurality of controlled variables adjustable as to operating setpoint which includes the steps of:

modifying the operating setpoints for the controlled variables in time varying fashion in an open loop mode during discontinuous phases of operation;

sensing the value of a plurality of actual variables representing a plurality of different operating conditions;

computing and maintaining modified setpoints from the actual variables to maintain a closed loop system during continuous phases of operation; and

concurrently superimposing a separate closed loop control during continuous phases of operation, the separate closed loop controlling a given related set of controlled variables in response to a given related set of actual variables.

12. The method of preventing breakout of molten metal from a continuously cast ingot which includes the steps of:

monitoring selected directly measurable variables representative of the physical characteristics of the metal being cast;

computing the value of indirect variables which cannot be directly measured, including skin thickness at the exit end of the mold, solidification profile and heat transfer coefficient from the monitored variables; and

regulating the cooling of the ingot and the withdrawal rate of the ingot to maintain the indirect variables within selected limits.

13. The invention as set forth in claim 12, including in addition the steps of monitoring the thickness of the ingot, and interrupting ingot withdrawal when the ingot thickness undergoes a change in excess of preselected limits.

14. The method of controlling the total length of each of two or more ingots formed by continuous casting from a single given supply of limited amount including the steps of:

continuously measuring the amount remaining in the supply;

monitoring the length of each ingot being cast;

computing the cutting length of each ingot from the monitor lengths and the measured amount; and

modifying the flow from the supply to each ingot to provide total ingot lengths of selected proportions.

15. The method of substantially continuously casting steel from a system employing a curved mold and a casting straightener which includes the steps of:

storing a number of average operating setpoints for particular controllable variables for known steels;

sensing the states of determinable variables during

casting, the sensed variables being in the majority different from the controllable variables;
identifying the steel being cast;
adjusting the operating setpoints for the controllable variables in accordance with the stored setpoints and the relation of the steel being cast to the known steels;
computing the profile of the solidified portion of the casting;
computing the temperature gradient required along the casting for a desired profile;
modifying the operating setpoints on the basis of the computations to maintain the profile of the solidified portion such that the point of complete solidification is kept ahead of the casting straightener, and the thickness of the casting at the exit end of the mold is maintained within selected limits; and
concurrently operating one of the controllable variables to maintain the computed temperature gradient along the casting.

16. The invention as set forth in claim **15** wherein the states of the variables are sensed in scanning fashion and averaged for each variable.

17. The invention as set forth in claim **15**, wherein the computation of the profile of the solidified portion and the temperature gradient are arranged to anticipate needed changes in the control of the particular variables.

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