

[72] Inventors **Myron Robert Hurlbut**
Peabody, Mass.;
Robert Arthur Phillips; Leland Chester
Tupper, Schenectady, N.Y.

[21] Appl. No. **861,424**
 [22] Filed **Sept. 26, 1969**
 [45] Patented **May 11, 1971**
 [73] Assignee **General Electric Company**

3,469,828 9/1969 Lane 263/32

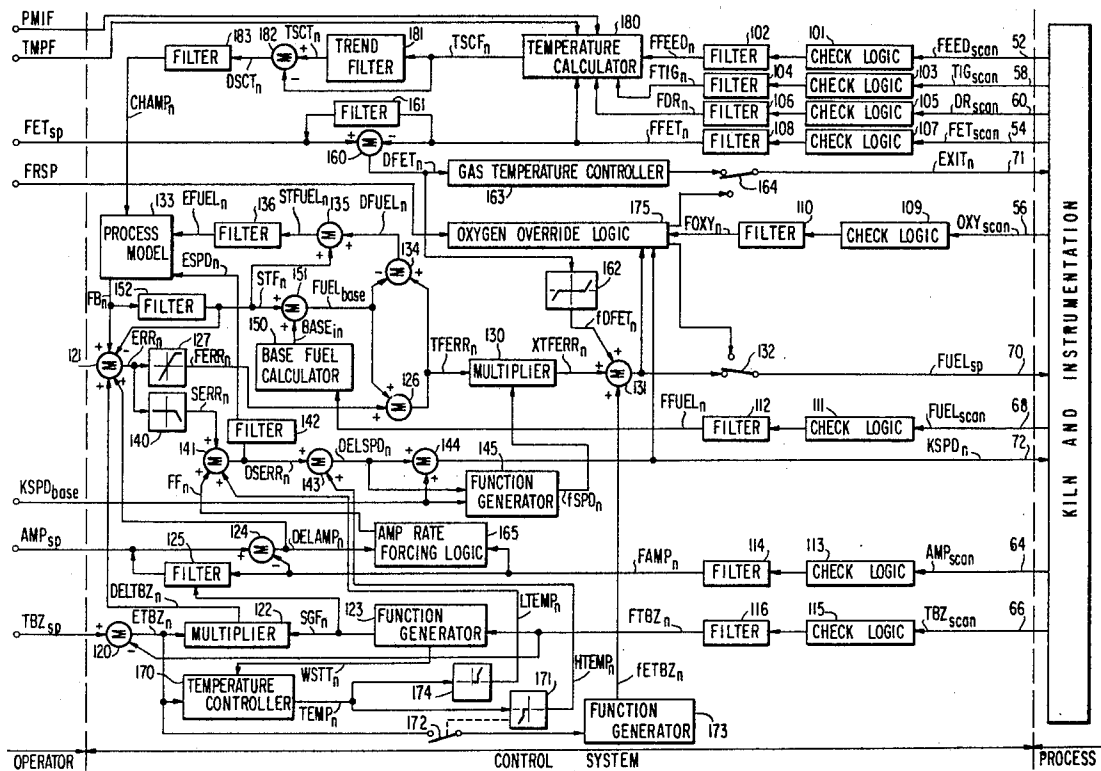
Primary Examiner—John J. Camby
Attorneys—William S. Wolfe, Gerald R. Woods, Oscar B. Waddell and Joseph B. Forman

[54] **METHOD AND APPARATUS FOR CEMENT KILN CONTROL**
19 Claims, 1 Drawing Fig.

[52] U.S. Cl. **263/32**
 [51] Int. Cl. **F27b 7/20**
 [50] Field of Search **263/32**

[56] **References Cited**
UNITED STATES PATENTS
 3,366,374 1/1968 Bay et al. **263/32**

ABSTRACT: A rotary cement kiln control system and method. Burning zone temperature and torque measurements generate a total process error apportioned to fuel and speed control for the kiln. The control system responds to short-term process disturbances to maintain thermal stability in the kiln and the contributions of the burning zone temperature and torque measurements are modified in accordance with thermal stability. Feedback representing expected variations in the measurements is provided. Unusual or adverse conditions are sensed to generate override signals. The effect of torque in the chain section of the wet kiln is also considered in control.



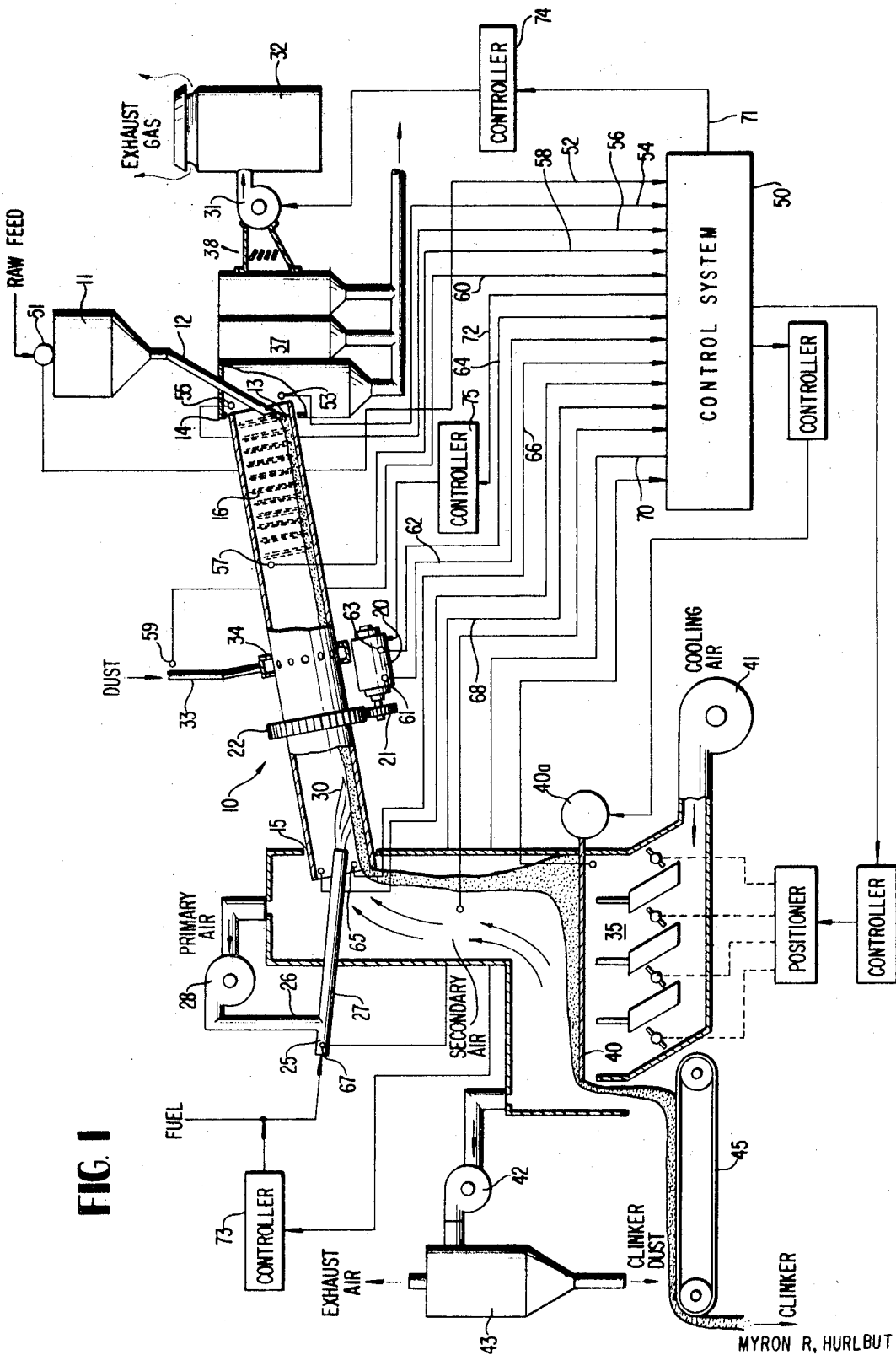


FIG. 1

MYRON R. HURLBUT
ROBERT A. PHILLIPS
LELAND C. TUPPER

BY *George A. Hurlbut*

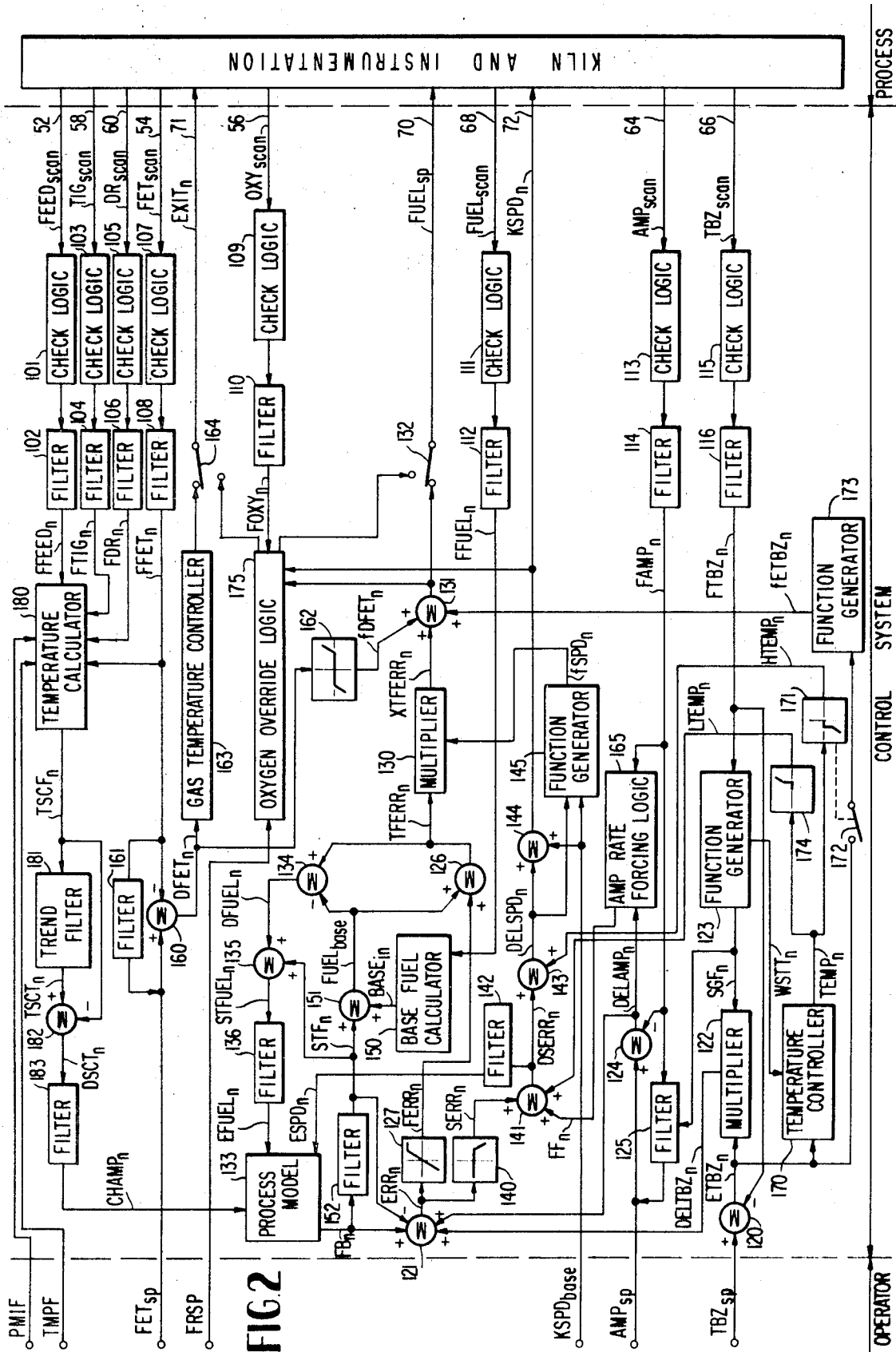
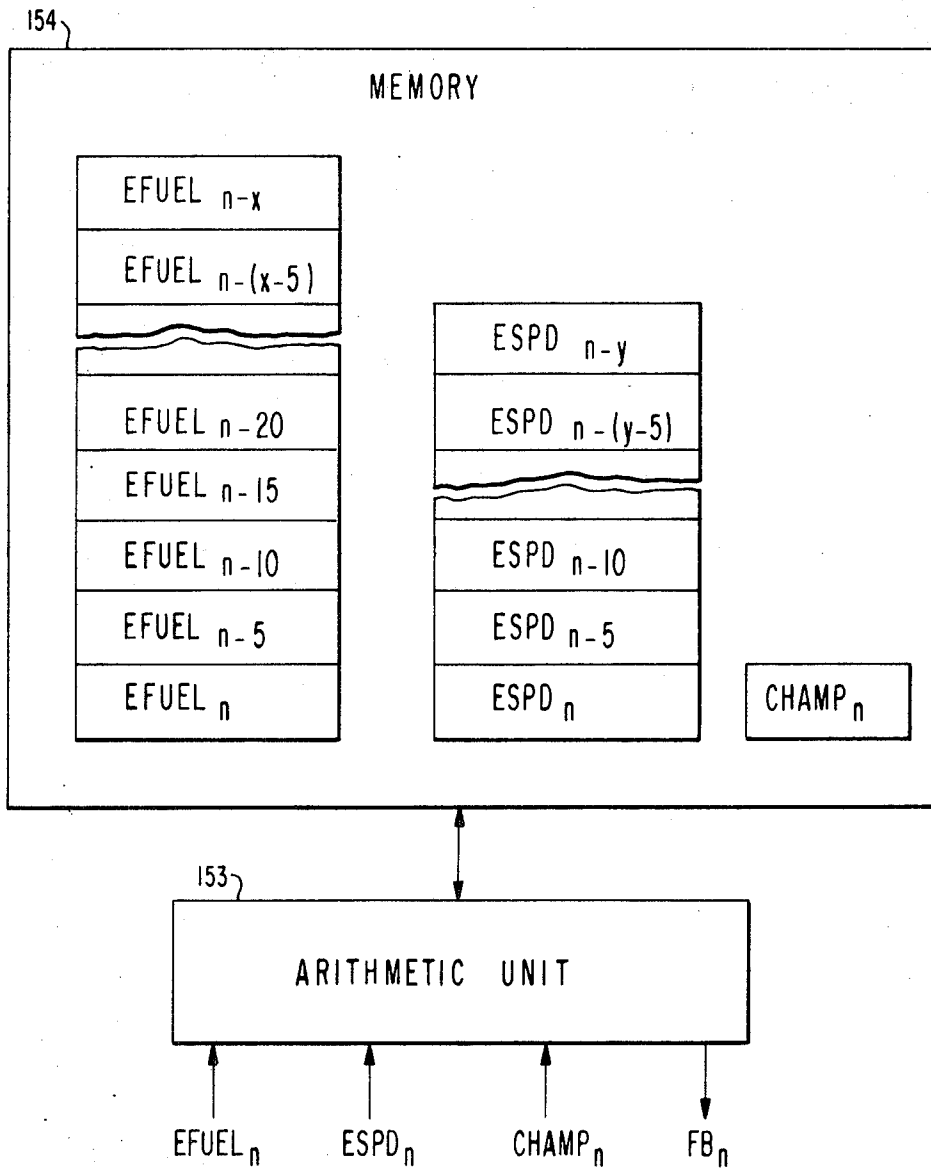


FIG. 2

FIG. 3



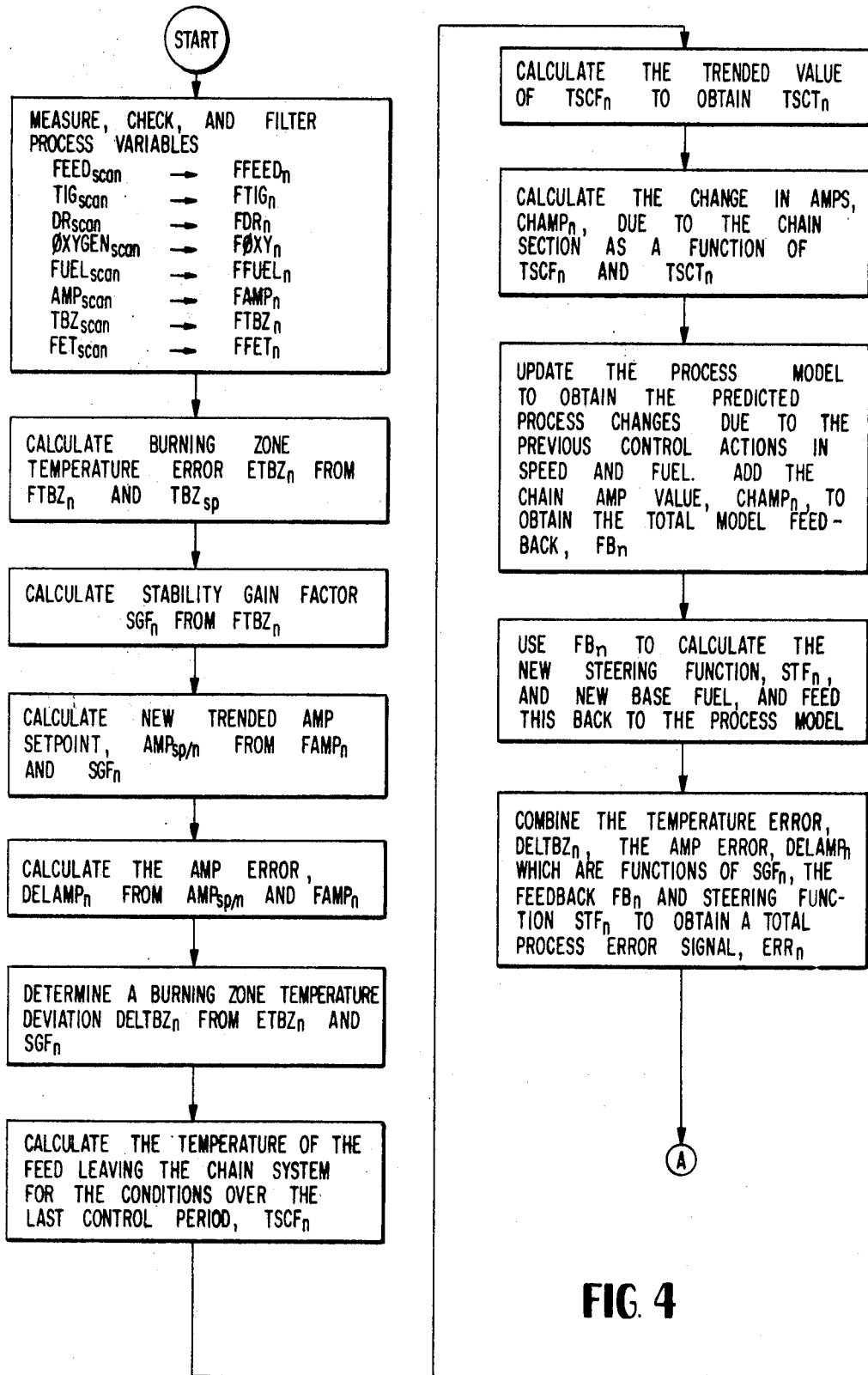


FIG. 4

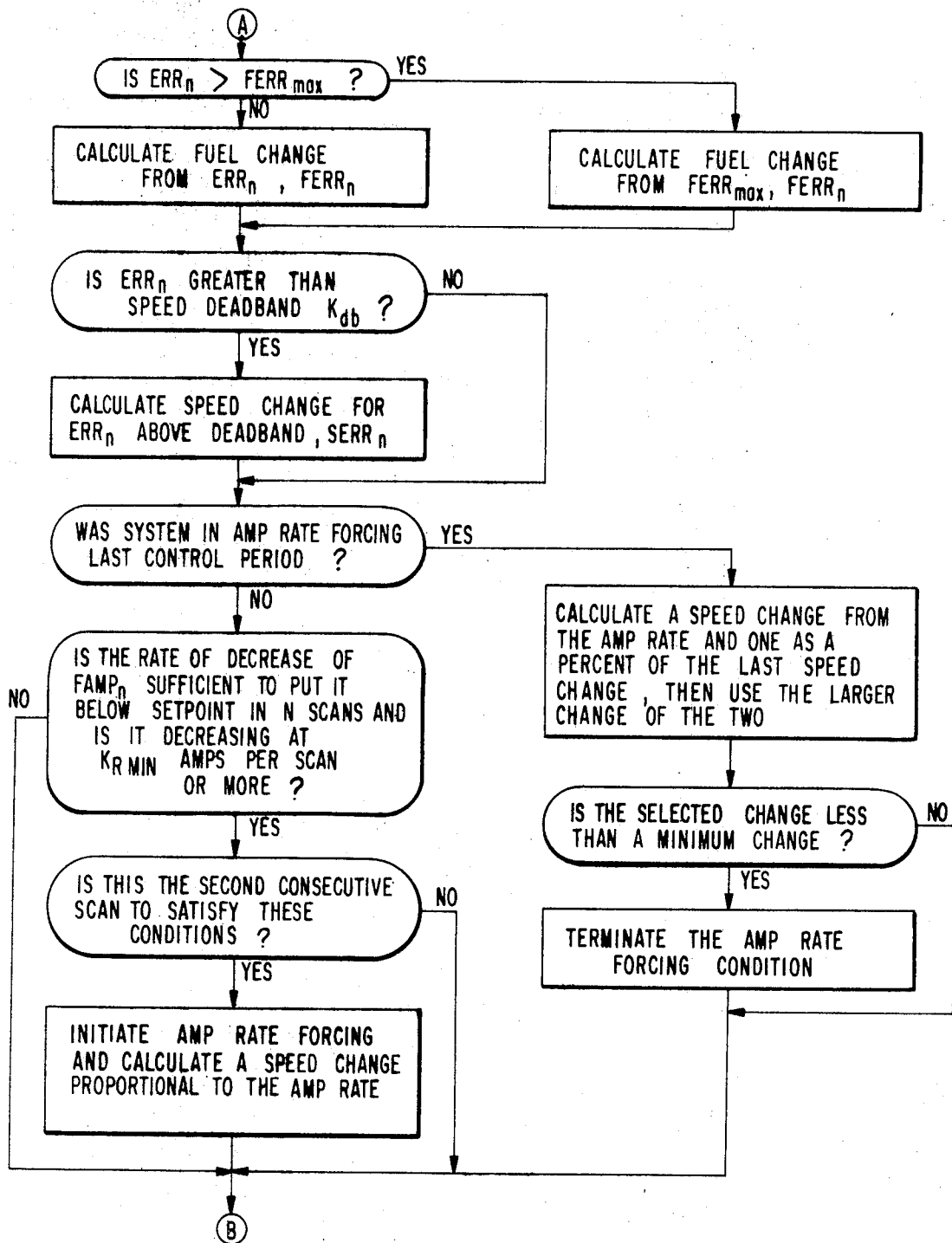


FIG. 4A

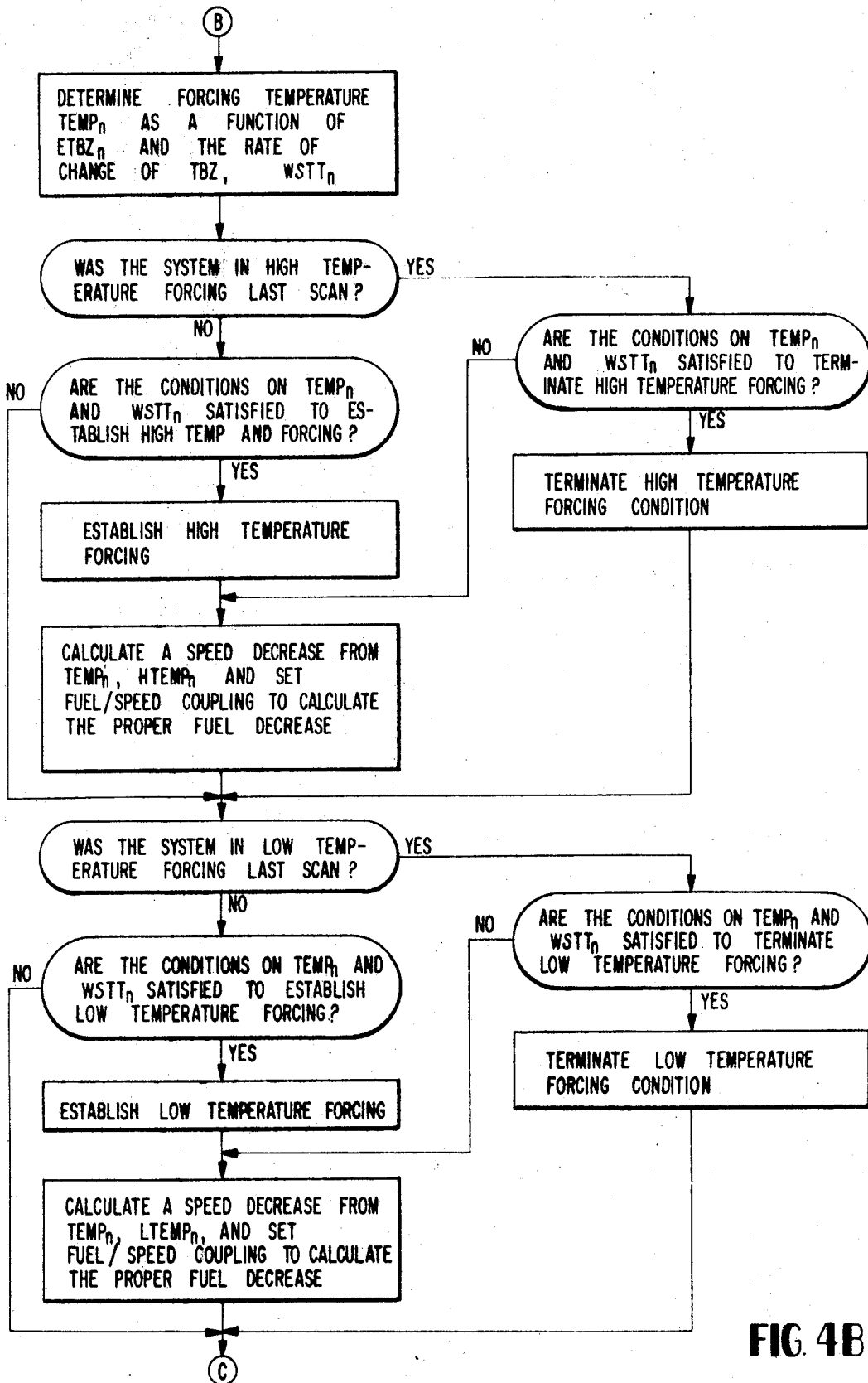


FIG 4B

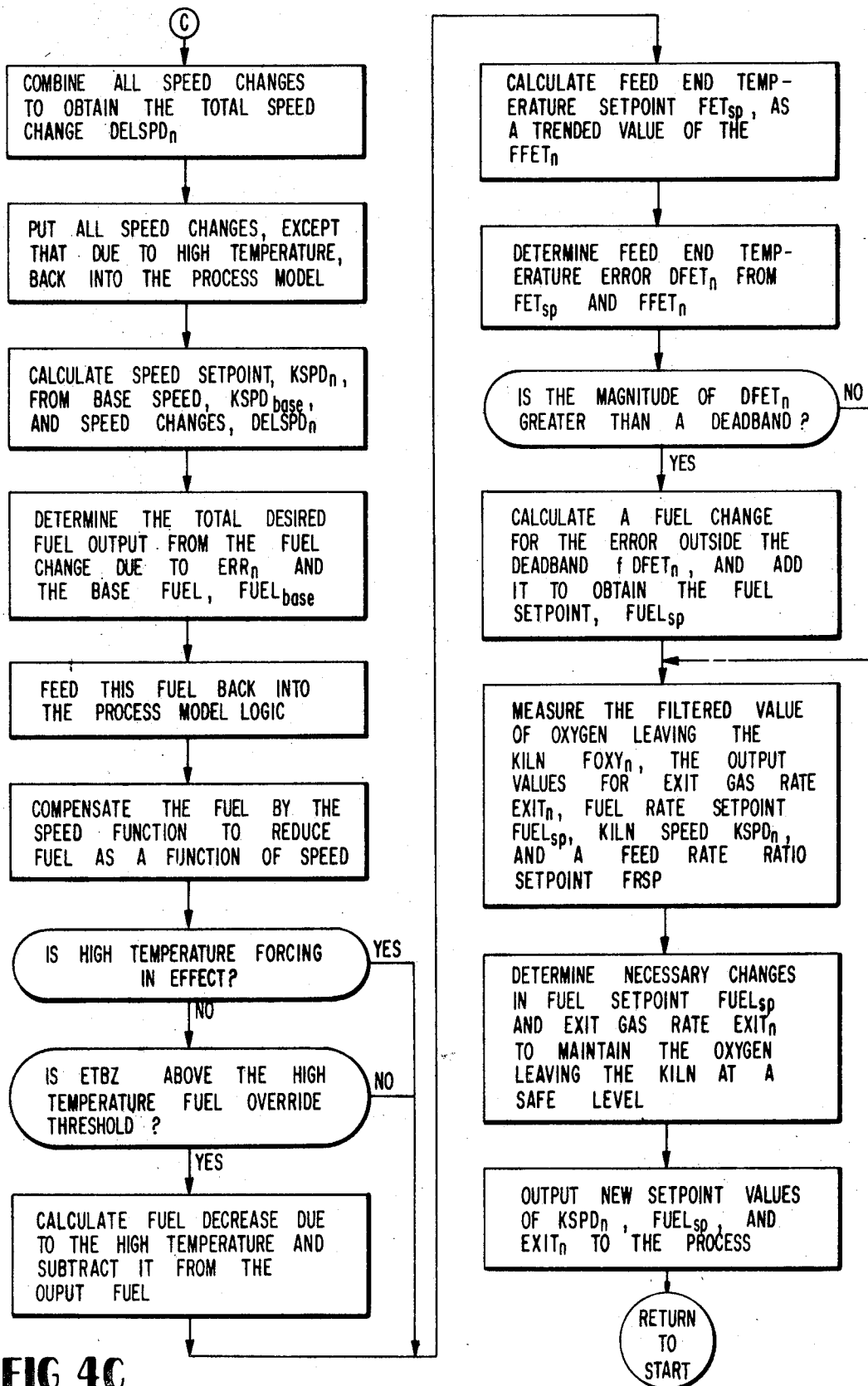


FIG. 4C

METHOD AND APPARATUS FOR CEMENT KILN CONTROL

BACKGROUND OF THE INVENTION

This invention relates to the production of cement in rotary kilns and, in particular, to an improved method and apparatus for controlling and regulating the operation of rotary cement kilns to provide stable kiln operation with resulting uniformity of product quality and improved fuel efficiency.

Typical rotary kilns employed in the production of portland cement are steel cylinders 8 to 25 feet in diameter and between 100 and 700 feet long. The cylinders are lined with refractory brick and inclined 2° to 3° from the feed end to the discharge end. The steel cylinder is supported at spaced points and rotated through a gear drive by an electrical motor at speeds in the order of 20 to 120 revolutions per hour. Cement raw material, such as finely ground limestone, clay or shale intermixed in the desired proportions and either in the form of a finely ground slurry or a dry pulverized, intermixed material are fed into the upper or feed end of the rotary kiln.

During rotation of the kiln, the raw materials move slowly down the kiln at a rate which is a function of the kiln rotational speed and pass through successive zones known as the drying or chain zone, the preheating zone, the calcining zone and the clinkering or burning zone. If the raw materials enter the feed end of the kiln in the form of a wet slurry, the moisture is evaporated in the chain zone which may extend for 25 percent of the kiln length. Chains are suspended from the kiln to contact the slurry and serve as a heat exchanger to drive off moisture. The drying or chain zone is not necessary in a kiln which is specifically adapted to use only a dry mix. As the materials move down the kiln, they are slowly heated by a stream of hot gases which are produced by a burner positioned at the lower or discharge end of the kiln and which flow counter to the direction of material movement in the kiln. A fan at the feed end of the kiln creates a slightly negative pressure in the kiln and draws the hot combustion gases produced by the burner through the kiln to heat the raw materials moving in the opposite direction, causing the raw materials to undergo successive changes due to the steadily increasing temperature of the materials.

The temperature of the dried raw materials increases until the calcining temperature is reached at which time carbon dioxide is liberated from the raw materials, changing the carbonates to oxides. The calcining zone occupies the major portion of the kiln length. The temperature of the material changes little within the calcining zone since the calcining reaction is endothermic and requires heat. A measurement of the material temperature within this zone gives little indication of the degree of calcination. At a point down the kiln where calcination is complete, a large temperature difference exists between the solid materials and the counter-flowing hot gases. Thus, when calcination is complete, the temperature of the solid material begins to increase rapidly to the point where the exothermic clinkering reactions are initiated. The heat generated by these chemical reactions causes the solid material temperature to rapidly increase 700°—800° F. The clinkering or burning zone is near the discharge end of the kiln and the material remains at or near the high temperature until it leaves the kiln and is thereafter cooled. The degree of completion of the chemical reaction in the clinkering or burning zone depends upon the feed composition, the temperature in this zone and the residence time of an increment of feed within the zone.

The kiln must be controlled in such a manner as to produce a clinker product having a satisfactory quality and preferably a uniform quality. The variables over which a kiln operator has immediate control and which directly influence the kiln operation are the kiln feed rate, i.e. the rate at which the raw materials are fed into the upper end of the kiln, the kiln rotational speed, the fuel rate, i.e. the rate at which fuel is injected into the kiln and burned, and the exit gas rate, i.e. the rate at which the combustion gases and other gaseous kiln products

are drawn through the kiln and exhausted from the feed end into the atmosphere. The kiln operator attempts to select values for each of these control variables which will result in stable kiln operation producing a desirable product at the required product volume.

In early rotary cement kilns, the operator visually observed the color of the burning zone, the position of the boundary between the calcining and burning zones and the clinker size and consistency and took corrective action based upon these observations, using judgment gained by past experiences. In general, kiln performance based on this type of control was poor in terms of product quality, product uniformity and fuel efficiency. More recently, elaborate instrumentation has been employed to sense various parameters during kiln operation. This provided the operator with more information of higher accuracy for determining proper control action. However, the results obtained are still a function of the operator's interpretation of the measurements and his judgment.

The range over which any controller is effective is a direct function of how well the relation between the manipulated variable and the controlled variable has been defined. If the relation is known exactly and never changes, then a controller can be defined which will perform satisfactorily for all deviations of the controlled variable from the set point value. However, in most processes, the relation between the manipulated and controlled variables can only be approximated and a control relationship, for example, in the form of an equation, is derived which fits this relationship over a reasonable range. Consequently, the more complicated the relation between the manipulated and controlled variables, the more sophisticated the equation required to provide a controller which will function over a reasonable range. The range of effective control of a controller may be defined by specifying the maximum allowable deviation of the controlled variable from a normal or setpoint value.

If the controlled value deviates outside the effective range of the controller, the controller may be incapable of exercising control over the process and external intervention is normally required to maintain control. In a cement kiln control system, control of the kiln may be lost if burning zone conditions deviate outside the effective control range. For example, if the length of the burning zone becomes too short due to a disturbance in kiln operation, the amount of dense clinker material in the burning zone may not be sufficient to resist the force of the feed dammed up behind the burning zone. Consequently, the feed may push forward to the discharge end of the kiln without completion of the clinkering reaction resulting in a poor quality product. The corrective action initiated by the control system may not be sufficient to prevent this occurrence. Accordingly, it is desirable to detect and to anticipate deviations of the controlled variable outside the effective range of the controller and to correct the disturbance before control is lost.

Two diverse controllers have been used in the prior art. A first controller responded to burning zone temperature measurements to control either the heat input to the kiln or the kiln speed because the burning zone temperature is the best representation of conditions in the kiln which is known. Notwithstanding severe environmental difficulties which hamper the measurement, burning zone temperature has remained as the primary variable for process control. When it is used alone to control the heat input to the kiln, kiln speed or both, the measurement is additionally and independently susceptible to another ambiguity. A thermal gradient exists along the kiln length, and the burning zone temperature is defined at a specific kiln position. It is possible, however, for the material in the kiln to shift longitudinally. Such longitudinal shifts will alter the thermal gradient and may cause erroneous changes in the measured burning zone temperature. These errors can lead to incorrect control action and, in severe cases, positive feedback action with loss of kiln control.

The second controller is commonly known as an amp controller. It responds to the motor torque variations required to

turn the kiln by altering the heat input, kiln speed or both. This variable is easily measured and measurement techniques are generally not sensitive to the environment. It is also generally unaffected by variations in the thermal gradient. However, the drive torque is not directly related to the burning zone temperature and is affected by changes in the kiln. While certain compensation techniques are available, it is difficult to compensate for buildup on the kiln walls and drive function variations especially when they are coupled with process variations such as changes in the feed composition.

Certain control systems have implemented both temperature controllers and amp controllers. However, each controller has been used independently. Hence, the problems of each controller remain in the total control system.

Therefore, it is an object of this invention to provide an improved apparatus and method for controlling a rotary cement kiln.

Another object of this invention is to provide an improved apparatus and method for controlling a rotary cement kiln which compensates for certain measurement ambiguities.

Still another object of this invention is to provide an improved apparatus and method for controlling a rotary cement kiln which compensates for ambiguities in measuring burning zone temperature.

Yet another object of this invention is to provide a method and apparatus for controlling a rotary cement kiln which compensates for ambiguities in torque measurements.

Yet still another object of this invention is to provide a method and apparatus for controlling a rotary cement kiln which combines temperature and amp controllers in a complementary manner.

SUMMARY

In accordance with one aspect of this invention, separate measurements of the torque required to turn the kiln and the burning zone temperature are made. A first signal is generated in response to the error in the actual burning zone temperature when compared to a predetermined burning zone temperature. A second signal is generated in response to the torque measurements. The first and second signals are then combined to control the input to the kiln to maintain the burning zone temperature at the predetermined value. Only heat input control is exercised over a narrow band to process disturbances. For larger process disturbances kiln speed is controlled in conjunction with the heat input. Out of limit temperature conditions are controlled in a nonlinear fashion. A base fuel level for the kiln is also controlled to move in accordance with current operating conditions in the kiln.

The subject matter of the invention is particularly pointed out and distinctly claimed in the concluding portion of the specification. The above and further objects and advantages of this invention may be better understood by reference to the following description taken in connection with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic diagram depicting a rotary cement kiln embodying and utilizing the present invention;

FIG. 2 is a block diagram illustrating a control system incorporating the invention and employed to control the operation of the rotary cement kiln of FIG. 1;

FIG. 3 is a block diagram illustrating the organization of the process model in the control system of FIG. 2; and

FIGS. 4, 4A, 4B, and 4C are a flow diagram illustrating the operation of the control system of FIG. 2.

DESCRIPTION OF AN ILLUSTRATIVE EMBODIMENT

Referring to FIG. 1, a typical rotary cement kiln with its associated equipment is schematically illustrated. Rotary cement kiln 10 has at its upper end or feed end a kiln feed hopper 11 and a kiln feed pipe 12 for feeding blended raw materials 13 into the upper end of kiln 10. The raw materials

normally include Al_2O_3 , SiO_2 , Fe_2O_3 , $MgCO_3$ and $CaCO_3$ plus small amounts of K_2O , Na_2O and sulfur. The blended raw materials may be in the form of a dry powder or a slurry and may be preheated in a heat exchanger utilizing the kiln exit gases. The specific embodiment shown is particularly adapted for use with a slurry. A chain section 16 is suspended along the kiln adjacent to the feed end 14 to remove moisture from the slurry. A chain section 16 may or may not be used if a dry mixture is input to the kiln. If a chain section is used in a dry kiln, then it preheats the dry mixture. Kiln 10, inclined downward at an angle of approximately 3° from feed end 14 to discharge end 15, is rotated by an electric motor 20 shown here driving a pinion gear 21 that engages a ring gear 22 encircling and attached to kiln 10. As kiln 10 is rotated by kiln drive motor 20 through gears 21 and 22, the kiln rotation causes the raw materials or feed to slowly cascade forward, the rate of forward progress of the feed within kiln 10 being approximately proportional to kiln rotational speed. Motor 20 is normally controlled to drive kiln 10 at a predetermined constant rotational speed.

At the discharge end of the kiln, a fuel supply line 25 and a primary air supply line 26 are connected to a fuel-air mixing chamber 27. Natural gas, pulverized coal, oil or combinations thereof may be employed as fuel, the fuel being fed into line 25 from a suitable source. The primary air is forced through line 26 and into chamber 27 by fan 28.

The interior of kiln 10 is lined with a refractory material (not shown) which is capable of absorbing heat from flame 30 and transmitting it to the gases and feed travelling through kiln 10. The combustion gases and other gaseous kiln products are drawn through the kiln by an induced draft fan 31 which exhausts the gases through a dust collector and stack 32. Induced draft fan 31 creates a slightly negative pressure in the kiln drawing secondary air from clinker cooler 35 through the kiln. The gases emerging from feed end 14 of kiln 10 pass through a series of dust collectors 37 which recover the dust and an exit gas damper 38. The dust may be reintroduced to the kiln through a conduit 33 to a dust feeder 34.

As the feed proceeds slowly down the kiln, it is heated by hot gases flowing counter to it and also by the heated refractory walls of the kiln. The temperature of the dry feed increases until the calcining temperature is reached. At this point, the calcium carbonate $CaCO_3$ and the magnesium carbonate $MgCO_3$ begin to decompose, forming CaO and MgO . The released carbon dioxide CO_2 joins the combustion gas and is drawn from kiln 10 by fan 31. The zone of kiln 10 where this reaction occurs is called the calcining zone. This reaction continues over a major portion of the kiln length. The temperature of the feed changes very little within this zone since the calcining reaction is endothermic and requires heat. A measurement of feed temperature within this zone will not give a meaningful indication of the degree of calcination of the feed.

At the point in kiln 10 where calcination of the feed is complete, a large temperature difference exists between the feed and the combustion gases and, therefore, a rapid increase in feed temperature results. The temperature at which the exothermic clinkering reaction occurs is reached quickly and the heat generated by the clinkering reaction causes the temperature of the feed to increase still further to the point where the solids become partially liquefied. The clinkering reaction for the formation of $(CaO)_2(SiO_2)$, $(CaO)_3(Al_2O_3)$, $(CaO)_4(Al_2O_3)_2O_3$, which are the crystalline compounds that determine the physical properties of the cement, occurs rapidly. The resulting partly fused mass of varying size continues to move down the burning zone of the kiln and remains near its maximum temperature until it nears discharge end 15 of the kiln. While at this temperature, most of the remaining CaO combines with the $(CaO)_2(SiO_2)$ to form $(CaO)_3(SiO_2)$. The degree of completion of this clinkering reaction depends upon the feed composition, the temperature in the burning zone and the residence time of an increment of feed within the zone.

As the hot clinker material approaches the end of the kiln, it begins to lose some of its heat to the incoming secondary air.

At the exit end of the kiln, the clinker drops onto a travelling grate 40 usually reciprocated by a motor 40a. Air is blown through the grate 40 by fan 41 to cool the clinker. Part of the resulting heated air becomes secondary air which is drawn through kiln 10 by fan 31, the remainder being exhausted by fan 42 through dust cyclone 43 to the atmosphere. The cooled clinker is transported by conveyor 45 to grinding apparatus (not shown) which pulverizes the clinker to form cement.

Process Variable Measurement

A number of sensors are provided to monitor various parameters of kiln operation and to generate electrical signals representing the values of these parameters. These signals are employed by the control system of the invention to direct the operation of the kiln. As illustrated in FIG. 1, a signal indicating the rate at which feed is being supplied to the kiln is provided for control system 50 by a feed rate detector 51 associated with the hopper 11 on a line 52. A temperature measuring device 53, for example a thermocouple, is provided near feed end 14 of kiln to provide a signal indicating the feed end and temperature transmitted to control system 50 on line 54. Analyzer 55 is also provided near the feed end 14 of the kiln to measure the oxygen content of the gases being exhausted from the kiln, the signal representative of the oxygen content being applied to control system 50 on line 56. A second temperature measuring device 57 is provided adjacent to termination of the chain section 16 of the kiln to provide a signal transmitted to control system 50 on line 58 indicating the temperature of the gases flowing through the kiln at that point.

A signal representing the rate of dust flow through the conduit 33 and dust feeder 34 is provided to control system 50 by a device 59 for measuring the dust flow rate, the signal being applied to control system 50 on line 60. A sensor 61 associated with kiln drive motor 20 provides a signal to control system 50 on line 62 representing the rotational speed developed by the motor 20 as it rotates the kiln. Sensor 63 associated with kiln drive motor 20 provides a signal to control system 50 on line 64 representing the torque developed by motor 20 as required to rotate kiln at a predetermined rotational speed. The temperature at the burning zone is determined by a burning zone temperature sensor 65 such as a color ratio pyrometer which optically determines the temperature at a prefocused point. The signal from the burning zone temperature sensor 65 is supplied to the control system 50 on line 66. A signal representing the rate of fuel flow to mixing chamber 27 is provided to control system 50 by fuel supply sensor 67 associated with the fuel supply line 25, a signal being supplied on line 68.

Control system 50 utilizes the information concerning kiln operation provided on lines 52, 54, 56, 58, 60, 62, 64, 66 and 68 to produce kiln control signals on lines 70, 71 and 72. The control signal on line 70 represents a fuel rate set point and is applied to controller 73 to control the rate of flow of fuel to mixing chamber 27 and, therefore, the heat input to kiln 10. The control signal on line 71 represents an exit gas rate set point and is applied to controller 74 to control the speed of induced draft fan 31 and, therefore, the exit gas flow rate. The signal on line 71 representing an exit gas rate set point may, alternatively, be employed to control the position of damper 38, thereby adjusting the exit flow rate. The control signal on line 72 represents a kiln speed set point and is applied to controller 75 to control a rotational speed of kiln drive motor 20 and, therefore, the rotational speed of kiln 10. Controllers 73, 74 and 75 are standard analog controllers as known in the art and will not be described in detail.

Signal Conditioning

FIG. 2 illustrates the details of control system 50 shown in FIG. 1. Referring to FIG. 2, the signal on line 52 representing the drive feed rate to the kiln from the hopper 11 is applied to check logic 101. This signal FEED_{scan} therefore represents the

instantaneous feed rate to the kiln. Check logic 101 compares the present signal FEED_{scan} with the previous signal FEED_{scan}. If the present and previous values differ by more than a given amount, it is assumed that some unusual conditions exist within the kiln and the output signal from check logic 101 is not used until it returns to within a reasonable range of the previous value of FEED_{scan}. Check logic 101 serves to mask momentary or short-term disturbances and to indicate a failure of the sensor 51. Continued failure of check logic 101 to pass the signal FEED_{scan} to filter 102 may also be used to implement an alarm function. Check logic 101 may be implemented with a digital computer.

Filtering and smoothing of the FEED_{scan} signal to remove noise and other signal variations unrelated to the feed rate is performed in filter 102. The output signal of filter 102 is FFEED_n. The filtering action of filter 102 is described in the equation:

$$FFEED_n = FFEED_{n11} + K_{feed}(FEED_{scan} - FFEED_{n11})$$

Where

FFEED_n is the new filtered value,

FFEED_{n11} is the last filtered value,

FEED_{scan} is the present scan value, and

K_{feed} is the filter constant.

The function of filter 102 may conveniently be performed in a digital computer with K_{feed}, FFEED_n and FFEED_{n11} being stored in the computer memory. This calculation is performed at short intervals, for example every 5 seconds, to insure that signal FFEED_n represents the current condition of the feed rate. K_{feed} is selected to be small enough to eliminate noise and other irrelevant effects, but not so small as to damp out the signal.

Check logic 103 receives successive values of a signal TIG_{scan} representing the gas temperature in the kiln adjacent the discharge end of chain section 16 which appears on line 58 from sensor 57. If two successive signals differ by more than a given amount, it is assumed that the measuring device, such as a thermocouple, has failed and the present value of TIG_{scan} is not used. Rather, the previous value of TIG_{scan} is used. Check logic 103 can also respond to a continued failure to pass the signal TIG_{scan} to filter 104 by initiating an alarm function. Filter 104 receives TIG_{scan} and filters it in accordance with the following equation:

$$FTIG_n = FTIG_{n11} + K_{tig}(TIG_{scan} - FTIG_{n11})$$

Where

FTIG_n is the present filtered value,

FTIG_{n11} is the previous filtered value,

TIG_{scan} is the present measured value, and

K_{tig} is the filter constant.

Typically, the FTIG_n can be calculated once every minute. The functions of filter 88 and check logic 89 may be conveniently performed in a digital computer with signals FTIG_n, FTIG_{n11} and TIG_{scan} and the constant K_{tig} being stored in the computer memory.

A signal representing the rate at which dust is admitted to the kiln 10 through the dust feeder 34 is generated by dust rate sensor 59 and coupled to control system 50 on line 60. The signal DR_{scan} is monitored by check logic 105 to determine whether the signal is accurate representation of the actual dust rate. As with other check logic, check logic 105 can mask momentary disturbances and, through alarm functions, can detect a sensor failure. The signal DR_{scan}, when coupled through check logic 105, is applied to filter 106 which generates the signal FDR_n in accordance with the following equation:

$$FDR_n = FDR_{n11} + K_{dr}(DR_{scan} - FDR_{n11})$$

Where

FDR_n is the present filtered value,

FDR_{n11} is the last filtered value,

DR_{scan} is the present measured value, and

K_{dr} is the filter constant.

Filter 106 thereby performs similar functions to filters 102 and 104 with respect to the dust rate signal. The functions of check logic 105 and 106 may conveniently be performed in a digital computer.

Check logic 107 receives on line 54 a signal representing gas temperature at the feed end 14 of the kiln, as measured by device 53. The gas temperature information represented by the signal is coupled through check logic 107 to mask out momentary disturbances and verify the operation of the sensor 53. The signal, FET_{scan} , is then applied to filter 108 to be filtered in accordance with the following equation:

$$FFET_n = FFET_{n11} + K_{fet}(FET_{scan} - FFET_{n11})$$

Where

$FFET_n$ is the present filtered value,
 $FFET_{n11}$ is the previous filtered value,
 FET_{scan} is the present measured value, and
 K_{fet} is the filter constant.

The filter constant K_{fet} is selected to be small enough to eliminate noise and other effects on the signal for the rate of calculation, an example being a calculation each minute. The functions of check logic 107 and filter 108 may be conveniently performed in a digital computer with signals $FFET_n$, $FFET_{n11}$, FET_{scan} and K_{fet} being stored in the computer memory.

The oxygen content of the exit gas is determined by analyzer 55 to generate OXY_{scan} on line 56 which is coupled through check logic 109 to filter 110. Check logic 109 can perform one or more of the functions of check logic 101 for this particular signal. Filter 110 provides an output signal $FOXY_n$ in accordance with the equation:

$$FOXY_n = FOXY_{n11} + K_{oxy}(OXY_{scan} - FOXY_{n11})$$

Where

$FOXY_n$ is the present filtered value,
 $FOXY_{n11}$ is the previous filtered value,
 OXY_{scan} is the present measured value, and
 K_{oxy} is the filter constant.

The functions of check logic 109 and filter 110 can also be conveniently performed in a digital computer with $FOXY_n$, $FOXY_{n11}$, OXY_{scan} and the filter constant K_{oxy} being stored in computer memory.

Another process parameter which is used in certain embodiments of the control system 50 is the rate of fuel flow to the fuel air mixing chamber 27. Fuel supply sensor 67 generates a signal $FUEL_{scan}$ on line 68. After being examined in check logic 111, the signal $FUEL_{scan}$ is applied to filter 112. Filtering action of filter 112 can be described by the following equation:

$$FFUEL_n = FFUEL_{n11} + K_{fuel}(FUEL_{scan} - FFUEL_{n11})$$

Where

$FFUEL_n$ is the present filtered value,
 $FFUEL_{n11}$ is the previous filtered value,
 $FUEL_{scan}$ is the present measured value, and
 K_{fuel} is the filter constant.

The value of constant K_{fuel} will be dependent upon various process parameters and the rate at which the signal $FFUEL_n$ is calculated. The function of check logic 111 and filter 112 may be conveniently performed in a computer with the signals $FFUEL_n$, $FFUEL_{n11}$ and $FUEL_{scan}$ and the filter constant K_{fuel} being stored in computer memory.

Signal AMP_{scan} generated by sensor 63 on motor 20 and coupled to control system 50 on line 64 can represent the instantaneous heat state within the kiln while changes in the value of AMP_{scan} can indicate corresponding changes in the condition of the burning zone. If kiln drive motor 20 is an AC motor, assuming a constant speed of rotation of kiln 10, the signal on line 64 is a measure of the kilowatt power input to motor 20 which represents the torque developed by motor 20 to rotate the kiln 10. If kiln drive motor 20 is a constant field, DC motor, the signal on line 64 is a measure of the armature current of kiln drive motor 20 which represents the torque developed by motor 20 to rotate kiln 10, with constant field and supply voltages. For purposes of this description, motor 20 is assumed to be a constant field, DC motor; and the signal AMP_{scan} on line 64 represents armature current in and torque developed by motor 20. Various means for obtaining a torque signal from other motors are known in the art. The use of torque measurements represented by the signal AMP_{scan} to ef-

fect control of kiln operation independent of actual burning zone measurements is claimed in U.S. Pat. (Ser. No. 678,851), now U.S. Pat. No. 3,469,828, issued (filed Oct. 30, 1967) and granted to James W. Lane and assigned to the same assignee of the present invention. Filtering and smoothing of the AMP_{scan} signal to remove noise and other signal variations unrelated to the condition of the burning zone, for example of kiln rotation on the signal, is performed, after examining the signal AMP_{scan} and check logic 113, by a filter 114. The output signal of filter 114 $FAMP_n$ is described in the equation:

$$FAMP_n = FAMP_{n11} + K_{amp}(AMP_{scan} - FAMP_{n11})$$

Where

$FAMP_n$ is the new filtered value,
 $FAMP_{n11}$ is the last filtered value,
 AMP_{scan} is the present scan value, and

K_{amp} is the filter constant. The function of filter 114 may be conveniently performed in a digital computer with K_{amp} , $FAMP_n$ and $FAMP_{n11}$ being stored in the computer memory. This calculation is performed at short intervals, for example every 5 seconds, to insure that signal $FAMP_n$ represents the current condition of motor torque forming an accurate basis for control action. K_{amp} is selected to be small enough to eliminate noise and the effect of kiln rotation on the signal but not so small as to damp out the signal. The function of check logic 113, which compares successive values of the signal AMP_{scan} may also be performed in a digital computer with AMP_{scan} being stored in memory.

The burning zone temperature sensor 65 generates a signal TBZ_{scan} on line 66. This sensor may take several forms although the use of optical pyrometers or other optical measuring devices is widely accepted. Burning zone temperature signal TBZ_{scan} is coupled on line 66 to check logic 115. Check logic 115 compares the present signal AMP_{scan} with the previous signal. If the present and previous signals differ by more than a given amount, it is assumed that some unusual condition exists within the kiln or kiln instrumentation and the value of TBZ_{scan} is not used until it returns to within a reasonable range of the previous value. Check logic 115 thereby serves to mask momentary or short-term disturbances. It can also indicate the failure of the burning zone temperature sensor 65 and initiate an alarm function. The function performed by check logic 115 may be conveniently implemented in a digital computer with successive signals from the kiln instrumentation being stored in computer memory.

The output signal of filter 116, $FTBZ_n$, which is energized by the signal TBZ_{scan} , is described by:

$$FTBZ_n = FTBZ_{n11} + K_{tbz}(TBZ_{scan} - FTBZ_{n11})$$

Where

$FTBZ_n$ is the new filtered value,
 $FTBZ_{n11}$ is the last filtered value,
 TBZ_{scan} is the present scan value, and
 K_{tbz} is the filter constant.

The function of filter 116 may conveniently be performed in a digital computer with $FTBZ_n$, $FTBZ_{n11}$ and TBZ_{scan} and filter constant K_{tbz} being stored in computer memory. The value of K_{tbz} depends upon the repetition rate of calculations or $FTBZ_n$ and other circuit parameters and selected to be small enough to eliminate noise and other irrelevant effects on the signal TBZ_{scan} .

Control system 50 responds to actual process measurements represented by the signals $FFUEL_n$, $FTIG_n$, FDR_n , $FFET_n$, $FOXY_n$, $FFUEL_n$, $FAMP_n$, and $FTBZ_n$ to perform various control functions on the heat input, kiln speed and exit gas rate in the kiln. In accordance with one aspect of this invention, the signals $FAMP_n$ from filter 114 and $FTBZ_n$ from filter 116 are combined to control the fuel rate. In response to the filtered signals $FAMP_n$ and $FTBZ_n$ control system generates an output signal $FUEL_{sp}$ on line 70 which is coupled to controller 73 to thereby control the quantity of fuel supplied to fuel-air mixing chamber 27.

Basic Controller

The control system of FIG. 2 is shown in a preferred embodiment. As will become obvious in the following discussion, certain of the objects and advantages of this invention may be obtained by eliminating certain sections or control loops in the control system 50. A basic embodiment of a control system utilizing this invention would primarily respond to burning zone temperature represented by signal $FTBZ_n$ which is converted to an error signal $ETBZ_n$ summing amplifier 120 additionally responsive to a burning zone temperature set point signal TBZ_{sp} . The burning zone temperature set point represented by the signal TBZ_{sp} is controlled by the operator by means of a potentiometer, a value stored in a digital computer or other equivalent means and will normally be based upon the chemical analysis of the kiln product periodically reported to the operator. For example, if free lime (uncombined CaO) content of the kiln product is too low, the operator will decrease the burning zone temperature set point. Whereas if the free lime content is too high, the operator will increase the burning zone temperature set point. Typical burning zone temperature set point values for a particular type and rate of feed and for a particular type kiln product based on past experience would be employed by the operator to select an initial burning zone temperature set point.

Summing amplifier 120 is of the type well known in the art and provides the error signal $ETBZ_n$ proportional to the difference between the burning zone temperature set point TBZ_{sp} and the present filtered value of the burning zone temperature represented by the signal $FTBZ_n$, as expressed by the equation:

$$ETBZ_n = TBZ_{sp} - FTBZ_n$$

The burning zone temperature signal $ETBZ_n$ is positive if the present filtered value of burning zone temperature is less than the burning zone temperature set point and is negative if the present filtered value of burning zone temperature exceeds the burning zone temperature set point. The function of summing amplifier 120 may conveniently be performed in digital computer. The signal $ETBZ_n$ is then coupled to a summing amplifier 121 as signal $DELTBZ_n$. As specifically shown, that this signal is coupled through a multiplier 122 which is additionally responsive to the burning zone temperature value $FTBZ_n$ and function generator 123. However, in accordance with this specific embodiment being described multiplier 122 and function generator 123 are not necessary so $DELTBZ_n = ETBZ_n$. Their utilization in the control system 50 of FIG. 2 will be described hereinafter.

Another summing amplifier 124 responds to the difference between a kiln amp set point AMP_{sp} and the present filter value of kiln amps represented by signal $FAMP_n$. A filter 125, energized by the present filter value of kiln amps $FAMP_n$ normally controls the value of the amp set point signal AMP_{sp} . The filter 125 may be a fixed value filter which provides a trend set point signal in accordance with a trending function. In the preferred embodiment the rate at which the set point is trended is a function of a stability gain factor explained hereinafter. Generally, the faster the set point is trended the less the influence of kiln amps on the control system. The operator may override the signal produced by filter 125. Summing amplifier 124, therefore, produces a signal $DELAMP_n$ representing the difference between the kiln amp set point AMP_{sp} and the present filtered value of kiln amps represented by signal $FAMP_n$, as expressed by the equation:

$$DELAMP_n = AMP_{sp} - FAMP_n$$

Amp error signal $DELAMP_n$ is positive if the present filter value of kiln amps is less than the kiln amp set point and is negative if the present filter value of kiln amps exceeds the kiln amp set point. The function of summing amplifier 124 may conveniently be performed in a digital computer.

The outputs of summing amplifier 120, $ETBZ_n$, and summing amplifier 124, $DELAMP_n$, are applied to the summing amplifier 121 to be combined with a feedback signal.

The output of the summing amplifier 121 is then coupled to summing amplifier 126 which adds a base fuel level through changeover circuit 127. Changeover circuit 127 is not required for an understanding of this embodiment of the invention. Similarly, multiplier 130, summing amplifier 131 and the switching means represented by switch 132 are not necessary for this embodiment of the invention. The output of summing amplifier 121 is coupled to process model 133 through changeover circuit 127, summing amplifier 126, additional summing amplifiers 134 and 135 and filter 136. The output of filter 136 is a signal $EFUEL_n$ which represents a fuel error at that time in the process. In accordance with this embodiment of the invention, the fuel error signal $EFUEL_n$ is placed in process model 133 to be delayed for a time equivalent to the process delay in reacting to a change in fuel. At the time of the delay, the process model 133 uses a previous value of the fuel error signal to generate a feedback signal FB_n which accounts for previous control actions on fuel and this is applied to summing amplifier 121. The output of summing amplifier 121 can, for purposes of this specific discussion, be represented by the equation:

$$ERR_n = DELTBZ_n + DELAMP_n + FB_n$$

where ERR_n represents the present total composite error signal. The function of summing amplifier 121 may conveniently be performed in a digital computer. The composite error signals ERR_n may, in a basic controller, constitute the fuel set point $FUEL_{sp}$, the fuel set point signal $FUEL_{sp}$ on line 70 then being applied to controller 73 to adjust the fuel set point. In this basic controller, therefore, both the burning zone temperature and the motor torque required to turn the kiln have been combined to generate, with appropriate feedback, a total error signal which controls the heat input to the kiln by controlling the fuel to the primary air fuel mixing chamber 27.

Improved operation of this basic controller can be obtained by implementing the functions of multiplier 122 and function generator 123 to control filter 125 and thereby trend the kiln amp set point AMP_{sp} in accordance with changes in the burning zone temperature represented by the filter value $FTBZ_n$. The output of summing amplifier 120, $ETBZ_n$, is applied to the multiplier 122 together with the output of function generator 123 which is a signal SGF_n . If signal SGF_n is zero, there is no contribution of temperature error to the controller and all control is based on kiln amps. The output of function generator 123 is a stability gain factor and is used because the burning zone temperature apparently becomes more unreliable as a control variable when the kiln becomes upset and cycles due to unusual disturbances. Conversely, as the kiln becomes stable, the burning zone temperature becomes more reliable; the amp set point for proper kiln operation drifts and attempts to hold it at a constant value cause over or under heating of the kiln. As previously indicated, during upsets it is possible for the burning zone temperature measurement to provide unreliable indications of the conditions in the kiln as the temperature profile of the kiln shifts longitudinally as a result of upsets. In these cases, the kiln amp signal can give an earlier indication of actual changes in kiln condition so that kiln amps become a better control variable to stabilize an upset kiln. Multiplier 122 and function generator 123 combine with the filter 125 to provide improved operation of the basic controller by dynamically controlling the selection of or the relative emphasis on the amp and temperature signals based on the stability of the process.

Process stability can be measured by a signal $WSTT_n$ which is variable in accordance with the filtered derivative of the burning zone temperature signal in accordance with:

$$WSTT_n = K_{t0}(FTBZ_n) + K_{t1}(FTBZ_{n11}) + \dots + K_{tm}(FTBZ_{n1m})$$

Where K_{t0} through K_{tm} are the filter constants, and the value of m is one less than the number of terms in the filter,

$FTBZ_n$ is the present filter value,

$FTBZ_{n11}$ is the previous filter value, and

$FTBZ_{n1m}$ is the filter value m times before the present filter value.

Normally, five filter sections are used so that $m=4$ to provide a rate of change of temperature calculated as a weighted average of the change over the last five calculations of the burning zone temperature. The weighted scan trend of temperature signal generated within function generator 123 is then filtered to obtain a filtered signal in accordance with equation:

$$FAWST_n = FAWST_{n11} + K_{wst} / (WSTT_n - FAWST_{n11})$$

Where

FAWST_n is the present filter value,

FAWST_{n11} is the previous filter value,

WSTT_n is the absolute value of the weighted scan trend of temperature, and

K_{wst} is a filter constant.

The stability gain factor SGF_n is limited to a positive value and normally should not be permitted below a minimum value. For example, values of the signal SGF_n between 0.2 and 1.0 indicate a normal range.

The stability gain factor signal SGF_n is then applied both to multiplier 122 and filter 125. As a result, the error value from multiplier 122 is the product of the stability gain factor SGF_n and the burning zone temperature error signal ETBZ_n. Filter 125 in this form is energized by the signal FAMP_n and the stability gain factor signal SGF_n to normally produce an amp set point signal AMP_{sp/n} in accordance with:

$$AMP_{sp/n} = AMP_{sp/n11} + K_{esp} SGF_n (FAMP_n - AMP_{sp/n11})$$

Where

AMP_{sp/n} is the new kiln amp setpoint,

AMP_{sp/n11} is the last kiln amp setpoint,

FAMP_n is the present filtered kiln amp value,

SGF_n is the present stability gain factor, and

K_{esp} is the filter constant.

Therefore the stability gain factor varies the kiln amp setpoint. It also varies the burning zone temperature deviation represented by DELTBZ_n in accordance with the equation:

$$DELTBZ_n = SGF_n ETBZ_n$$

Where

DELTBZ_n is the new compensated temperature deviation,

ETBZ_n is the present burning zone temperature error, and

SGF_n is the present stability gain factor.

As the process becomes unstable, the gain on the burning zone temperature error DELTBZ_n is decreased so that the more stable amp signals are emphasized. However, when the system is stable, the gain factor is maximized so the burning zone temperature signals become the primary control variable. In this manner, the control emphasis of the two input signals is constantly varied to achieve control on the fuel set point FUEL_{sp} which is responsive to the more reliable control variable existing at a particular time.

As will be obvious the functions of multiplier 122, function generator 123 and filter 125 may also be conveniently performed in a digital computer.

Cement kilns are known to be nonlinear processes that must be maintained within relatively narrow controllable regions. When a cement kiln becomes cold, the clinker quality is unacceptable. More extreme conditions can stop the clinking process and extinguish the flame. Whenever a trend to a cold condition is detected, it is necessary to take control action that will correct the trend as quickly as possible without upsetting the kiln. In addition to the feed rate and the fuel rate control, it is also possible to control the speed of the kiln. The process response to speed changes is faster than the response to fuel changes. Hence, another embodiment of the basic controller responds to large disturbances by controlling kiln speed while using fuel control in response to smaller disturbances which can take longer to correct. In accordance with this addition to the basic controller, such a procedure is possible which then allows the production rate, which otherwise is reduced when the kiln speed is reduced, to be maximized. Further, speed changes are implemented only as necessary thereby avoiding the generation of other upsets in other portions of the kiln, especially wet kilns where a speed change can cause an upset adjacent the feed end which propagates through to upset the

burning zone conditions and thereby cause subsequent cycling.

In accordance with the control system shown in FIG. 2, the output signal from summing amplifier 121 ERR_n, is applied to changeover circuit 127 and to changeover circuit 140. The output signal from changeover circuit 127 is FERR_n, and is calculated in accordance with equation:

$$FERR_n = K_{feh} ERR_n$$

Where

FERR_n is the present effective fuel system error,

ERR_n is the present composite error, and

K_{feh} is a proportionality constant.

Changeover circuit 127 also limits the value of FERR_n to a maximum value FERR_{max}. Changeover circuit 140 generates a signal SERR_n in accordance with the equation:

$$SERR_n = K_{serr} (ERR_n - K_{db})$$

Where

SERR_n is the present effective speed error,

ERR_n is the present composite error signal,

K_{serr} is a proportionality constant, and

K_{db} is a dead band constant (i.e., K_{db} = FERR_{max}). Changeover circuits 127 and 140 permit the switching of control modes between speed and fuel. The system errors represented by signal ERR_n up to a threshold value, indicated by the change to a zero slope line in changeover circuit 127, and the change to a negative slope line in changeover circuit 140, pass through the changeover circuit 127 and are blocked from passing through the changeover circuit 140. Therefore, signal errors up to the threshold value only affect fuel set point. Errors above the threshold value pass through the changeover circuit 140 and affect the kiln speed.

The signal SERR_n which represents the portion of the composite error signal from summing amplifier 121 which will be used to control the kiln speed is applied to the input of summing amplifier 141. The output signal shown in FIG. 2 is DSERR_n. If amp rate forcing and low temperature speed control are not utilized, then DSERR_n equals SERR_n and, in fact, summing amplifier 141 is not necessary. The amp rate forcing and low temperature speed control concepts will be discussed hereinafter. The output of summing amplifier 141 is then coupled to the process model 133 as a speed error through filter 142. Filter 142 produces an error speed signal in accordance with:

$$ESPD_n = ESPD_{n11} + K_{espd} (DSERR_n - ESPD_{n11})$$

Where

ESPD_n is the present filtered value,

ESPD_{n11} is the previous filtered value,

DSERR_n is the present speed error signal, and

K_{espd} is a filter constant.

The function of filter 142 may be conveniently performed in a digital computer with the signals ESPD_n, ESPD_{n11}, DSERR_n and proportionality constant K_{espd} being stored in the computer memory. With this feedback signal, it can be seen that the feedback signal FB_n from the process model 133 is a function of the fuel and speed error signals EFUEL_n and ESPD_n.

Signal DSERR_n is then coupled through summing amplifier 143 to generate a signal DELSPD_n which is equal to the signal DSERR_n if high temperature speed control is not utilized. In summing amplifier 144 the speed error signal DELSPD_n is combined with the base speed which is input by the operator KSPD_{base} to generate the output signal on line 72 KSPD_n in accordance with:

$$KSPD_n = KSPD_{base} + DELSPD_n$$

During normal control operations when the composite error signal ERR_n is of a magnitude which permits fuel control, the kiln speed is maintained at the base speed KSPD_{base}. However, for positive errors exceeding the threshold value of changeover circuit 140, the fuel signal FUEL_{sp} remains at a maximum, except as provided hereinafter, while the kiln speed is varied to cause more rapid control action and reaction by the kiln. Changeover circuits 127 and 140 and summing amplifiers 143 and 144 may be conveniently implemented by digital computers.

It has been found, however, that when kiln speed is altered it is advisable to reduce the fuel rate. To accomplish this, function generator 145 is energized by the signals $KSPD_{base}$ and $DELSPD_n$ and generates an output signal $fSPD_n$ which is coupled as an input to multiplier 130. The multiplier $fSPD_n$ is generated by function generator 145 in accordance with:

$$fSPD_n = 1 + \frac{K_{cpl}(DELSPD_n + K_{th})}{KSPD_{base}}$$

Where

$fSPD_n$ is a present value of a coupling factor,

$DELSPD_n$ is a negative number representing the present speed error,

$KSPD_{base}$ is the present base speed,

K_{cpl} and K_{th} are functions of the required forcing function which vary depending on whether the particular function generator 145 is adapted for high or low speed forcing.

For purposes of further understanding function generator 145, assume that it is adapted for low temperature forcing. The output of function generator 145 has been coupled to multiplier 130 to produce an output signal $XTFERR_n$ according to:

$$XTFERR_n = (fSPD_n)(TFERR_n)$$

Where

$XTFERR_n$ is the present value of the factored or multiplied signal $TFERR_n$.

This produces coupling between the fuel and speed calculations. Whenever the kiln speed is reduced, the total feed entering the kiln is decreased which means that less total heat will be required at the feed end to sustain the same conditions. This problem is especially critical in a wet process kiln where about 40 percent of the total heat is exchanged in the chain section for evaporation of water in the feed. If too much heat is put in the chains for the amount of feed going through, overheating occurs as the feed progresses through the kiln. By adding function generator 145 and multiplier 130, both of which may conveniently be implemented by a digital computer, fuel is decreased whenever speed is decreased with the proportion of fuel decrease being specified by constants K_{cpl} and K_{th} . In this manner, the kiln adjacent the feed end is controlled without waiting for the feed end temperature to react.

As previously indicated, the operation of the control system shown in FIG. 2 is enhanced by the use of process model 133. Process model 133 permits control of the process by accounting for all changes caused by control actions. Any difference between actual process response and this predicted response is then interpreted as a process disturbance to be corrected by the controller. Therefore, predicted effects of the speed changes must be entered into the model to prevent these from looking like the process disturbance to the fuel controller in addition to fuel changes. As indicated earlier, the kiln speed changes are fed into process model 133 as the signal $ESPD_n$ while fuel changes are fed as $EFUEL_n$. The error signal $EFUEL_n$ can be generated by summing amplifiers 126 and 134 and filter 136. However, such a system is effective only if the average operating level of the kiln does not change. The error signal ERR_n reflects short-term disturbances as well as long-term changes. This is undesirable because changeover or threshold circuits 127 and 140 must operate on changes above the current operating level of the kiln. To eliminate the effect of long-term changes and permit the threshold circuits 127 and 140 to be responsive to short-term changes, a base fuel calculator 150, summing amplifier 151 and filter 152 are added to the circuit. This section of the circuit steers base fuel to an average operating value on a continuous or dynamic basis and, therefore, may be denoted as a dynamic steering unit. To accomplish dynamic steering, the feedback signal FB_n is applied to filter 152 to generate an output STF_n representing a steering function in accordance with:

$$STF_n = STF_{n11} + K_{stf}(FB_n - STF_{n11})$$

Where

STF_n is the present value of the steering function,

STF_{n11} is the previous value of the steering function,

FB_n is the present feedback signal; and

K_{stf} is a filter constant.

The filter constant is chosen so that the feedback signal FB_n is provided with a time constant delay. The output STF_n is then applied to summing amplifier 121, summing amplifier 135, and summing amplifier 151. This affects the composite error signal ERR_n which is generated in the summing amplifier 121 in accordance with:

$$ERR_n = SGF_n DELTBZ_n + DELAMP_n + FB_n - STF_n$$

The steering function also affects the calculation of the signal $FUEL_{base}$ the output of the summing amplifier 151. The second input to summing amplifier 151 is a signal $BASE_{in}$ generated by base fuel calculator 150. Base fuel calculator 150 generates a signal $BASE_{in} = FFUEL_n$ when control of the system is initiated. Therefore, the signal $FUEL_{base}$ is generated in summing amplifier 151 in accordance with:

$$FUEL_{base} = BASE_{in} + STF_n$$

thereby causing the base fuel signal $FUEL_{base}$ to vary in accordance with changes caused by previous control actions. The base fuel signal $FUEL_{base}$ is applied to summing amplifier 126 so the signal representing the total fuel error $TFERR_n$ is calculated in accordance with:

$$TFERR_n = FERR_n + FUEL_{base}$$

The output of summing amplifier 134 represented by signal $DFUEL_n$ is generated in accordance with:

$$DFUEL_n = TFERR_n - FUEL_{base}$$

The steering factor also affects the signal $DFUEL_n$ by being added thereto in summing amplifier 135 to generate a steered total fuel error $STFUEL_n$ in accordance with:

$$STFUEL_n = DFUEL_n + STF_n$$

The input to process model 133 $EFUEL_n$ is then generated in filter 136 in accordance with:

$$EFUEL_n = EFUEL_{n11} + K_{fuel}(STFUEL_n - EFUEL_{n11})$$

Where

$EFUEL_n$ is the new filtered value,

$EFUEL_{n11}$ is the previous filtered value,

$STFUEL_n$ is the present steered total fuel error, and

K_{fuel} is a filter constant.

It will be obvious that the function of filter 136 can be implemented in a digital computer with signals $EFUEL_n$, $EFUEL_{n11}$ and $STFUEL_n$ and constant K_{fuel} being stored in computer memory. Likewise the functions of summing amplifiers 126, 134 and 135, base fuel calculator 150 and filter 152 may conveniently be implemented in a digital computer with signals STF_n , STF_{n11} and FB_n and constant K_{stf} for filter 152 being stored in computer memory.

Through these functions, dynamic steering effectively transfers long-term changes in the composite error signal ERR_n to permanent changes in the base fuel signal $FUEL_{base}$. In accordance with this circuitry, the feedback signal FB_n is passed through filter 152 to generate a time constant. Although a quantity of fuel is added in response to the feedback signal, a similar quantity is subtracted and added to the base fuel in summing amplifier 151. It is also subtracted from the output of summing amplifier 121 leaving only shorter term changes in the composite error. As process model 133 must still be responsive to total system changes in order to maintain the output of filter 152 at the changed value, the output of filter 152 is returned to process model 133 through summing amplifier 135.

Process model 133, identified by reference symbol 133 in FIG. 2 and shown in detail in FIG. 3, comprises two delay tables in which the error signals $EFUEL_n$ and $ESPD_n$ are stored each time a control action is taken. If, for example, a control value is calculated every 5 minutes to initiate a control action, if required, this control value is stored in the process model and control values previously stored are shifted through one storage position in the process model each time a new value is entered. Assuming an interval of 5 minutes between control value calculations, the fourth storage position on the table will contain the control value calculated 20 minutes earlier. The actual delay incorporated in the process model is the time period which elapses between initiation of a control action and the kiln response to the control action as reflected by a change in burning zone condition, this delay being a function

of the characteristics of a particular kiln. In a typical kiln, the delay between a control action causing a change in fuel set point and the response thereto in the burning zone may be of the order of 30 to 35 minutes or more. On the other hand, responses to control actions changing the speed set point and the response thereto in the burning zone of the kiln may be less. The delay table of the process model contains a sufficient number of storage positions so that the delay range available in the delay table for both error signals encompasses delay characteristic of the kiln being controlled. As specifically shown in FIG. 3, the error signals EFUEL_n and ESPD_n are coupled through arithmetic unit 153 to memory 154 which, in a digital computer, constitutes the delay table. Arithmetic unit 153 generates feedback signal FB_n which is applied to summing amplifier 121. At an interval equal to every control action, arithmetic unit 153 is instructed to calculate a feedback signal FB_n in accordance with the following equation:

$$FB_n = EFUEL_{n1r} + ESPD_{n1v}$$

Where

FB_n is the present feedback signal value,

EFUEL_{n1r} is the fuel error signal calculated and stored in the process model table corresponding to the delay between a control action for fuel and the reaction in the burning zone characteristic of the particular kiln, and

ESPD_{n1v} is the value of speed error signal calculated and stored in process model table corresponding of the delay between a speed control action and the reaction in the burning zone which is characteristic of the particular kiln.

If a wet kiln is being implemented and an improvement to be described hereinafter is utilized for generating a feedback input CHAMP_n which is responsive to the effect of the change on torque, the feedback signal FB_n is calculated in accordance with the equation:

$$FB_n = EFUEL_{n1r} + ESPD_{n1v} + CHAMP_n$$

Signal CHAMP_n may be stored in memory 154 and coupled thereto by arithmetic unit 153 as shown in FIG. 3.

At this point, a control system for a rotary cement kiln has been described which senses motor torque in burning zone temperature and in response thereto controls the fuel set point and kiln speed set point. The parameter having the greatest effect on the subsequent control action is chosen in response to kiln stability with the burning zone temperature being the better control variable when the process is stable and the torque signal being the better control variable when the process is unstable. Means have been shown which respond to these two signals to determine the stability by smoothly shifting emphasis from one to the other of the control variables. As a result, the composite error signal, which, through the use of dynamic steering and a dynamic process model, reflects only errors due to process disturbances, is then analyzed to determine its magnitude in comparison with a threshold magnitude. If the magnitude is less than the threshold, it indicates the disturbance can be corrected by varying fuel. If the disturbance is greater than the threshold, it indicates that more drastic action is necessary and the kiln speed is altered. Such speed changes, however, are coupled to the fuel control to decrease the fuel level to thereby tend to stabilize the feed end temperature when kiln speed changes.

Feed End Temperature Control

As previously indicated, about 40 percent of the heat transfer in a wet kiln takes place in the chain section which has a definite influence on changes in torque. In addition, equipment constraints exist which dictate that the temperatures in the feed end of the kiln be maintained within given limits. Good control of the temperatures at the feed end should minimize disturbances that are propagated to upset burning zone conditions. Further if the feed temperature leaving the chain section is constant the remainder of the system should remain constant and the control should be minimized. However, the feed temperature in wet kilns as the feed leaves the

chain section and dry kilns as the feed leaves the heat exchange is not available. A feed temperature can be calculated on the basis of other variables which are subject to error and which are unreliable. The feed end temperature, however, is a reliable and accurately obtainable signal and has indicated itself to contribute to good overall kiln control if the feed end temperature is held constant. Such control can be accomplished in a control loop comprising check logic 107 and filter 108 which generate the signal FFET_n together with summing amplifier 160, filter 161, dead band amplifier 162, and gas temperature control 163. This control serves to maintain a relatively constant gas temperature near feed end 14 to provide a relatively constant source of heat for the feed entering the kiln and a relatively constant temperature profile from the discharge end to the feed end of the kiln. The gas temperature at the feed end of the kiln is thereby decoupled from control actions which vary the rate of fuel flow and, therefore, the rate of heat input into the kiln due to control actions initiated in the torque control loop or the burning zone control loop previously described. Normally as the fuel rate is increased or decreased to adjust burning zone conditions, the feed end temperature control loop adjusts the exit gas flow rate to maintain sufficient heat availability in the feed preparation section of the kiln comprising the drying end or preheating zones.

A feed end temperature error signal DFET_n is generated in summing amplifier 160 by comparing the actual feed end temperature represented by filtered signal FFET_n with a trended set point signal FET_{sp} generated by filter 161. Filter 161 produces an output signal FET_{sp} in accordance with:

$$FET_{sp/n} = FET_{sp/n11} + K_{fetsp}(FFET_n - FET_{sp/n11})$$

Where

FET_{sp/n} is the present trended set point value,

FET_{sp/n11} is the previous trended set point value,

FFET_n is the present value of the measured variable, and

K_{fetsp} is a filter constant.

The function of filter 161 may be conveniently performed in a digital computer with the signals FET_{sp/n}, FET_{sp/n11} and FFET_n and the constant K_{fetsp} being stored in computer memory. In addition, the set point signal may be overridden by the operator who can input a signal FET_{sp}.

An error is determined by summing amplifier 160 which generates an output signal representing the error DFET_n in accordance with:

$$DFET_n = FET_{sp/n} - FFET_n$$

The function of summing amplifier 160 also may be conveniently performed in a digital computer.

Gas temperature controller 163 determines a desired exit gas flow rate in the kiln and provides both proportional and integral modes. The function of gas temperature controller 163, which may be implemented by a digital computer, is represented by the equation for output signal EXIT_n of controller 163, as follows:

$$EXIT_n = EXIT_{n11} + K_1 DFET_n + K_2 DFET_{n11}$$

Where

EXIT_n is the desired exit gas flow rate,

EXIT_{n11} is the previous exit gas flow rate,

DFET_n is the present feed end temperature error signal,

DFET_{n11} is the previous feed end temperature error signal, and

K₁ and K₂ are control constants.

Output signal EXIT_n of gas temperature controller 163 is applied to line 71 for application to controller 74 through logic switch 164. In the illustrated embodiment, signal EXIT_n is employed to control the speed of fan 31 but may, as an alternative, serve to control the position of damper 38. Logic switch 70 164 normally connects temperature controller 163 to controller 74, as illustrated, but may also serve to interrupt the connection, as subsequently described. If the function of gas temperature controller 163 is performed in a digital computer, signals EXIT_n, EXIT_{n11}, DFET_n and DFET_{n11} and constants K₁ and K₂ would be stored in the computer memory.

Excessive values of error $DFET_n$ indicate the kiln will be upset in a short time if corrective action is not taken. For instance, the discharge end of the kiln could be hot with fuel being taken off to cool it down. An excessive feed end temperature decrease indicates that too much fuel has been taken off. Such a condition can cause an excessive temperature drop when the colder feed gets to the front of the kiln. When this happens, dead band amplifier 162 forces the fuel set point to tend to override the main fuel set point thereby attempting to correct the problem before it really develops. Such an action is especially helpful in decreasing the fuel level when the kiln speed is decreased to maintain the feed end temperature within limits. Therefore, dead band amplifier 162, which may be conveniently implemented by a digital computer, generates a signal $fDFET_n$ in accordance with the equation:

$$fDFET_n = K_{dfer}(DFET_n + K_{dfer})$$

Where

$fDFET_n$ is the present function,

$DFET_n$ is the present error,

K_{dfer} is an amplifying factor, and

K_{dfer} is a dead band constant which causes dead band amplifier 162 to generate a signal

$$fDFET_n = 0 \text{ for values of } DFET_n \text{ less than } K_{dfer}.$$

Therefore, $fDFET_n$ affects the fuel set point only during excessive deviations of the feed end temperature represented by the signal $FFET_n$. The fuel set point is affected because dead band amplifier 162 is coupled to an input of summing amplifier 131. Therefore, when this function of feed end temperature control is added, the fuel set point output from summing amplifier 131 represented by signal $FUEL_{sp}$ is generated in accordance with equation:

$$FUEL_{sp} = XTFERR_n + fDFET_n$$

Where

$FUEL_{sp}$ is the fuel set point,

$XTFERR_n$ is the present fuel error signal compensated for speed changes, previous control actions and long-term changes, and

$fDFET_n$ is the feed end temperature control function.

Hence, if the feed end temperature is cold by a first amount less than the threshold value of the dead band amplifier 162, $EXIT_n$ is increased to increase the gas flow through the kiln and the feed end temperature. However, if the feed end temperature becomes sufficiently low, the fuel rate will be increased. Similarly, if the feed end temperature becomes too high the draft will initially be lowered and then dead band amplifier 162 will cause the fuel set point $FUEL_{sp}$ to be decreased.

Not only does this control loop respond to fuel changes and speed changes caused by differences in burning zone conditions, it also controls the system in response to the characteristics of raw materials entering the feed end or to changes in feed rate. For example, if the raw materials require a greater quantity of heat, the gas temperature at the kiln feed end will decrease. The control loop will increase exit gas flow to transfer more heat to the feed end of the kiln thus maintaining the desired temperature profile. Further, if a sufficient feed change occurs, this control loop will cause the fuel set point to be altered to increase the heat input. If such action were not taken, the resulting decrease in gas temperature at the kiln feed end could eventually affect burning zone conditions and appear as a disturbance requiring more drastic corrective action by the torque control loop previously described. This feed end temperature control loop, therefore, tends to compensate for disturbances and for the effects of other control actions taken by the control system.

Amp Rate Forcing

Amp rate forcing logic 165 detects kiln upsets and tends to take corrective action earlier than the rest of the control system would detect it. Therefore, it improves the basic controller system by allowing corrective action to be initiated sooner to thereby minimize the magnitude of the upset.

A good measure of the magnitude of an upset is the rate at which the signal $FAMP_n$ changes. By previous definition, the signal $FAMP_n$ represents the torque and is a more reliable process parameter during nonstable conditions. Therefore, amp rate forcing logic 165 responds to $DELAMP_n$ representing the amp error signal and $FAMP_n$ to generate a forcing function represented by signal FF_n . The signal FF_n is calculated by first determining a rate of kiln amp change $DERAMP_n$ in accordance with the equation:

$$DERAMP_n = K_{damp}(FAMP_n - FAMP_{n-1}).$$

Therefore, the value of the signal $DERAMP_n$ varies as the rate of change of the signal $FAMP_n$. $DERAMP_n$ is compared with a function of $DELAMP_n$ which varies so that amp rate forcing is required if $DERAMP_n$ is large enough to indicate that $FAMP_n$ will go below a set point in a predetermined number of scans or control actions and if $DERAMP_n$ is greater than a constant. If such a condition exists, no immediate action is taken. Rather after a time delay the $DELAMP_n$ and $FAMP_n$ are reexamined to determine if the condition still exists. If the condition persists, amp forcing occurs. In accordance with a preferred embodiment, two speed factors are determined. In one, a speed change is calculated which is proportional to the rate and is compared with a given proportion of the previous forcing signal. Therefore, two signals exist, one proportional to the present rate of change and the other proportional to the last forcing function. The greater is used to generate the signal FF_n .

With this amp rate forcing kiln speed can be decreased as much as required by rate on each scan. However, kiln speed will return only a given percent during each scan. Kiln speed changes which would otherwise result from transient rate changes are limited. For example, a large speed change may cause the signal $FAMP_n$ to stop decreasing for one scan and then to continue decreasing in successive scans. If speed changes responded only to $DERAMP_n$, the kiln speed would return to its base value during the second scan and then decrease during the third scan. Implementing the dual signal technique avoids this condition. The forcing function will also be responsive to other changes. In normal system operation where kiln amp forcing is utilized, regular speed logic will tend to reduce kiln speed as the rate logic tends to increase kiln speed with the net effect of holding speed and thereby providing a lead on the speed change. The forcing function signal FF_n is applied to summing amplifier 141 so that, with the addition of amp rate forcing through the system, the signal $DSERR_n$ representing the composite error apportioned to speed changes is generated in accordance with:

$$DSERR_n = SERR_n + FF_n$$

with the value FF_n being stored in a computer memory if the function of the summing amplifier 141 is implemented in a digital computer. Therefore, the kiln speed $KSPD_n$ will be responsive to proper combinations of the rate of change of torque determined by comparing the values of the torque signal represented by $FAMP_n$ and the magnitude of the total deviation represented by the signal $DELAMP_n$ to generate speed forcing.

High Temperature Speed Forcing And Override

If the burning zone temperature represented by $FTBZ_n$ becomes excessive, error $ETBZ_n$ goes negative. $ETBZ_n$ in addition to being applied to multiplier 122 is also applied to a temperature controller 170 which is also coupled to function generator 122 to be responsive to the trended temperature value $WSTT_n$ to generate an output signal $TEMP_n$ in accordance with:

$$TEMP_n = ETBZ_n + K_{tr} WSTT_n$$

Where

$TEMP_n$ is the present value of the temperature control function,

$ETBZ_n$ is the present burning zone temperature error,

$WSTT_n$ is the present weighted temperature function, and

K_{tr} is a proportionality constant.

During normal operation $ETBZ_n$ represents normally controllable burning zone temperature errors with errors caused by high temperature being represented by negative values of $TEMP_n$. These negative values will not be sufficient to cause threshold circuit 171 to generate high temperature forcing function signal $HTEMP_n$ during normal operation. However, if excessively high temperatures exist, output signal $HTEMP_n$ is generated in accordance with:

$$HTEMP_n = K_{htf} TEMP_n$$

Where

$HTEMP_n$ is the present speed forcing function,
 $TEMP_n$ is a present modified temperature error, and
 K_{htf} is a proportionality constant.

The output of threshold circuit is such that $HTEMP_n$ is always less than a minimum value $HTEMP_{min}$. When generated, the signal $HTEMP_n$ is then applied to summing amplifier 143 to modify the speed error signal $DELSPD_n$, generated thereby so that the output of summing amplifier 143 is represented by

$$DELSPD_n = DSERR_n + HTEMP_n$$

Therefore, the speed and, through function generator 145, the fuel are modified for temperature excursions above a particular value. That is, kiln speed will decrease and will cause a decrease in the fuel. In this manner an overtemperature condition may be quickly corrected without causing long-term upsets in the kiln. If a small speed increase were implemented, it could result in a fairly gentle action and could make the kiln respond in an orderly way to bring the temperature down. It could, however, cause a temperature rise with a final large burning zone temperature drop causing the kiln to go cold. Such a situation could exist if the load in the kiln moved toward the discharge end 15. Therefore, thermal runaway of the kiln is prevented by significantly decreasing speed and fuel while leaving the gas flow rate through the kiln as high as possible. Once the high temperature condition is corrected, fuel can be added. At the lower temperature, the flame position stabilizes to maintain the proper heat distribution or temperature profile in the kiln. By affecting the speed, feed is decreased to help maintain thermal balance and allow greater fuel changes to break thermal runaway while tending to avoid upsets causing succeeding cycles. Therefore, the percent fuel decrease is greater than the percent speed decrease so there will still be a decrease in the total heat balance of the kiln.

A fuel override is also provided when the temperature becomes too high. This is generated by a switch 172 which couples the burning zone temperature error $ETBZ_n$ to function generator 173 until signal $TEMP_n$ reaches the threshold value of threshold circuit 171. Function generator 173 generates an output signal $fETBZ_n$ which is applied to summing amplifier 131. The signal $fETBZ_n$ is generated in accordance with:

$$fETBZ_n = K_{funo} \left(\frac{ETBZ_n - K_{del}}{K_{tr}} \right)^2$$

Where

$ETBZ_n$ is the present value of the override function,
 $ETBZ_n$ is the present burning zone temperature error,
 K_{funo} is a proportionality constant,
 K_{del} is a dead band function, and
 K_{tr} is a proportionality constant.

Function generator 173 also is formed so that the signal $fETBZ_n$ is zero until $ETBZ_n$ signifies that the burning zone temperature has reached a level indicated by K_{del} and the set point TBZ_{sp} . Therefore, the function is always negative and, by being applied to a positive input of summing amplifier 131, reduces the fuel set point when generated. Therefore, with switch 132 shown in the position of FIG. 2, this embodiment of the invention, which includes the feed end temperature control, generates a fuel set point in accordance with the equation:

$$FUEL_{sp} = XFERR_n + fDFET_n + fETBZ_n$$

Where

$XFERR_n$ is the error apportioned to fuel modified by a function of the error apportioned to speed,
 $fDFET_n$ is a function of the feed end temperature error, and

$fETBZ_n$ is the present value of the override function. In this manner, the fuel set point is responsive to the effect of the excessive burning zone temperatures in addition to the basic burning zone temperature error. If high temperature forcing is being utilized, threshold circuit 171 opens switch 172, so the front end override and high temperature signals cannot exist simultaneously.

Low Temperature Speed Forcing

If the temperature of the burning zone represented by the signal $FTBZ_n$ goes below the burning zone temperature set point represented by the signal TBZ_{sp} , the error signal $ETBZ_n$ goes positive. At a positive threshold value, threshold circuit 174 generates a low temperature forcing signal $LTEMP_n$ applied to summing amplifier 141. The value of the low temperature forcing function represented by the signal $LTEMP_n$ which must be greater than a minimum value, is calculated in accordance with the equation:

$$LTEMP_n = K_{ltf} (TEMP_n - K_{dlf})$$

Where

$LTEMP_n$ is the present value of the forcing function,
 $TEMP_n$ is the present modified temperature error,
 K_{ltf} is a proportionality constant, and
 K_{dlf} is a dead band constant.

When the low temperature forcing function is added, the speed error signal $DSERR_n$ is generated by summing amplifier 141 in accordance with:

$$DSERR_n = SERR_n + FF_n + LTEMP_n$$

so that the output signal is a function of that portion of the composite error attributable to speed, the forcing function and, where excessive low temperatures exist, the low temperature forcing function. The addition of the low temperature forcing function has the effect of slowing the kiln and, as it is added to summing amplifier 141 the coupling effect on fuel also exists. Furthermore, the low temperature conditions are fed back to process model 133 and become a part of the model as a composite speed error signal $ESPD_n$.

Oxygen Override

Oxygen override logic 175 receives the fuel set point signal $FUEL_{sp}$ on line 70 and the speed output signal $KSPD_n$ on line 72 in addition to the output $EXIT_n$ of controller 163. Signal $FOXY_n$, the filtered value of the oxygen from the feed end generated by the oxygen sensor 55 on line 56 is input to the oxygen override logic. Finally, a feed ratio set point is applied to the oxygen override logic to generate, in conjunction with the speed, a feed rate. Basically, oxygen override logic 175 has the capability of calculating predicted oxygen content and employing this as a substitute for measured oxygen content. One embodiment of oxygen override logic has been described in U.S. Pat. (Ser. No. 678,851) issued (filed Oct. 30, 1967) by James W. Lane and assigned to the same assignee as the present invention. Basically, oxygen override logic 175 calculates the present exit gas rate and calculates a predicted oxygen content of the exit gas based on new conditions within the kiln. If the predicted oxygen content is less than this rate minimum, a new overriding exit gas rate is calculated. If the recalculated gas rate is greater than the capacity of fan 31, a new overriding fuel rate which will be less than the fuel set point signal $FUEL_{sp}$ is determined using the maximum capacity of the fan 31. The recalculated, overriding fuel rate set point results in a minimum safe exit gas oxygen content when the exit gas rate is at the maximum. A signal representing the overriding exit gas rate is calculated by override logic 175; or a signal representing the maximum exit gas rate, if required, is applied from oxygen override logic 175 to switch 164 and takes precedence over the exit gas rate $EXIT_n$ determined by gas temperature controller 163. Similarly, if the new fuel overriding set point is calculated by oxygen override logic 175, a signal representing this new fuel set point is applied to logic switch 132 and takes precedence over fuel rate set point $FUEL_{sp}$ determined by summing amplifier 131. The functions of oxygen override logic 175 may be conveniently performed

in a digital computer, with the computer memory being employed to store the signals required for computations.

Oxygen override logic 175 assures that the oxygen content is above a minimum safe level and that no combustibles or carbon monoxide appear in the exit gases. Oxygen override logic 175 monitors the oxygen content of the exit gas and determined what the new oxygen content will be after the contemplated control actions are taken. If the predicted oxygen content is less than the prescribed minimum level overriding action is taken. Priority is such that the exit gas rate calculated by gas temperature controller 163 is sacrificed first to prevent the desired fuel rate determined by summing amplifier 131, override logic 175 calculating a new exit gas rate set point which will result in the predicted oxygen content of the minimum safe level of the desired fuel rate. However, if the exit gas cannot adjust sufficiently to provide the required minimum oxygen logic, the fuel rate is also adjusted by override logic 175 to produce the safe minimum oxygen content of the maximum exit gas rate. Oxygen override logic 175 thus prevents dangerous conditions from occurring by preventing the selection of fuel and exit gas flow rates which reduce the oxygen content of the exit gas below minimum safe level.

Wet Kiln Controller

While the above described embodiment with its various commutations is directly adapted for control in a dry kiln, it has been found that in wet kilns where a slurry mixture is added to the kiln 10 at the feed end 14, a significant effect on torque is generated by conditions within the chain section 16. These are not related to changes in the burning zone temperature but can affect the signal FAMP_n directly.

As the slurry comes into the chain section and dries, it becomes sticky and rides up on the walls giving a large angle of repose. As the feed dries, the weight of water is lost and the powder that remains flows down the kiln with a small angle of repose requiring very little torque. The total torque required to turn the chain section has been very much a function of the amount of wet heavy feed that must be moved. The faster the feed is dried, the less wet material there will be to turn and the less torque will be required. If the material is dried sooner, the temperature of the dried feed leaving the chain section should be greater and a longer time will be available to heat the material. Therefore, the temperature of the feed at the exit from the chains is a function of the torque required to turn the chain section. As the temperature goes up, the required torque goes down. Therefore, as heat input to the chain section 16 is increased, the torque requirements for the chain section will decrease. If this change is interpreted as being due to burning zone change, it will look like fuel should be added. However, in such a condition fuel should be decreased. Thus, the effective changes at feed end of the kiln in the chain section 16 when interpreted as coming from the burning zone will cause wrong control actions to be taken. It has been determined that in some kilns the changes in torque resulting from changes in the chain section can be of the same order of magnitude as changes caused by changes in the burning zone region. This effect can be properly handled by generating a signal CHAMP_n which represents the effect on torque of changing conditions in the chain section.

The filtered signals representing the dry feed rate FFEED_n, the intermediate gas temperature FTIG_n, the dust ratio FDR_n, the front end temperature FFET_n, the kiln speed as indicated by the set point KSPD_n and, from the operator, a signal PMIF representing the percent moisture in the feed and the signal TMPF representing the input temperature of the feed are applied to temperature calculator 180. Initially a feed temperature function at the exit from the chain section is calculated by implementing a heat balance around the chain section using the dust, feed and the intermediate gas temperature as indicating heat inputs. Heat is carried from the chain section by the dry gas exiting the feed end, moisture driven from the slurry as steam, dust leaving the chain section and the feed leaving the

chains. Therefore the temperature function of the feed leaving the chains represented by signal TSC_n can be approximated by:

$$TSC_n = \frac{[K_{rad} + (FFEED_n C_{p-feed} FTMP) / (1 - PMIF) + EXIT_{n11} (C_{p-g} FTIG_n - C_{p-chgas} FFET_n) + FDR_n (K_{td} FTIG_n + K_{dt} - FFET_n) C_{p-dust} + PMIF FFEED_n (C_{p-vapor} + 1000 FFET_n) / (1 - PMIF)]}{(FFEED_n C_{p-feed})}$$

Where FTMP and PMIF are operator inputs representing the feed temperature and percent moisture in the feed respectively,

C_{p-feed} , C_{p-g} , $C_{p-chgas}$, C_{p-dust} and $C_{p-vapor}$ are the specific heat for the feed, incoming gas to the chain section, gas exiting the chains and dust and heat of vaporization respectively,

K_{rad} is a radiation constant, and

K_{td} and K_{dt} are constants related to determining the actual dust in the kiln.

The instantaneous value TSC_n is filtered in temperature calculator 180 to obtain a value TSCF_n in accordance with:

$$TSCF_n = TSCF_{n11} + K_{ref} (TSC_n - TSCF_{n11})$$

Where

TSCF_n is the present filtered value,

TSCF_{n11} is the previous filtered value,

TSC_n is the new calculated value, and

K_{ref} is a filter constant.

This filtered instantaneous number is trended to obtain an output signal TSCT_n from filter 181 in accordance with the equation:

$$TSCT_n = TSCT_{n11} + K_{tr} (TSCF_n - TSCT_{n11})$$

Where

TSCT_n is the present trended filtered value,

TSCT_{n11} is the previous trended filtered value,

TS(F_n) is the present filtered value, and

K_{tr} is a constant.

An error function DSCT_n is then determined by summing amplifier 182 energized by the trended temperature signal TSCT_n and the instantaneous filtered signal TSCF_n in accordance with the equation:

$$DSCT_n = TSCT_n - TSCF_n$$

Where

DSCT_n is the present difference value,

TSCT_n is the present trended value, and

TSCF_n is the present instantaneous value.

This difference signal is then applied to filter 183 to generate the output signal CHAMP_n coupled to process model 133 in accordance with the equation:

$$CHAMP_n = CHAMP_{n11} + K_{champ} (DSCT_n - CHAMP_{n11})$$

Where

CHAMP_n is the present calculated change in torque due to changes in the chain section,

CHAMP_{n11} is the previous change in torque,

DSCT_n is the present difference in the temperature, and

K_{champ} is a proportionately constant.

Therefore, a change in the chain section which immediately appears in the signal FAMP_n will, without the addition of the chain amp section, appear as a burning zone temperature disturbance. However, the feedback signal FB_n from process model 133 is, with the addition of the chain amp, calculated with the equation:

$$FB_n = EFUEL_{n1x} + ESPD_{n1y} + CHAMP_n$$

so it immediately appears as an offsetting factor in the composite error signal ERR_n from summing amplifier 121 and the effect of changes are thereby minimized.

FIGS. 4, 4A and 4B (hereinafter FIG. 4) illustrate a flow chart of the operation of the control system of FIG. 2. Referring to FIG. 4, initially several parameters to include dry feed rate, intermediate gas temperature, dust rate, feed end temperature, discharge oxygen rate, fuel rate, motor torque and burning zone temperature are measured, checked and filtered. Each of these signals are scanned on a continuous basis and made available to the filters to obtain periodic filtered values

FFED_n, FTIG_n, FDR_n, FFET_n, FOXY_n, FUEL_n, FAMP_n and

FTBZ_n. The check logic associated with each input compares successive inputs and if two values differ by more than a predetermined value, the previous value is saved and used in lieu of the present value.

Error signal ETBZ_n at the end of the control period is determined from the filtered value of burning zone temperature FTBZ_n and the set point TBZ_n. A stability gain factor SGF_n is produced from the burning zone temperature FTBZ_n to indicate the stability of the process. The signal representing motor torque FAMP_n is trended to obtain a set point signal AMP_{sp,n} which is also a function of the stability gain factor signal SGF_n. The trended amp set point and the filtered value FAMP_n are then combined to generate an error DELAMP_n. Also the stability gain factor is combined with the burning zone temperature error ETBZ_n to obtain a burning zone temperature deviation DELTBZ_n.

In the preferred form of the wet kiln control system, it is necessary to next calculate the temperature of the feed leaving the chain system for the conditions which have existed over the last control period, the signal being TSCF_n and then trending this to obtain a signal TSCT_n. With these two values it is possible to calculate that portion of a change in kiln amps which is due to changes in the chain section conditions represented by signal CHAMP_n. This signal CHAMP_n is a function of TSCF_n and TSCT_n. Once the various errors have been obtained, it is possible to update the process model. Predicted process changes due to previous control actions in speed and fuel are obtained and added to changes related to variations in the chain section conditions to generate a total feedback signal FB_n. The feedback signal FB_n is filtered to determine a new steering function STF_n and a new base fuel signal FUEL_{base}. Both these signals are fed back in combination with other signals, to the process model as fuel error input EFUEL_n.

In addition, the burning zone temperature deviation DELTBZ_n, the kiln amp error DELAMP_n, and the feedback signal FB_n are combined with the steering function STF_n, being subtracted therefrom to obtain a total composite error signal representing short term disturbances in the burning zone ERR_n. The short term disturbance represented by ERR_n is compared with a threshold value FERR_{max} representing a maximum error for fuel control to limit the portion of ERR_n is also compared with a speed dead band to implement a kiln speed variation if it exceeds the dead band, the portion of ERR_n which is apportioned to speed being designated as SERR_n.

If amp rate forcing is utilized, the control system determines whether amp rate forcing existed during the previous control action. If it did, a first speed decrease as a function of the rate of change of kiln amps and a second speed decrease as a function of the percent of the last speed change are calculated. The larger speed decrease is compared with a minimum acceptable change. If the predicted change is less than the minimum, amp rate forcing is terminated. If it is not, the larger speed decrease is implemented. If amp rate forcing was not implemented during the prior control action, the rate of change of amps is examined. If the rate of change will cause the signal FAMP_n representing motor torque to fall below a set point within a predetermined number of scans and if the rate of change exceeds a constant value, additional tests are made. If these two conditions do not exist, amp rate forcing is not required. If the conditions are met and if the control system indicates that the present scan is the second consecutive scan to satisfy the conditions, amp rate forcing is initiated and a speed change proportional to the amp rate is calculated and implemented.

If high or low temperature speed forcing or high temperature fuel override are utilized, a temperature function is determined from the burning zone temperature error ETBZ_n. High or low temperature forcing are implemented only if the burning zone temperature error leaves a dead band region. Considering high temperature forcing first and assuming that high temperature forcing was implemented, the temperature func-

tion TEMP_n and the weighted, trended temperature WSTT_n are analyzed to determine whether the forcing can be terminated. If termination is not feasible, a high temperature speed forcing function HTEMP_n is generated. Whenever this speed function is implemented, the fuel is decreased in accordance with fuel speed coupling function fSPD_n. If forcing were not implemented on the previous scan, TEMP_n and WSTT_n would be examined to determine if forcing were necessary. If it were HTEMP_n would be generated.

Similar action is taken for low temperature forcing. If forcing was previously practiced, the conditions of TEMP_n and WSTT_n are examined to determine the feasibility of termination. If the forcing function is not terminated, a speed decrease and appropriate fuel decrease are determined. If forcing was not previously practiced, the conditions of TEMP_n and WSTT_n are examined and low temperature forcing is implemented if necessary.

After these fuel and speed changes are determined based upon the various process measurements, all speed changes are combined to obtain a speed deviation signal DELSPD_n. Further, all speed changes except the speed change determined by the high temperature forcing function HTEMP_n are combined and filtered to obtain a feedback signal ESPD_n which is applied to the process model. Alternatively, speed and fuel forcing functions might be added into the control signals but not into the feedback signal. This feedback signal is generated on the basis of past history with each factor being delayed in accordance with process characteristics. The resulting total speed change DELSPD_n is added to base speed KSPD_{base} to obtain the kiln speed set point signal KSPD_n.

Fuel feedback is based upon a base fuel level FUEL_{base} and total process error apportioned to fuel TFERR_n to obtain a signal representative of the change in fuel DFUEL_n to which is added the steering function STF_n to achieve a steered fuel change representation STFUEL_n. When this function is filtered, the output signal EFUEL_n is an input to the process model. The signal TFERR_n is then compensated by fuel-speed coupling fSPD_n to achieve a factored fuel change XTFERR_n.

If the burning zone temperature is above the set point but below a value which would cause high temperature forcing an override function FEBTZ_n is added to the factored fuel level XTFERR_n. A feed end temperature set point FET_{sp} is obtained as a function of the filtered feed end temperature FFET_n and an error DFET_n is calculated. If DFET_n lies outside a dead band, a fuel change fDFET_n is combined with the signal FEBTZ_n and XTFERR_n to obtain a fuel set point FUEL_{sp} which is utilized to set the fuel supply controller.

Feed end temperature error DFET_n is also utilized to determine a new exit gas rate. The oxygen leaving the kiln represented by FOXY_n, present exit gas rate EXIT_n, the fuel rate set point FUEL_{sp} and kiln speed KSPD_n and a feed ratio set point are also measured for determining the new exit gas rate. The predicted exit gas rate is then compared with flow capacities and predicted oxygen flow from the kiln. The new exit gas rate is then determined to assure a safe oxygen level. If necessary, previously determined exit gas rates and fuel set points are modified.

After these functions are completed, the new kiln speed KSPD_n, fuel level FUEL_{sp} and exit gas rate EXIT_n are coupled from the control system to their respective controllers to effect kiln control. After a predetermined time increment, the control system shown in FIG. 4 determines a new set of conditions.

Accordingly, there has been described herein a method and apparatus for kiln control embodying the instant invention. All the principles of the invention have now been made clear in the illustrated embodiment, and there will be immediately obvious to those skilled in the art many modifications in structure, steps, arrangement, proportions, elements, materials and components used in the practice of the invention.

The appended claims are, therefore, intended to cover and embrace any such modifications, within the limits only of the true spirit and scope of the invention.

What is claimed as new and desired to be secured by Letters Patent of the United States is:

I claim:

1. In a rotary cement kiln control system including drive means for normally rotating the kiln at a constant speed, heating means for causing a material transformation in the kiln at a burning zone, first sensing means responsive to the torque developed by the drive means to rotate the kiln for providing a corresponding output, second sensing means responsive to the material temperature in the burning zone for providing a corresponding output and control means including means responsive to said second sensing means for indicating the thermal stability of the kiln, means responsive to said first sensing and thermal stability indicating means for generating a torque signal, means responsive to said second sensing and thermal stability sensing means for generating a burning zone temperature deviation, means responsive to the torque signal and burning zone temperature deviation for deriving a total process error and means responsive to the total process error for varying the heat input to the kiln.

2. A control system for a rotary cement kiln as recited in claim 1 additionally comprising means responsive to said total process error determining means for deriving therefrom a fuel error for the first range of process errors and a speed error for process errors beyond the first range, the heating means being responsive to fuel errors and the drive means being responsive to speed errors for varying kiln speed, the means for storing speed and fuel errors previously produced by said control means and responsive to one previous speed error and one previous fuel error for generating a feedback signal representing an expected variation in the output of said first and second measuring means due to previous control actions, the feedback signal being combined with the burning zone deviation and torque error by said total process error determining means.

3. A control for a rotary cement kiln as recited in claim 2 additionally comprising steering function generating means in response to the feedback signal for combination with the burning zone temperature deviation, the torque error signal and the feedback signal in said total process error determining means, means responsive to said fuel error derivation means and said steering function generating means for generating a base fuel level variable in response to long term process changes for combination with the fuel error to obtain a fuel level, said heat input means being responsive to the fuel level for controlling the heating in response to short term process disturbances.

4. In a rotary cement kiln control system including drive means for normally rotating the kiln at a constant speed, heating means for causing a material transformation in the kiln at a burning zone, first sensing means responsive to the torque developed by the drive means to rotate the kiln for supplying a corresponding output, second sensing means responsive to material temperature in the burning zone for providing a corresponding output and control means comprising:

- a. means responsive to said second sensing means and a predetermined burning zone temperature for indicating the burning zone temperature deviation,
- b. means responsive to said first sensing means for indicating a torque error,
- c. means for generating process feedback and means responsive thereto for generating a steering function,
- d. means for combining the burning zone temperature deviation, torque error, feedback and steering function to obtain a total process error,
- e. means responsive to a first range of total process errors for deriving therefrom a fuel-related error and to total process errors beyond the first range for deriving therefrom a speed-related error,
- f. means responsive to an initial fuel level and said steering function for generating a base fuel variable in accordance with long term process changes for addition to the fuel-related error and a fuel-related error feedback, said heating

means being responsive to the combined base fuel and fuel-related error, and

g. means responsive to the speed-related error for generating a speed-related error feedback, said feedback means storing previous fuel and speed feedback for combining selected ones representing expected variations in the output of said first and second sensing means due to previous control actions to generate the feedback and said steering function means being responsive to the feedback to cause the heating means and drive means to be controlled in response to short term disturbances.

5. A rotary cement kiln control system as recited in claim 4 additionally comprising means responsive to said second sensing means for generating a representation of kiln thermal stability, said burning zone temperature deviation indicating means and said torque error indicating means being responsive to said thermal stability indicating means to vary the relative contributions of burning zone temperature deviation and torque error to the total process error in accordance with kiln thermal stability.

6. A rotary cement kiln control system as recited in claim 4 additionally comprising means responsive to said first sensing means and said torque error generating means for generating a rate amp forcing function to be added to the speed-related error in response to predetermined rates of change of torque whereby such variations in torque measurement alter kiln speed.

7. A rotary cement kiln control system as recited in claim 4 including means responsive to the speed-related error for generating a speed change signal, first means responsive thereto for obtaining a speed signal from the speed change signal and a predetermined base speed signal and second means responsive to the speed change and base speed signals for modifying the fuel-related error whereby decreases in the speed cause decreases in the fuel-related error.

8. A rotary cement kiln control system as recited in claim 7 comprising means responsive to said burning zone temperature for indicating kiln thermal stability in response to said burning zone temperature deviation means, means responsive to the speed-related error for generating a speed change signal and means responsive to said thermal stability indicating means and a burning zone temperature error generated by said burning zone temperature deviation means for generating a high temperature speed forcing signal when the burning zone temperature error exceeds a predetermined error range.

9. A rotary cement kiln control system as recited in claim 4 wherein said burning zone temperature deviation means includes means responsive to said second sensing means for determining a burning zone error additionally comprising means responsive to burning zone temperatures in a range above the predetermined burning zone temperature for decreasing the heat input to the kiln by a factor which is variable in accordance with burning zone temperature error.

10. A rotary cement kiln control system as recited in claim 4 wherein said burning zone temperature deviation means generates a burning zone temperature error in response to said second sensing means, said control system additionally comprising means responsive to the burning zone temperature error for generating a low temperature speed forcing function when said burning zone temperatures exceed a range lower than the predetermined burning zone temperature and adding the low temperature forcing function to the speed-related error.

11. A rotary cement kiln control system as recited in claim 4 adapted for controlling a wet kiln having chain means for contacting wet feed entering the kiln and driving moisture therefrom, said control system additionally comprising means for measuring gas flow through the kiln, gas temperatures at the ends of the chain means and the rates at which feed and dust enter the kiln and means responsive to said measuring means and coupled to said feedback means for indicating the effect on torque measured by said first sensing means by conditions in the chain means for immediately and directly alter-

ing the feedback signal to nullify such variations in said first sensing means output.

12. A method for controlling a rotary cement kiln including drive means for normally rotating the kiln at a constant speed and heating means for causing a material transformation in the kiln at a burning zone, said method comprising the steps of:

- a. measuring the torque developed by the drive means to rotate the kiln and the material temperature in the burning zone of the kiln,
- b. determining a burning zone temperature deviation from a predetermined burning zone temperature and said burning zone temperature measurement and a torque error from said torque measurement,
- c. generating process feedback and a steering function related thereto,
- d. combining the burning zone temperature deviation, torque error, feedback and steering function to obtain a total process error,
- e. apportioning a first range of total process errors to a fuel error, said fuel error apportionment serving as a basis for heating means control, and total process errors beyond the first range to a speed error, said speed error apportionment serving as a basis for drive means control,
- f. determining a base fuel level in response to an initial fuel level and said steering function generation whereby said base fuel level generation varies in response to long term process changes,
- g. controlling the heat input to the kiln in response to said fuel error apportionment and base fuel generation and the drive means in response to said speed error apportionment, and
- h. storing previous fuel and speed errors, said feedback generation including combining selected ones of the fuel and speed error representing expected variations in said burning zone temperature and torque measurements due to previously implemented drive and heating means control, said steering function generation being in response to said feedback generation whereby said control method is effective to control the heat input to the kiln and the drive means in response to short term disturbances.

13. A control method for a rotary cement kiln as recited in claim 12 including the additional step of determining the thermal stability of the kiln from said burning zone temperature measurement, and said burning zone temperature deviation and torque error determinations being responsive to said thermal stability determination to vary the relative contributions thereof to the total process error in accordance with the thermal stability of the kiln.

14. A control method for a rotary cement kiln as recited in claim 12 including the additional step of controlling the drive means to reduce kiln speed in response to predetermined rates of change of torque as obtained from said torque measurement.

15. A control method for a rotary cement kiln as recited in claim 12 wherein said drive means control determines a speed change from said speed error apportionment and combines said speed change with a base speed and, in response to the base speed and said speed change determination modifies said heating means control in response to said fuel error apportionment whereby decreases in said combination of speed change and base speed cause said heat input control to decrease heat input to the kiln.

16. A control method for rotary cement kiln as recited in claim 15 wherein said drive means control responds to a burning zone temperature error determination in response to said burning zone temperature measurement and kiln thermal stability as determined from said burning zone temperature measurement by decreasing kiln speed in response to burning zone temperature errors indicating burning zone temperatures exceeding a range above a predetermined burning zone temperature.

17. A method for a rotary cement kiln as recited in claim 12 wherein said burning zone temperature deviation includes the step of determining a burning zone temperature error in response to said burning zone temperature measurement, said control method additionally causing said control of heat input to respond to burning zone temperature error for errors above predetermined values.

18. A control method for a rotary cement kiln as recited in claim 12 wherein said drive means control responds to burning zone temperature errors generated in response to said burning zone temperature measurement which represent burning zone temperatures below a predetermined burning zone temperature to decrease kiln speed.

19. A control method for a rotary cement kiln as recited in claim 12 having chain means for contacting wet feed entering the kiln and driving moisture therefrom including the additional steps of measuring gas flow through the kiln, gas temperatures at the ends of the chain means and material and dust feed rates and responding to said measurements by indicating the effect on said torque measurement which is related to conditions in the chain means and immediately and directly altering the feedback signal to nullify variations in the said torque measurement caused by variations of conditions in the chain means.

50

55

60

65

70

75

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,578,298Dated May 11, 1971

Inventor(s) Myron R. Hurlbut,
 Robert A. Phillips and Leland C. Tupper

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Column 4, line 64, " $2O_3).2O_3)$," should be -- $2O_3).(Fe_2O_3)$ --;
 Column 6, line 18, "nll" (both occurrences) should be -- n-1 --;
 line 21, "nll" should be -- n-1 --; line 25, "nll" should be -- n-1 --;
 line 44, "nll" (both occurrences) should be -- n-1 --;
 line 47, "nll" should be -- n-1 --; line 53, "nll" should be -- n-1 --;
 line 66, "nll" (both occurrences) should be -- n-1 --;
 line 69, "nll" should be -- n-1 --; Column 7, line 8, "nll" (both occurrences) should be -- n-1 --;
 line 11, "nll" should be -- n-1 --; line 19, "nll" should be -- n-1 --;
 line 27, "nll" (both occurrences) should be -- n-1 --; line 30, "nll" should be -- n-1 --;
 line 35, "nll" should be -- n-1 --; line 45, "nll" (both occurrences) should be -- n-1 --;
 line 48, "nll" should be -- n-1 --; line 55, "nll" should be -- n-1 --;
 Column 8, line 11, "nll" (both occurrences) should be -- n-1 --; line 14, "nll" should be -- n-1 --;
 line 18, "nll" should be -- n-1 --; line 51, "nll" (both occurrences) should be -- n-1 --;
 line 54, "nll" should be -- n-1 --; line 58, "nll" should be -- n-1 --; Column 9, line 50, "ETBZD" should be -- ETBZ --;
 Column 10, line 69, "nll" should be ⁿ-- n-1 --; line 69, ⁿ"nlm" should be -- n-m --;

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,578,298Dated May 11, 1971

Myron R. Hurlbut,
 Inventor(s) Robert A. Phillips and Leland C. Tupper

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

line 73, "nll" should be -- n-l --; line 74, "nlm" should be -- n-m --; Column 11, line 8, "nll" (both occurrences) should be -- n-l --; line 11, "nll" should be -- n-l --; line 26, "sp/nll" (both occurrences) should be -- sp/n-l --; line 29, "sp/nll" should be -- sp/n-l --; Column 12, line 46, "nll" (both occurrences) should be -- n-l --; line 49, "nll" should be -- n-l --; line 53, "nll" should be -- n-l --; Column 13, line 58, "this" should be -- This --; line 70, "nll" (both occurrences) should be -- n-l --; line 73, "nll" should be -- n-l --; Column 14, line 29, "STFUEL =DFUEL+ⁿSTFn." should be -- STFUEL =DFUEL+STFⁿ. --; line 32, "nll" (both occurrences) should be -- n-l --; line 35, "nll" should be -- n-l --; line 39, "nll" should be -- n-l --; line 44, "nll" should be -- n-l --; Column 15, line 18, "nlx" should be -- n-x --; same line, "xly" should be -- x-y --; line 21, "nlx" should be -- n-x --; line 26, "nly" should be -- n-y --; line 36, "nlx" should be -- n-x --; same line, "nly" should be -- n-y --; Column 16, line 32, "sp/nll" (both occurrences) should be -- sp/n-l --; line 35, "sp/nll" should be -- sp/n-l --; line 40, "sp/nll" should be -- sp/n-l --; line 56, "nll" (both occurrences)

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,578,298 Dated May 11, 1971
 Inventor(s) Myron R. Hurlbut,
 Robert A. Phillips and Leland C. Tupper

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

should be -- n-l --; line 59, "nll" should be -- n-l --; line 62, "nll" should be -- n-l --; line 74, "nll" (both occurrences) should be -- n-l --; Column 17, line 15, "FDFET " should be -- fDFET --; Column 18, line 10, "nll" should be ⁿ-- n-l --; Column 22, line 6, "nll" should be -- n-l --; line 22, "nll" (both occurrences) should be -- n-l --; line 25, "nll" should be -- n-l --; line 31, "nll" should be -- n-l --; same line, "nll18 l" should be -- n-l --; line 49, "nll" (both occurrences) should be -- n-l --; line 53, "nll" should be -- n-l --; line 63, "nlx" should be -- n-x --; same line, "nly" should be -- n-y --.

Signed and sealed this 29th day of August 1972.

(SEAL)
 Attest:

EDWARD M. FLETCHER, JR.
 Attesting Officer

ROBERT GOTTSCHALK
 Commissioner of Patents