

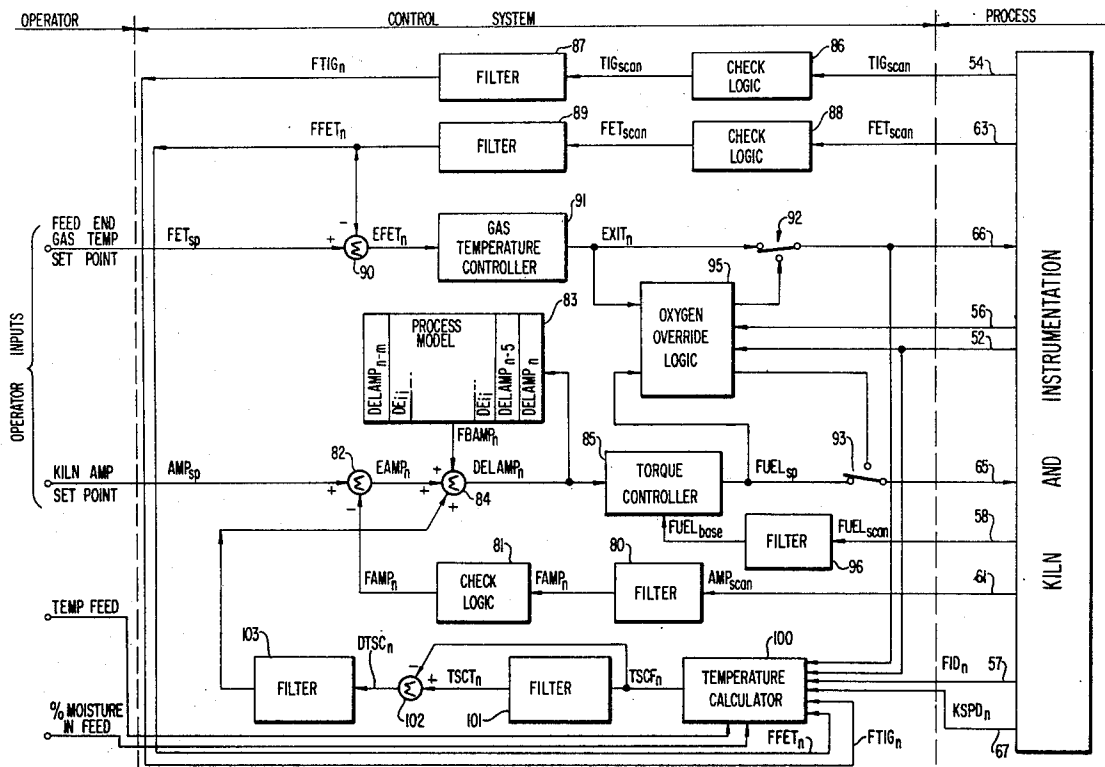
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[21] Appl. No. **861,425**
[22] Filed **Sept. 26, 1969**
[45] Patented **May 11, 1971**
[73] Assignee **General Electric Company**

3,469,828 9/1969 Lane 263/32
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[54] **METHOD AND APPARATUS FOR CEMENT KILN CONTROL**
10 Claims, 6 Drawing Figs.
[52] U.S. Cl. **263/32**
[51] Int. Cl. **F27b 7/20**
[50] Field of Search **263/32**

[56] **References Cited**
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ABSTRACT: A method and apparatus for controlling the operation of a rotary cement kiln which is fed with an incoming slurry. The fuel rate set point and the exit gas rate set point are controlled. The control of fuel rate set point is based upon kiln drive motor torque measurements in conjunction with feedback signals generated by a dynamic kiln model which stores a record of past control actions and a calculated effect of the slurry drying characteristics in the kiln. Control of the exit gas rate set point is based upon measurements of gas temperature at the feed end of the kiln. Oxygen content of the exit gas is monitored and employed to exercise overriding control to insure that no combustibles which might cause an explosion appear in the exit gas.



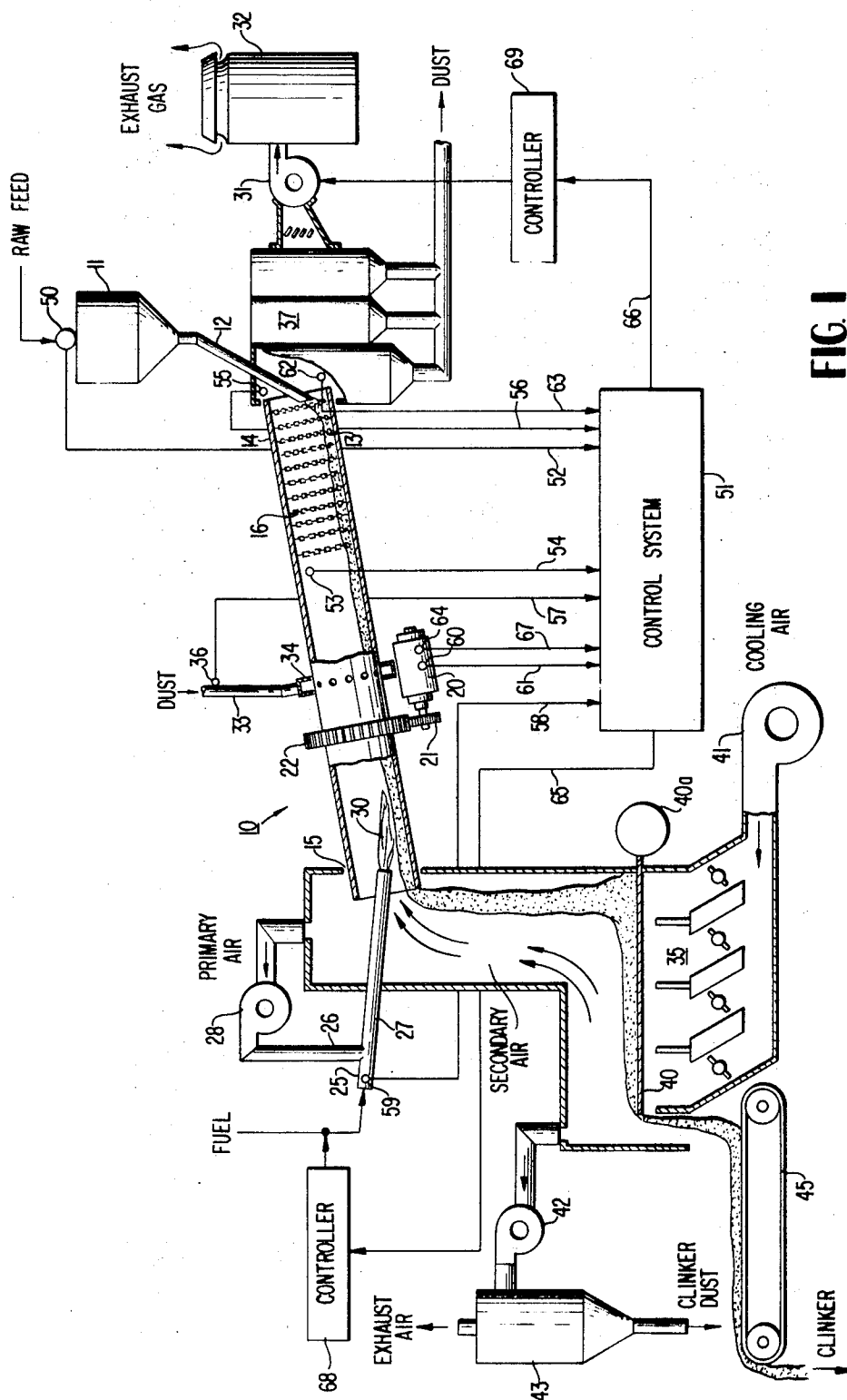
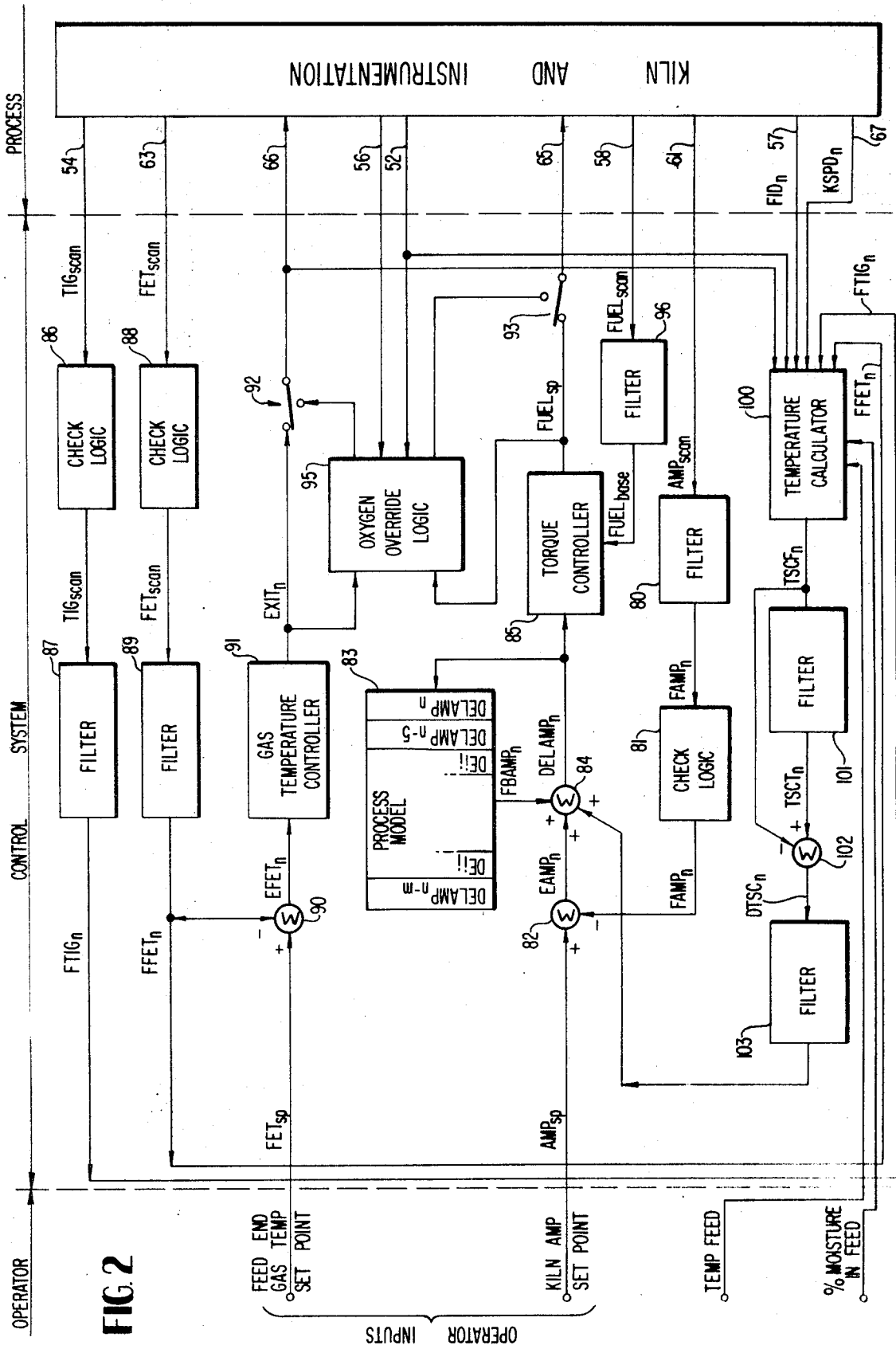


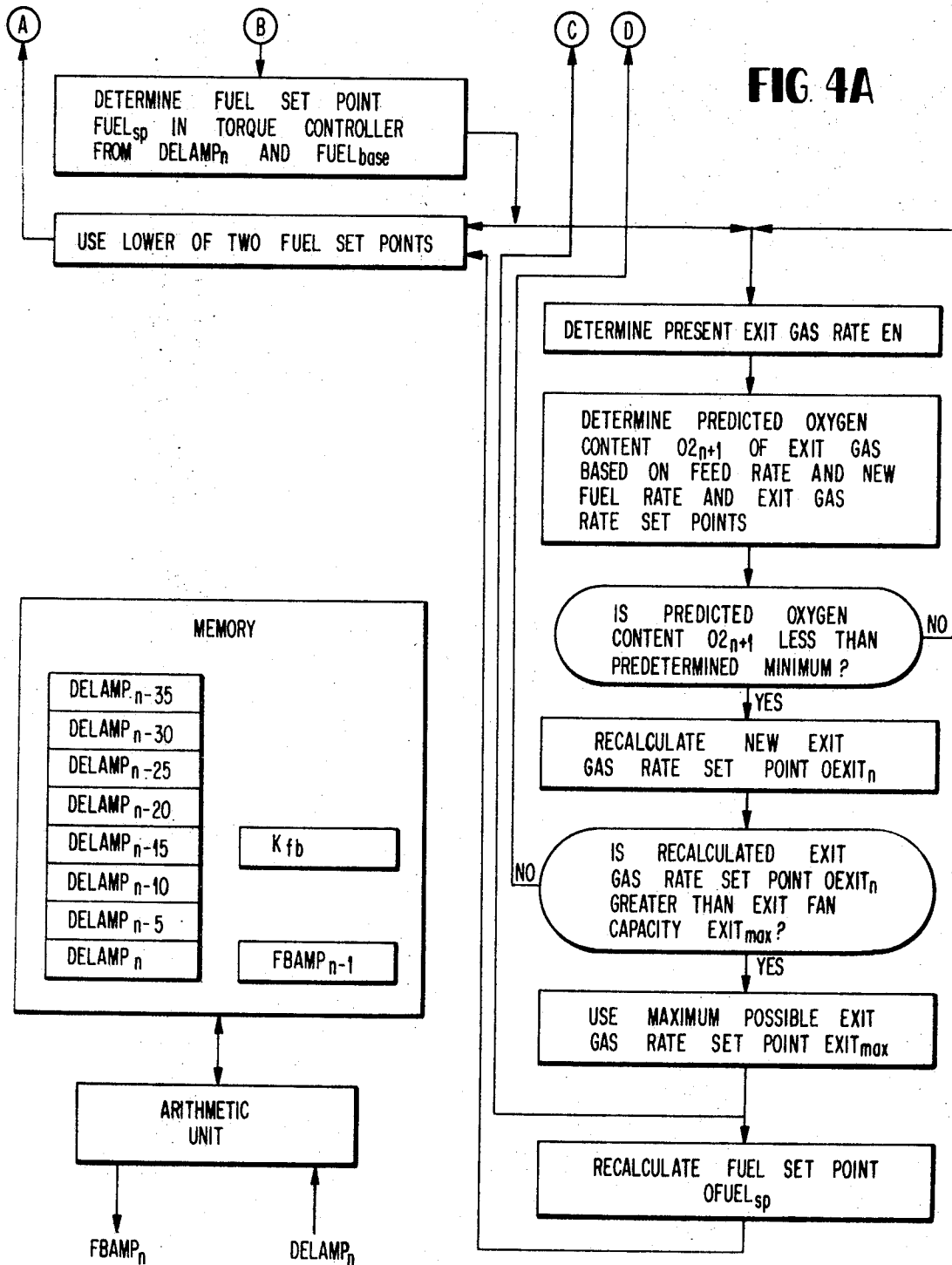
FIG. 1

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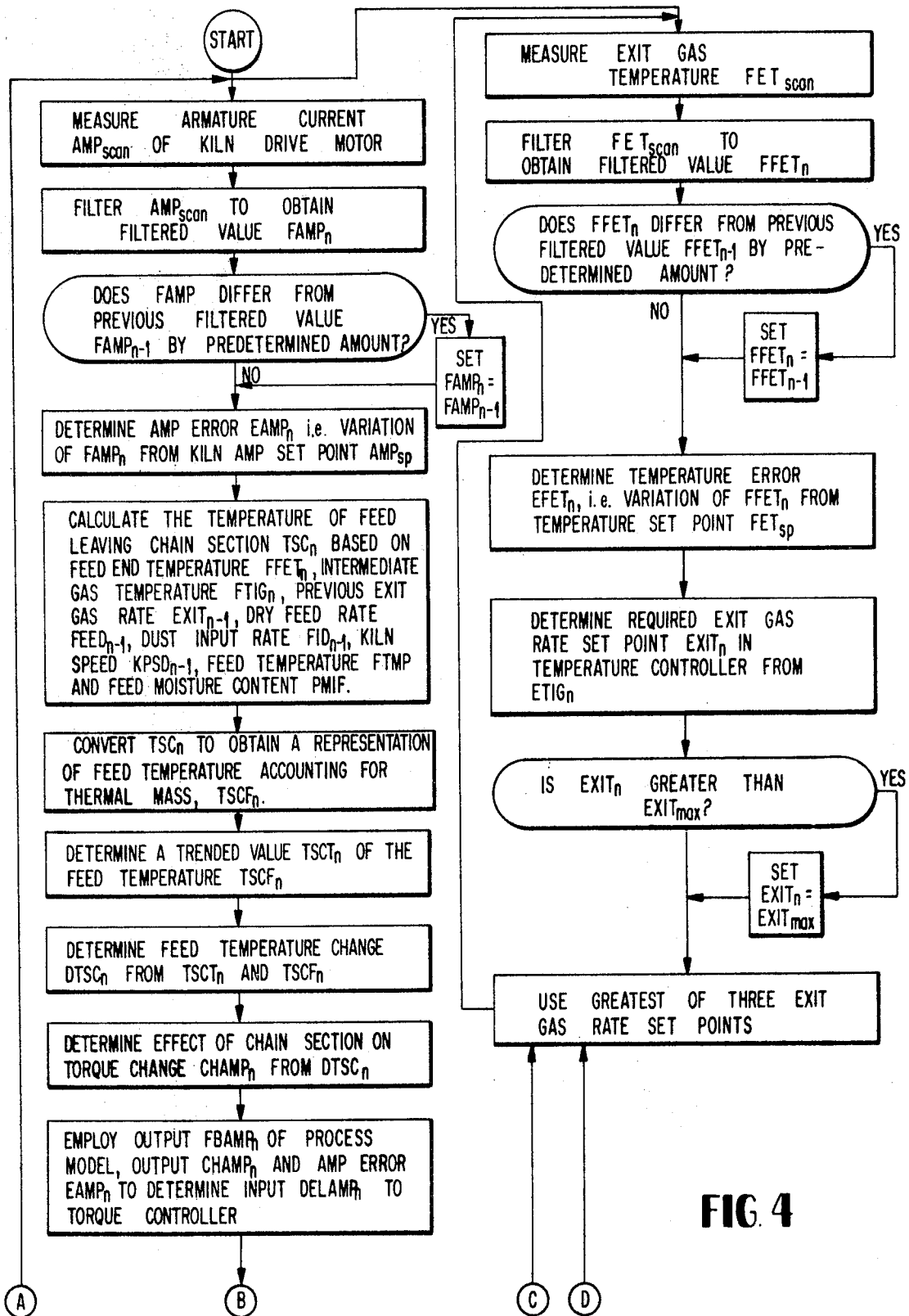


FIG. 4

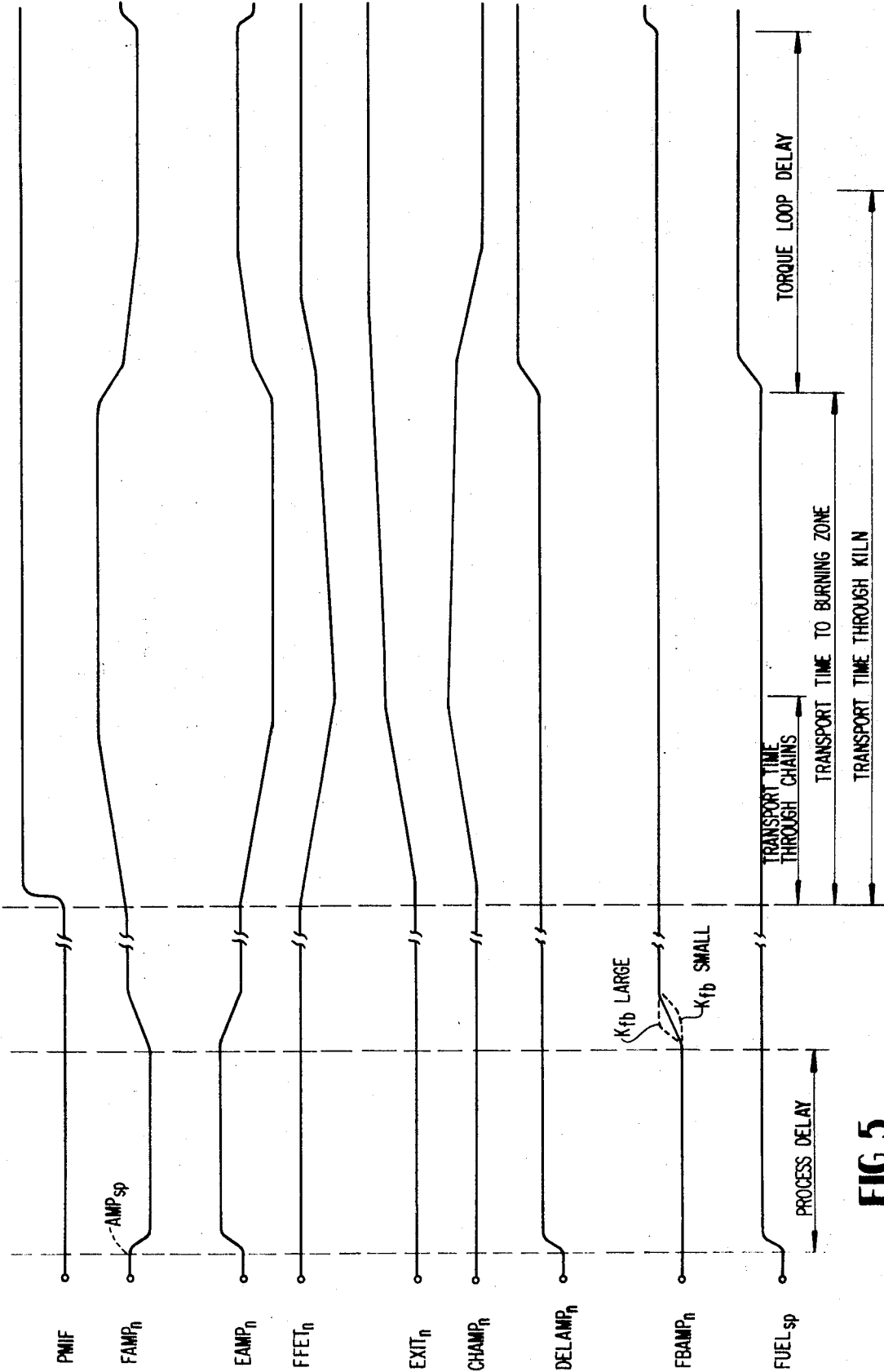


FIG 5

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 a group of rotary cement kilns known as wet 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.

In wet kilns, to which this invention is adapted, the raw, input materials are in a slurry. As the raw materials move slowly down the kiln at a rate which is a function of the kiln rotational speed, they engage chains suspended from the kiln through approximately 25 percent of the kiln length. The chains generally comprise the drying zone of the kiln and may comprise a portion of a preheating zone. After the feed passes through the chains, it progresses through successive zones including the remainder of the preheating zone, the calcining zone and the clinkering or burning zone. The chains are suspended from the kiln to contact the slurry and serve as a heat exchanger to drive off moisture. 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.

Still more recently, several automatic control arrangements for rotary cement kilns have been proposed. One such system which is effective to control rotary cement kiln operation is described in U.S. Pat. Ser. No. 678,851 issued (filed Oct. 30, 1967), now U.S. Pat. No. 3,469,828, to James W. Lane and assigned to the same assignee as the present invention. As described in that patent, kiln drive amps are a measure of the torque required to turn the kiln and accurately indicate the temperature in the burning zone as the torque increases as the temperature increases. With wet kiln operation where a slurry is being introduced, the slurry is converted to a sticky form which rides up on the walls giving a large angle of repose in the chain section. As the feed dries, the weight of the 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 then is a function of the amount of wet feed that must be moved. Therefore, as the heat input to the chains is increased, the amps due to the chain section will decrease. When the amp controller of the aforesaid Lane patent was implemented, it was found that this amp change could be interpreted as being due to the burning zone requiring additional fuel when, in reality, the fuel rate should have been decreased.

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

It is another object of this invention to provide a control method and apparatus for maintaining control of a rotary wet cement kiln by eliminating control ambiguities which can occur in this particular type of cement kiln.

It is a further object of this invention to provide a method and apparatus for maintaining control of burning zone conditions in a wet rotary cement kiln in conjunction with a control system which responds to drive torque.

SUMMARY

Generally, a torque control apparatus including a sensor for measuring the torque developed by the kiln drive motor to rotate the kiln and a filter for smoothing and filtering the sensor output are provided. The filtered signal is checked to insure that it falls within a predetermined range and is then compared to a setpoint signal. The error signal representing the difference between the filtered signal and the setpoint signal is applied to a summing amplifier which also receives the output of a process model. The output of the summing amplifier is applied to the process model and to a torque controller which receives a signal indicating the base rate of fuel flow to the kiln. In response to a variation in the output of the summing amplifier, the torque controller calculates a new fuel rate setpoint which tends to correct the burning zone conditions and return the drive motor torque to the setpoint value.

Ambiguities in the control of the process are obviated by measuring the temperature drop across the chain section and heat rates into and from the chain section. This indicates the condition of the process materials and permits compensation of the process model output for the torque required to turn the chains. This torque bears no specific relationship to the burning zone temperature which is the primary parameter being observed and controlled.

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 conjunction 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;

FIGS. 4 and 4a are flow diagrams illustrating the operation of the control system of FIG. 2;

FIG. 5 is a signal diagram illustrating the operation of the control system of FIG. 2 in controlling rotary cement kiln operation.

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 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 or feed will be in the form of a slurry. Chains 16 would be suspended along the kiln adjacent the feed end to remove moisture from the slurry. 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 of 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 which injects a high-energy flame 30 into kiln 10. 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 10. 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. A sensor 36 senses the rate of dust reintroduction.

As the feed proceeds slowly down the kiln, it is heated by hot gases flowing counter to it and also by the heated refracto-

ry 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 $(CaO)_2(SiO_2)$, $(CaO)_3(Al_2O_3)$ and $(CaO)_4(Al_2O_3)(Fe_2O_3)$, 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 the travelling grate 40 usually reciprocated by a motor 40a. Air is blown through 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.

A number of sensor 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, hopper 11 has a feed rate detector 50 associated therewith which provides a signal to control system 51 over line 52 indicating the rate at which feed is being supplied to the kiln. A temperature measuring device 53, for example a thermocouple, is provided at the lower end of the chain section 16, of the kiln 10 to provide a signal transmitted to control system 51 on line 54 indicating the temperature of the gases flowing through the kiln at that point. Analyzer 55 is 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 51 on line 56. A signal from the dust feed rate sensor 36 is provided to the control system 51 on a line 57.

A signal representing the rate of fuel flow to mixing chamber 27 is provided to control system 51 on line 58 by sensor 59 associated with fuel supply line 25. Sensor 60 associated with kiln drive motor 20 provides a signal to control system 51 on line 61 representing the torque developed by motor 20 as required to rotate kiln 10 at the predetermined rotational speed. A temperature measuring device 62, for example a thermocouple, is provided near feed end 14 of the kiln to provide a signal transmitted to control system 51 on line 63 indicating the feed end temperature of the gases flowing through the kiln at that point after they exit from the chain section 16. A signal representing the kiln speed is provided to control system 51 by a kiln speed sensor 64 coupled to the control system 51 by line 67.

Control system 51 utilizes the information concerning kiln operation provided on lines 52, 54, 56, 57, 58, 61, 63 and 67 to produce kiln control signals on lines 65 and 66. The control signal on line 65 represents a fuel rate setpoint and is applied to controller 68 to control the rate of flow of fuel into mixing chamber 27 and therefore the heat input to kiln 10. The control signal on line 66 represents an exit gas rate setpoint and is applied to controller 69 to control the speed of induced draft fan 31 and therefore the exit gas flow rate. The signal on line 66 representing an exit gas rate setpoint may, alternatively, be employed to control the position of damper 38, thereby adjusting the exit gas flow rate. Controllers 68 and 69 are standard analog controllers as known in the art and will not be described in detail.

FIG. 2 illustrates the details of control system 51 shown in FIG. 1. Referring to FIG. 2, the signal on line 61 representing the torque developed by kiln drive motor 20 to rotate kiln 10 is applied to filter 80. If kiln drive motor 20 is an AC motor, assuming a constant speed of rotation of kiln 10, the signal on line 61 is a measure of the kilowatt power input to motor 20 which represents the torque developed by motor 20 to rotate kiln 10. If kiln drive motor 20 is a constant field, DC motor, the signal on line 61 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 on line 61 representing the armature current in and the torque developed by motor 20 is termed AMP_{scan} . Various means for obtaining a torque signal from other motors are known in the art. Sensor 60 (FIG. 1) comprises an instrument capable of measuring and providing an output signal proportional to the armature current or torque of motor 20.

Experience has shown that when a signal directly proportional to the torque required to turn the kiln is filtered and smoothed, it can be reliable and sensitive indicator of the heat state within the kiln, in particular the condition of the burning zone, and of the relative amount of dense clinker material in the burning zone. The material in the burning zone undergoing the clinkering reaction is much denser than the remainder of the feed in the kiln. In addition, since normally 10 to 30 percent of the material in the burning zone is in a liquid state, the flow characteristics of this material differ drastically from the remainder of material in the kiln. The liquefied material in the burning zone is much stickier and tends to form a mass which adheres to the refractory surface. The material thus rides much higher on the kiln wall as the kiln rotates and requires more torque to carry the material along the kiln.

As the kiln temperature increases, the burning zone lengthens and the amount of this dense liquefied material increases, requiring an increase in the rotational torque supplied by kiln drive motor 20. As the kiln temperature decreases, the burning zone shortens and the amount of this dense liquefied material decreases, decreasing the torque developed by drive motor 20. Thus, changes in the torque developed by drive motor 20 in rotating the kiln indicate changing heat conditions within the kiln which are causing the burning zone to lengthen or shorten. Slow changes in the torque over a period of time indicate very small imbalances in heat input, normally undetected by an operator, which, if corrected immediately, will prevent larger upsets and more drastic corrective action at a later time. The signal AMP_{scan} therefore represents the instantaneous heat state within the kiln and changes in the value of AMP_{scan} indicate corresponding changes in the condition of the burning zone. The use of torque measurements represented by the signal AMP_{scan} to effect control of kiln operation independent of actual burning zone temperature measurements are claimed in the aforesaid U.S. Patent. 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 the effect of kiln rotation on the signal, is performed in filter 80. The output signal of filter 80 is $FAMP_n$. The filtering action of filter 80 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 80 may conveniently be 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 the burning zone, 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 and may be, for example .005.

Output signal $FAMP_n$ of filter 80 is applied to check logic 81. Check logic 81 compares the present output signal $FAMP_n$ of filter 80 with the previous output signal $FAMP_{n11}$. If the present and previous filtered values differ by more than a given amount, it is assumed that some unusual conditions exist within the kiln and output signal $FAMP_n$ of filter 80 is not used until it returns to within a reasonable range of $FAMP_{n11}$. Check logic 81 serves to mask momentary or short term disturbances. The function performed by check logic 81 may be conveniently implemented in a digital computer; it may be implemented either on $FAMP_n$ or on AMP_{scan} .

Output signal $FAMP_n$ of filter 80, if within the required range, is applied to summing amplifier 82. A kiln amp setpoint signal AMP_{sp} is also applied to summing amplifier 82. The kiln amp setpoint represented by signal AMP_{sp} is controlled by the operator by means of a potentiometer or a value stored in a digital computer and will normally be based upon the chemical analysis of the kiln product periodically reported to the operator. For example, if the free lime (uncombined CaO) content of the kiln product is too low, the operator will lower the kiln amp setpoint, whereas if the free lime content is too high, the operator will raise the kiln amp setpoint. Typical kiln amp setpoint values for a particular type and rate of feed and for a particular quality kiln product based on past experience will be employed by the operator to select an initial kiln amp setpoint.

Summing amplifier 82 is of the type well known in the art and provides an amp error signal $EAMP_n$ proportional to the difference between the kiln amp setpoint AMP_{sp} and the present filtered value of kiln amps represented by signal $FAMP_n$, as expressed by the equation:

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

Amp error signal $EAMP_n$ is positive if the present filtered value of kiln amps is less than the kiln amp setpoint and is negative if the present filtered value of kiln amps exceeds the kiln amp setpoint. The function of summing amplifier 82 may conveniently be performed in a digital computer.

If the process being performed in kiln 10 responded quickly to changes, for example a change in the rate of fuel combustion, the amp error signal $EAMP_n$ provided by summing amplifier 82 could be used directly to control the fuel rate setpoint. However, as previously described, the process in the kiln reacts very slowly to control action on fuel rate setpoint and normally the reaction to a control action may not be detected for a long period and then will normally continue for a long time thereafter. In responding to a control action, the process therefore has a long lag time plus a long time constant. The reaction time of a kiln, i.e. the time period between initiation of a control action and the resulting change in burning zone condition may be up to 30 minutes or more. Because of these characteristics, an analog controller cannot adequately perform the control function.

Effective control of kiln operation in dry kiln operation can be accomplished solely by employing a dynamic process model in accordance with the above-identified U.S. patent. The process model, identified by reference numeral 83 in FIG. 2, comprises a delay table in which control values 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 the 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 down 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 this control action as reflected in change of 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, e.g. a fuel setpoint change, and the response thereto in the burning zone of the kiln may be of the order of 30—35 minutes or more. The delay table of the process model comprises a sufficient number of storage positions so that the delay range available in the delay table encompasses the delay characteristic of the kiln being controlled.

Process model 83 also includes arithmetic apparatus for providing feedback signal $FBAMP_n$. Feedback signal $FBAMP_n$ is applied to summing amplifier 84 along with amp error signal $EAMP_n$ from summing amplifier 82. Output signal $DELAMP_n$ of summing amplifier 84 constitutes a control value and represents the sum of feedback signal $FBAMP_n$ and amp error signal $EAMP_n$ as expressed by the equation:

$$DELAMP_n = EAMP_n + FBAMP_n$$

The function of Summing amplifier 84 may conveniently be performed by a digital computer. Control value signal $DELAMP_n$ is applied to torque controller 85 which controls the fuel rate setpoint in accordance with the magnitude of $DELAMP_n$. Signal $DELAMP_n$ is also applied to process model 83 for storage in the delay table. The delay table of process model 83, assuming a period of 5 minutes between control value calculations, has stored therein the signals $DELAMP_n$, $DELAMP_{n15}$, $DELAMP_{n10}$, $DELAMP_{n15}$, ... $DELAMP_{n1m}$ where m is the number of minutes equal to or greater than the delay characteristic of the kiln being controlled.

The arithmetic apparatus forming part of process model 83 periodically, e.g. every 5 minutes, calculates feedback signal $FBAMP_n$ in accordance with the following equation:

$$FBAMP_n = FBAMP_{n11} + K_{fb} (DELAMP_{n1x} - FBAMP_{n11})$$

Where $FBAMP_n$ is the present feedback signal generated by the process model,

$FBAMP_{n11}$ is the last feedback signal generated by the process model,

K_{fb} is the process model feedback constant, and

$DELAMP_{n1x}$ is a selected control value stored in the process model table (x =delay time of kiln in minutes)

Feedback constant K_{fb} may, for example, have a value in the range 0.005. The signal $DELAMP_{n1x}$ may be any of the stored control values in the process model table corresponding to the delay between a control action and the reaction in the burning zone which is characteristic of the particular kiln. If the delay characteristic of the kiln is 35 minutes, stored control value $DELAMP_{n135}$ is used by the process model to calculate feedback signal $FBAMP_n$. Feedback signal $FBAMP_n$ may be calculated by the arithmetic apparatus of process model 83 and control signal $DELAMP_n$ generated at any desired interval, for example every 5 minutes. After calculation of feedback signal $FBAMP_n$, the resulting value of control signal $DELAMP_n$ furnished by summing amplifier 84 is stored in the process model table and the previously stored values of signal $DELAMP$ are shifted down the table in the process model.

The storage of successive control signals $DELAMP$ and the calculation of feedback signal $FBAMP_n$ may conveniently be accomplished in a digital computer. The table of process model 83 may, for example, comprise a selected series of memory locations within the stored control values with the stored control values being shifted through the series of memory locations as the control values are entered into the table, as illustrated diagrammatically in FIG. 3. Feedback constant K_{fb} and the previously calculated feedback signal $FBAMP_{n11}$ may also be stored in the computer memory. The arithmetic unit of the digital computer serves to control the storage of successive control values $DELAMP_n$ in the table

and utilizes the contents of the table and the stored values of K_{fb} and $FBAMP_{n11}$ to calculate feedback signal $FBAMP_n$.

In wet kilns, significant portions of the overall torque changes sensed by torque sensor 60 are due to changes in the feed material condition in the chain section 16. It has been found that such torque changes can be closely approximated with knowledge of the feed rate and moisture content, the temperature across the chain section 15 and the gas flow rate through the chain section 16. One of the parameters used to determine or calculate the effect of the chains is the intermediate gas temperature measured by the intermediate gas temperature sensor 53 which generates a signal TIG_{scan} on line 54. Check logic 85 compares successive signals TIG_{scan} . If two successive signals differ by more than a given amount, it is assumed that the sensor 53 has failed and the previous value of TIG_{scan} is used. Filter 87 receives the signal TIG_{scan} and produces intermediate gas temperature information represented by the signal filter 87 in accordance with the following equation:

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

Where $FTIG_n$ is the present filtered value,

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

TIG_{scan} is the present measured value, and

K_{ftg} is the filter constant.

A typical value for constant K_{ftg} is 0.2 when $FTIG_n$ is calculated once every minute. The functions of check logic 86 and filter 87 may be conveniently performed in a digital computer with the signals $FTIG_n$, $FTIG_{n11}$, successive values of TIG_{scan} and the constant K_{ftg} being stored in the computer memory. Filtered gas temperature signal $FTIG_n$ is used in conjunction with other parameters to determine the signal $CHAMP_n$.

Check logic 88 receives on a line 63 a signal representing the feed end gas temperature at exit end 14 of the kiln, as measured by device 62. The gas temperature information represented by the signal is applied to check logic 88 to be compared with the previous value of the signal FET_{scan} . If the two successive signals differ by more than a given amount, it is assumed that the device 62 has failed and the first signal FET_{scan} is used. Filter 89 receives the signal FET_{scan} and filters the value 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 filtered constant.

A typical value for constant K_{fet} is 0.2 when $FFET_n$ is calculated once every minute.

In addition to being used with the signal $FTIG_n$ to determine the value of the signal $CHAMP_n$, filtered feed end temperature $FFET_n$ is applied to summing amplifier 90 along with signal FET_{sp} representing the gas temperature setpoint as determined by the operator. The summing amplifier 90 together with the temperature controller 91 and logic switch 92 constitute a control loop for maintaining a relatively constant gas temperature near the feed end 14 of the kiln 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 a torque control loop to be described hereinafter. As the fuel rate is increased or decreased to adjust burning zone conditions as reflected in required kiln drive torque, the temperature control loop adjusts the exit gas flow rate to maintain sufficient heat availability in the feed preparation section of the kiln comprising the chain section 16 and preheating zone.

Further, if heat requirements change due to changes in the characteristics of the raw materials entering the feed end of the kiln or due to changes in the feed rate, exit gas flow rate changes may become necessary. For example, if the raw materials require a greater quantity of heat, decreasing gas temperature at the kiln feed end an increase in exit gas flow is

required to carry more heat to the feed end of the kiln, thus maintaining the desired temperature profile in the kiln. If such action is not taken, the resulting decrease in gas temperature at the kiln feed end would eventually affect burning zone conditions and appear as a disturbance which would require more drastic corrective action to be taken in the torque control loop. The temperature control loop thus compensates for disturbances and for effects of control actions taken in the torque control loop so that the effect of these disturbances and control actions do not cause further disturbances in kiln operation requiring further control actions.

Gas temperature error signal $EFET_n$ produced by summing amplifier 90 is a function of signals $FFET_n$ and FET_{sp} , as expressed in the following equation:

$$EFET_n = FET_{sp} - FFET_n$$

and is applied to gas temperature controller 91. The function of summing amplifier 90 may conveniently be performed in a digital computer.

Gas temperature controller 91 determines a desired exit gas flow rate in the kiln and includes both proportional and integral modes. The function of gas temperature controller 91 is represented by the equation for output signal $EXIT_n$ of controller 91, as follows:

$$EXIT_n = EXIT_{n-1} + K_1 EFET_n + K_2 EFET_{n-1}$$

Where $EXIT_n$ is the desired exit gas flow rate,

$EXIT_{n-1}$ is the previous exit gas flow rate,

$EFET_n$ is the present temperature error signal,

$EFET_{n-1}$ is the previous temperature error signal, and

K_1 and K_2 are controller constants.

Typical values of constants K_1 and K_2 are 0.11 and -0.10, respectively, and $EXIT_n$ may be calculated, for example, every five minutes. Output signal $EXIT_n$ of gas temperature controller 91 is applied to line 66 for application to controller 69 through logic switch 92. 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 92 normally connects temperature controller 91 to controller 69, as illustrated, by may also serve to interrupt the connection, as subsequently described.

The function of gas temperature controller 91 may be conveniently performed in a digital computer with signals $EXIT_n$, $EXIT_{n-1}$, $EFET_n$ and $EFET_{n-1}$ and constants K_1 and K_2 being stored in the computer memory.

A major safety consideration in the operation of a cement kiln is the oxygen content of the exit gases. The oxygen content must be above a minimum safe level, usually 0.5 percent, to be assured that no combustibles, or carbon monoxide, appear in the exit gases which might cause an explosion in the dust collection system. The oxygen content of the exit gases depends upon the exit gas rate and the fuel rate. If the oxygen content of the exit gases falls below the minimum safe level, the exit gas rate determined in the gas temperature control loop, and possibly the fuel rate determined in the torque control loop, must be altered to maintain safe kiln operation. For example, if the fuel rate required by the torque control loop will result in an oxygen content below the minimum safe level at the exit gas rate determined by the gas temperature control loop, the exit gas rate determined by the gas temperature control loop must be overruled and a safe rate set. If the exit gas rate is already at a maximum, as limited by the position of damper 38 or by the speed of fan 31, and if the oxygen content is still below the minimum safe level, the fuel rate determined by the torque control loop must be overruled and a new fuel rate determined to insure safe operation.

Oxygen override logic 95 of the control system, as shown in FIG. 2, monitors the oxygen content of the exit gas and determines 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 safe level, logic 95 takes overriding action. The priority of the overriding logic is such that the exit gas rate calculated by gas temperature controller 91 is sacrificed first to permit the desired fuel rate determined by torque controller 85, override logic 95 calcu-

lating a new exit gas rate setpoint which will result in a predicted oxygen content at the minimum safe level for the desired fuel rate. However, if the exit gas rate cannot be adjusted sufficiently to provide the required minimum oxygen content, the fuel rate is also adjusted by override logic 95 to produce the safe minimum oxygen content at the maximum exit gas rate. Oxygen override logic 95 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 a minimum safe level.

Oxygen override logic 95 receives the outputs of torque controller 85 and gas temperature controller 91 in addition to the signal on line 56 from analyzer 55 representing exit gas oxygen content and the signal on line 52 from sensor 50 representing feed rate of raw materials into feed end 14 of the kiln. The output signals of oxygen override logic 95 are applied to logic switches 92 and 93 respectively to override, as required, the fuel rate setpoint and exit gas rate as determined by torque controller 85 and gas temperature controller 91 respectively, when such action is necessary to maintain a minimum safe level of oxygen in the exit gases. Normally, no action is taken for high oxygen content in the exit gas although such action can be taken with similar logic considerations. Oxygen override logic 95 has the capability of calculating predicted oxygen content and employing this as a substitute for measured oxygen content when analyzer 55 is unavailable due to, for example, operating problems.

Oxygen override logic 95 calculates the present exit gas rate as follows:

$$EN = \frac{[29.354 \text{ FUEL}_{sp-1} + 15.91 \text{ FEED}_n]}{1 - \frac{O2_n}{21}}$$

Where EN is the present exit gas rate in moles per hour, FUEL_{sp-1} is the old fuel rate setpoint in KSCF (thousands of standard cubic feet) per hour presently being used, FEED_n is the present feed rate in tons per hour, as measured by feed rate detector 50 and as represented by the signal on line 52,

$O2_n$ is the present oxygen content of the exit gas as measured by analyzer 55 and represented by the signal on line 56,

21 represents the normal percent oxygen in the atmosphere, and

29.354 and 15.91 are specific constants for a given fuel and feed composition.

The predicted oxygen content of the exit gas based on the new fuel rate FUEL_{sp} determined by the torque control loop can then be calculated as follows:

$$O2_{n+1} = 21 \left[1 - \frac{29.354 \text{ FUEL}_{sp} + 15.91 \text{ FEED}_n}{EXIT_n} \right]$$

Where FUEL_{sp} is the new required fuel rate determined by torque controller 85 in the torque control loop,

$EXIT_n$ is the new required exit gas rate determined by temperature controller 91 in the gas temperature control loop, and

$O2_{n+1}$ is the predicted oxygen content.

If the recalculated exit gas rate $OEXIT_n$ is greater than the capacity of fan 31, then a new overriding fuel rate $OFUEL_{sp}$ which will be less than FUEL_{sp} determined by torque controller 85 must be calculated using maximum capacity of fan 31 or $EXIT_{max}$ as follows:

$$OFUEL_{sp} = \frac{[EXIT_{max} \left(1 - \frac{O2_{min}}{21} \right) - 15.91 \text{ FEED}_n]}{29.354}$$

This recalculated fuel rate $OFUEL_{sp}$ will result in the minimum safe exit gas oxygen content when the exit gas rate is at the maximum. A signal representing exit gas rate $OEXIT_n$, as calculated by oxygen override logic 95, or a signal representing the maximum exit gas rate $EXIT_{max}$, if required,

is applied to logic switch 92 and takes precedence over the exit gas rate $EXIT_n$ determined by gas temperature controller 91. Similarly, if a new fuel setpoint $OFUEL_{sp}$ is calculated by oxygen override logic 95, a signal representing this new fuel setpoint is applied to logic switch 93 and takes precedence over the fuel rate setpoint $FUEL_{sp}$ determined by torque controller 85. The functions of oxygen override logic 95 may be conveniently performed in a digital computer, with the computer memory being employed to store the signals required for the computations.

The torque control loop responds not only to the difference between the kiln amp setpoint AMP_{sp} and the filtered signal indicating motor torque $FAMP_{sp}$ to produce an error signal which is then added to a feedback signal $FBAMP_n$, it is also responsive to a signal indicating the effect of the chains on the total torque, $CHAMP_n$. The effect of the chains is initially calculated in a temperature computer which responds to several signals. The filtered feed end and intermediate gas temperatures, $FFET_n$ and $FTIG_n$ together with the exit gas flow rate signal $EXIT_n$ on the line 66 and dry feed rate signal on line 52 $FEED_n$ are applied to the temperature computer 100. A dust feed rate signal $TSPD_n$ is applied on line 57. These signals may be either constant values or they may be and preferably are represented by constantly scanned variables which are treated by filtering and check logic in the same manner as the signal AMP_{scan} is converted to $FAMP_n$ by filter 80 and check logic 81. A kiln speed signal $KSPD_n$ can similarly be provided on line 67 from the kiln speed sensor 64 shown in FIG. 1. Operator inputs to the temperature computer 100 include a feed temperature $FTMP$ and a signal representing the percent moisture in the feed $PMIF$ which are normally relatively constant for a given process.

With these inputs, it is possible for the temperature computer 100 to calculate the temperature of the feed at the termination of the chain section 16, the signal being designated $TSCF_n$. This value is determined by performing a heat balance around the chain section 16. Initially, it can be assumed that the temperature of the dust carried back into the chain section 16 from the dust feeder 34 is a linear function of the intermediate gas temperature $FTIG_n$ in accordance with:

$$TID_n = K_{id} FTIG_n + K_{it}$$

Where TID_n is the temperature of the dust at the chain section,

$FTIG_n$ is the present desired intermediate gas temperature, K_{id} is a proportionality constant, and K_{it} is a dust temperature calculation constant.

If the feed rate sensor 50 generates a signal which is variable in accordance with the wet feed rate, then the signal on line 52 can be used directly. If, on the other hand, the dry feed rate is provided by sensor 50, the wet feed rate can be calculated by:

$$FEEDW_n = FEED_n / (1 - PMIF)$$

Where $FEEDW_n$ is the calculated wet feed rate,

$FEED_n$ is the dry feed rate, and

$PMIF$ is the per unit moisture in the feed as specified by the operator.

With these values, it is possible to analyze the heat inputs according to:

$$\text{Heat input (feed)} = FEEDW_n \times C_{p\text{-feed}} \times FTMP$$

Where $C_{p\text{-feed}}$ is the specific heat of the raw feed, and

$FTMP$ is the temperature of the slurry as entered by the operator.

The heat input from the dry gas coming into the chain section 16 is:

$$\text{Heat input (intermediate gas)} = EXIT_{n11} C_{p10} FTIG_n$$

Where $EXIT_{n11}$ is the previous value of exit gas rate,

C_{p10} is the specific heat of the gas passing into the chain section, and

$FTIG_n$ is the present value of intermediate gas temperature. The heat input from the dust is given by:

$$\text{Heat input (dust)} = TSPD_n TID_n C_{p\text{-dust}}$$

Where $TSPD_n$ is the measured dust rate,

TID_n is the calculated dust temperature, and

$C_{p\text{-dust}}$ is the specific heat for the dust.

This equation assumes that dust going into chain section 16 is equal to the dust feed rate; but it has been found that a circulating dust load exists which is greater than the dust input. The effect of this higher circulating load, which varies from kiln, can be factored into the equations by increasing K_{id} . Additional variations from actual conditions can be corrected somewhat by the use of a radiation constant K_{rad} in the equation representing the heat balance.

Heat losses occur as the dry gas and moisture exit, through evaporation and in the dust leaving the chains. The heat loss due to dry exit gas is:

$$\text{Heat loss (dry gas)} = EXIT_{n11} C_{p\text{-chgus}} FFET_n$$

Where $EXIT_{n11}$ is the previous value of the exit gas rate,

$C_{p\text{-chgus}}$ is the specific heat of the gas exiting the chain section, and

$FFET_n$ is the feed end temperature. The heat loss due to moisture from the feed that leaves as steam can be approximated by:

$$\text{Heat loss (steam)} = PMIF FEEDW_n FFET_n (1000)$$

Where $PMIF$ is the percent moisture content of the feed,

$FEEDW_{n11}$ is the previous value of the wet feed rate, and 1000 is the specific heat of one-half B.t.u. per pound $\times$ 2,000 pounds per ton.

The heat loss to vaporize water in the feed can be approximated by:

$$\text{Heatout (vaporization)} = PMIF FEEDW_n C_{p\text{-vap}}$$

Where $C_{p\text{-vap}}$ is the heat of vaporization of water plus a constant.

With these variables, it is possible to calculate the temperature of the heat lost in the dust leaving the chains which is represented by:

$$\text{Heat loss (dust)} = TSPD_n FFET_n C_{p\text{-dust}}$$

Finally, the heat loss of the feed leaving the chains is:

$$\text{Heat loss (Feed)} = FEED_n C_{p\text{-feed}} TSC_n$$

Where $FEED_n$ is the dry feed rate,

$C_{p\text{-feed}}$ is the specific heat for the dry feed and,

TSC_n represents a function of the temperature of dry feed leaving the chain section.

By balancing these equations, it is possible to obtain the temperature function TSC_n of the feed:

$$TSC_n = [K_{rad} + FEEDW_{n11} C_{p\text{-feed}} FTMP +$$

$$EXIT_{n11} (C_{p10} FTIG_n - C_{p\text{-chgus}} FFET_n) +$$

$$TSPD_n (TID - FFET_n) C_{p\text{-dust}} -$$

$$PMIF FEEDW_n (C_{p\text{-vap}} + 1000 FFET_n)] / (FEED_n C_{p\text{-feed}})$$

The instantaneous value for the feed temperature as it leaves the chain section is then converted and filtered to account for the thermal time constant of the chain system in accordance with:

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

Where $TSCF_n$ is the present filtered value of the feed temperature,

$TSCF_{n11}$ is the previous filtered value of the feed temperature,

K_{tsc} is a filter constant, and

TSC_n is the present instantaneous value of the feed temperature.

The output of the temperature computer, $TSCF_n$ is then applied to a trending filter 101 which responds to the input to generate an output signal $TSCT_n$ in accordance with:

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

Where

$TSCT_n$ is the present trended value of the feed temperature,

$TSCT_{n11}$ is the previous trended value of the feed temperature, and

K_{tr} is a trend constant for the filter.

The output of the filter 101 is applied to a positive input of a summing amplifier 102 while the input to the filter 101 is applied to a negative input of the summing amplifier 102. The output $DTSC_n$ from the summing amplifier 102 is:

$$DTSC_n = TSCT_n - TSCF_n$$

Where $DTSC_n$ is the change in the temperature of the feed.

This signal is then applied to filter 103 having an output signal $CHAMP_n$ generated in accordance with:

$$CHAMP_n = K_{ch} DTSC_n$$

Where $CHAMP_n$ is the calculated effect of the change on the total torque,

K_{ch} is a filter constant.

The functions of the temperature computer 100, the filter 101, the summing amplifier 102 and the filter 103 can all be accomplished conveniently by a digital computer.

Hence, as indicated earlier, the output of the summing amplifier 84 $DELAMP_n$ varies in accordance with:

$$DELAMP_n = EAMP_n + FBAMP_n + CHAMP_n$$

Output signal $DELAMP_n$ of summing amplifier 84 is applied to torque controller 85 along with signal $FUEL_{base}$ from filter 96 representing the filtered rate of fuel flow to mixing chamber 27 and, thus, the rate of input to kiln 10 at the time control of the kiln by control system 51 is commenced. Thereafter, $FUEL_{base}$ remains constant. Filter 96 receives on line 58 signal $FUEL_{scan}$ representing the output of fuel rate sensor 59 and filters and smooths signal $FUEL_{scan}$ in accordance with the following equation:

$$FFUEL_n = FFUEL_{n-1} + K_{fuel} (FUEL_{scan} - FFUEL_{n-1})$$

Where $FFUEL_n$ is the new filtered value,

$FFUEL_{n-1}$ is the last filtered value,

K_{fuel} is the filter constant, and

$FUEL_{scan}$ is the present output of sensor 59.

At the time automatic control of the kiln by control system 51 is initiated, filtering of $FUEL_{scan}$ in filter 96 is terminated and the value of $FFUEL_n$ at that time becomes $FUEL_{base}$ which thereafter remains constant. The function of filter 96 may conveniently be performed in a digital computer.

Torque controller 85, in response to signals $DELAMP_n$ and $FUEL_{base}$, generates signal $FUEL_{sp}$ representing the calculated fuel setpoint required to maintain or reach a stable operating condition in the kiln. Torque controller 85 calculates signal $FUEL_{sp}$ in accordance with the following equation:

$$FUEL_{sp} = FUEL_{base} + K_{fuel} DELAMP_n$$

Where $FUEL_{sp}$ is the calculated fuel rate setpoint,

$FUEL_{base}$ is the base fuel value represented by output signal $FFUEL_n$ of filter 96 at the time the kiln is placed under control of control system 51 and thereafter remains constant at this base value, and

K_{fuel} is the fuel/kiln amp proportionality constant.

Proportionality constant K_{fuel} is a function of the characteristics of the fuel and kiln being controlled. Torque controller 85 thus responds to the output of summing amplifier 84 represented by signal $DELAMP_n$ and to the value of the base fuel rate represented by the signal $FUEL_{base}$ to provide signal $FUEL_{sp}$ representing the desired fuel setpoint to maintain stable operation of the kiln or to regain stable operation after a disturbance. Fuel setpoint signal $FUEL_{sp}$ is applied to controller 68 on line 65, as shown in FIG. 1. The function of torque controller 85 may conveniently be performed in a digital computer.

Torque controller 85 is so named since changing the rate of flow of fuel to mixing chamber 27 changes the heat input to the kiln, eventually effecting the torque required from kiln drive motor 20 to rotate the kiln. For example, a decrease in the value of signal $FAMP_n$, indicating a shortening of the burning zone, results in an output signal from torque controller 85 increasing the fuel setpoint to cause the temperature in the kiln to increase with a resulting lengthening of the burning zone which will be reflected in an increased torque requirement and in an increase in the value of signal $FAMP_n$. Conversely, an increase in the value of signal $FAMP_n$ indicates a lengthening of the burning zone and the response of torque controller 85, acting under the influence of process model 83, is to decrease the fuel setpoint, reducing the heat input to the kiln which will eventually be reflected in the shortening of the burning zone and the reduction of the torque required to rotate the kiln, decreasing the value of signal $FAMP_n$.

If such a change in the kiln torque signal $FAMP_n$ were caused by changes in the chain section, however, then the signal $CHAMP_n$ is applied to the summing amplifier 84 to immediately increase the value of $DELAMP_n$ and thereby increase the fuel setpoint level $FUEL_{sp}$ to the torque controller 85. Such a disturbance would, without taking into account the

effect of the chains, actually result in a decrease of the fuel setpoint without this provision. Conversely, changes in the chains which would tend to decrease the torque and thereby cause a decrease in the fuel setpoint from the torque controller $FUEL_{sp}$, actually indicate that additional fuel is necessary so the signal from the torque controller 85 $FUEL_{sp}$ is increased.

This control arrangement thus tends to maintain a constant desired condition in the burning zone of the kiln, detecting changes in the condition of the burning zone by sensing drive motor torque and responding to such burning zone condition changes by varying the fuel rate setpoint in a direction which tends to return the burning zone to the desired condition. The effective changes in the chain section, which can significantly affect the sensed drive motor torque are thereby compensated. While the process model serves to prevent cycling of the kiln by introducing into each control arrangement the expected future response to each control action taken, the effective changes in the chain section are immediately inputted to the control. Thus, in response to a change in torque required to drive the kiln, indicating a change in the condition of the burning zone, a control action is taken in the form of an incremental change in fuel rate to compensate for burning zone disturbances only. Appreciably no effect occurs as a result of a change in the torque in the chains unless the total effect of the change of torque is caused by more than that. After an interval of time determined by the kiln characteristics, the effect of the incremental change in fuel rate is realized as a corrective change in the burning zone condition which again affects the torque required to rotate the kiln. The process model prevents the change in required kiln rotational torque due to the effects of a control action from again affecting the fuel rate setpoint, thus preventing cycling of the kiln. The process model prevents kiln cycling by remembering changes in kiln torque to be expected due to previous control actions and by introducing these expected changes in kiln drive torque into the control loop, so that only kiln drive motor torque changes due to kiln disturbances not directly caused by previous control actions or kiln drive torque changes caused by changes in the condition in the chains serve as a basis for further control action.

Fuel setpoint signal $FUEL_{sp}$ generated by torque controller 85 is transmitted to controller 68 on line 65 through logic switch 93, as illustrated in FIG. 2. Logic switch 93 normally connects the output of torque controller 85 to controller 68 but may serve to interrupt the controlling action or torque controller in response to the oxygen override logic 95.

The torque control loop comprising filters 80, 86, 101 and 103, check logic 81, summing amplifiers 82 and 84, process model 83, temperature computer 100 and torque controller 85 is capable of maintaining burning zone conditions within a desired range by adjustment of fuel rate setpoint. The torque control loop functions satisfactorily for variations in kiln torque within a predetermined range of values centered on the setpoint value. Heat imbalances reflected in torque variations which are caused by disturbances such as changes in secondary air temperature, changes in heat loss rate from the kiln due to change in ambient temperature, changes in coating thickness, changes in feed water content, changes in feed composition, etc. occur slowly and usually continuously, requiring almost constant correction of burning zone conditions which are well within the effective range of control of the torque control loop. The torque control loop will normally provide adequate control of the kiln burning zone for variations in kiln torque over a range of plus or minus 10 to 20 percent of the setpoint value and will compensate for changes in the chain amp torque.

FIG. 4 illustrates a flow chart of the operation of the control system of FIG. 2. Signal AMP_{scan} representing the armature current of kiln drive motor 20 and therefore the torque developed by motor 20 is made continuously available to the torque control loop. The signal is filtered periodically, e.g. every 5 seconds, to obtain a filtered value $FAMP_n$. Signal

FAMP_n is compared with the previous filtered value FAMP_{n-1} and if the two values differ by more than a predetermined amount, the previous value FAMP_{n-1} is saved and used in lieu of FAMP_n. Otherwise, the filtered value FAMP_n is compared to the kiln amp setpoint AMP_{sp} set by the operator and an error signal EAMP_n is generated representing the difference between FAMP_n and AMP_{sp}.

Several process related signals are available to temperature computer 100 and include EXIT_{n-1}, the gas rate setpoint, the feed rate signal FFEED_{n-1}, FID_n, the feed rate for the input dust, KSPD_n, the kiln speed, FFET_n, the feed end temperature and FTIG_n, the intermediate gas temperature. In response to these and operator inputs of the feed temperature, TMPF and the percent moisture in the feed, TMIF, the temperature computer produces a filtered value TSCF_n representing the temperature of the feed leaving the chain section. This is then filtered and summed to produce an output signal which represents the change in the temperature of the feed DTSC_n which then indicates the effect of the chain section by the signal CHAMP_n.

Feedback signal FBAMP_n provided by the process model, amp error signal EAMP_n and the chain torque signal CHAMP_n are employed to generate signal DELAMP_n. Torque controller of the torque control loop utilizes signal DELAMP_n and the signal FUEL_{base} representing the base fuel rate to calculating new fuel setpoint FUEL_{sp}.

Concurrent with the above-described operations in the torque control loop, the following operations occur in the temperature control loop. Signal FET_{scan} representing the temperature of the exit gas from the kiln is made available to the control system and the signal is filtered periodically, for example every 3 minutes to obtain filtered value FFET_n. Signal FFET_n is compared with the previous filtered value represented by signal FFET_{n-1} and if the two values differ by a predetermined amount, an alarm timeout occurs and previous value FFET_{n-1} is saved and used in lieu of FFET_n. Otherwise, filtered value FFET_n is compared with the gas temperature setpoint FET_{sp} provided by the operator and any difference between the filtered temperature value and the temperature setpoint is represented by gas temperature error signal EFET_n. The temperature controller in the temperature control loop utilizes the error signal EFET_n to calculate the new exit gas rate setpoint EXIT_n. If the exit gas rate setpoint EXIT_n is less than or equal to maximum fan capacity represented by signal EXIT_{max}, that it is used directly in a comparison with another calculated exit gas rate setpoint described herewith. Should the signal EXIT_n represent a setpoint having a greater capacity than the fan is capable of providing, the signal EXIT_n is set equal to the signal EXIT_{max} and used in the comparison.

Prior to utilizing the newly calculated feed rate and exit gas rate setpoint FUEL_{sp} and EXIT_n respectively, the oxygen override logic determines the present exit gas rate and calculates the predicted oxygen content O2_{n+1} of the exit gas based on new fuel rate and exit gas rate setpoints and on the rate of feed of raw materials in the kiln. If the predicted oxygen content is at least equal to a predetermined safe minimum oxygen content, the new fuel rate and exit gas rate setpoints determined in the torque controller and temperature control loops are employed to control the kiln operation. If, however, the predicted oxygen content is less than the predetermined safe minimum, the new exit gas rate setpoint OEXIT_n is calculated based on the required minimum safe oxygen content. If the recalculated exit gas rate setpoint OEXIT_n is not greater than the capacity of the EXIT_n and EXIT_{max}, the recalculated exit gas rate is used to control kiln operation in conjunction with the new fuel rate setpoint determined in the torque control loop. If the recalculated exit gas rate OEXIT_n required an exit gas rate greater than the capacity EXIT_{max} of the exit fan, the maximum exit gas rate setpoint EXIT_{max} is employed and a new fuel rate setpoint OFUEL_{sp} is calculated by the oxygen override logic. The maximum exit gas rate setpoint EXIT_{max} and the new fuel rate setpoint OFUEL_{sp} as determined by the oxygen override logic are then employed to control kiln operation.

FIG. 5 is a signal diagram graphically illustrating the operation of the torque control loop in the control system of FIG. 2. During the initial two portions, the system is shown as controlling disturbances within a normal control range. The illustration of normal the control operation is described in detail in the aforementioned U.S. patent. At the end of the second period shown in FIG. 5, the filtered value representing the torque FAMP_n increases above the setpoint value. As a result, the error signal EAMP_n goes negative thereby indicating that fuel should be increased. However, this change in torque is due primarily to a change in the conditions within the chain section and the signal CHAMP also increases.

The effect of utilizing signal CHAMP_n on the process can be understood best by assuming that the percent moisture in the feed, PMIF, increases to a new value. When the wet feed contacts the chain section, it causes the torque required to turn the kiln to increase during the transport time of the new material through the chain section. This increases in torque is caused because with the previous conditions in the kiln, a longer drying period initially result so that the drying zone within the chain section increases. Simultaneously with the increase in the torque represented by FAMP_n, the amp error signal EAMP_n decreases to a new value. Shortly after the new feed material enters the chain section, it will also affect the feed end temperature FFET_n which decreases to a new value causing, through the temperature control loop an increase in the gas rate through the kiln EXIT_n. Simultaneously with the increase in motor torque, the signal CHAMP_n representing the calculated effect of the new material in the chain section on motor torque will increase. Its increase normally will equal the decrease in the amp error signal EAMP_n. Therefore, with the feedback signal from the process model FBAMP_n remaining constant, the signal DELAMP_n and the fuel setpoint FUEL_{sp} remains constant. If the effect of the increased torque in the chain sections were not utilized, the torque control loop would respond by decreasing the fuel setpoint, which is exactly the wrong control response. It will also be obvious from the discussion hereinafter, that under this condition with a new feed input, the fuel setpoint FUEL_{sp} will eventually have to be increased. It is possible, therefore, to modify the chain section signal CHAMP_n to more than equal in magnitude the amp error signal EAMP_n and thereby force the fuel setpoint FUEL_{sp} to be increased.

During the time the new material passes from the chains to the burning zone, the motor torque, amp error signal EAMP_n, and chain section signal CHAMP_n will decrease slightly as a result of the action of changing the exit rate EXIT_n and thereby influencing the feed end temperature FFET_n. However, during this time, the feedback signal FBAMP_n, the signal DELAMP_n and the fuel setpoint FUEL_{sp} remain constant. The new material, however, will have a lower temperature than the previous material so as it reaches the burning zone, the motor torque will decrease substantially. This decrease in motor torque is then immediately reflected as a decrease in the magnitude of the error EAMP_n. However, the torque due to the mixture in the chains will not be altered significantly so the signal DELAMP_n increases thereby causing the fuel setpoint signal FUEL_{sp} to increase to a new value. Immediately after this initial change in the fuel setpoint, the motor torque will resume a decrease at approximately the rate caused prior to the fuel setpoint change along with the amp error signal EAMP_n and the chain section signal CHAMP_n so that the fuel setpoint signal FUEL_{sp} still remains constant at the new value. At some point after the fuel setpoint is changed, the feed end temperature FET_n will reach the setpoint and the exit gas rate EXIT_n will stabilize. Shortly thereafter, the drying through the chain section will also stabilize and so the chain section signal CHAMP_n will return to its original value. When the chain section stabilizes, the torque required to turn the kiln stabilizes as does the error until the torque loop delay period is completed. When this happens, the motor torque will increase thereby decreasing the error signal and the feedback signal FBAMP_n will increase as a result of the initial increase so that DELAMP_n and the fuel setpoint FUEL_{sp} remain constant at their

new values. At this point, the kiln is stabilized and operating at a new set of conditions for the new moisture content in the feed material.

In the description, the desirability of employing a digital computer to perform the functions of the torque control apparatus, temperature control apparatus, override logic and chain section apparatus has been indicated. In such an implementation of the method and apparatus of the invention, analog-to-digital and digital-to-analog converters would be employed to convert analog signals into digital quantities and digital representation into analog quantities, as required.

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, and otherwise, which are particularly adapted for specific environments and operating requirements without departing from those principles. For example, other measurements might be made in order to determine the temperature of the feed as it exits the chain section for purposes of compensating the torque control loop; other parameters or combinations of parameters described in conjunction with the temperature computer for calculating the feed temperature as it leaves the chain section can also be utilized. Certain kilns may be operated such that the material exiting the chain section is not completely dry. In such a situation, the same parameters can be utilized to perform a heat balance. However, the temperature of feeding exiting the chains would be essentially constant at the boiling point of water. The variable would be a signal representing the percent moisture in the exiting feed which would be condition in the same manner as the feed temperature signal to obtain the effect on torque of the chain section. It will also be obvious that the specific implementations of the control system shown in FIGS. 2 and 4 may also be altered without departing from the principles of the instant 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 wet kiln control system including chain means for contacting wet feed entering the kiln and driving moisture therefrom, drive means for rotating the kiln at a constant speed, heating means for causing a material transformation in the kiln at a burning zone, sensing means responsive to total torque developed by said drive means to rotate the kiln for providing a corresponding output, the total torque representing, in part, conditions in the chain means, means for determining feed temperature as the feed leaves the chain means, means responsive to said feed temperature determining means for providing an output variable in accordance with torque changes resulting from conditions in the chain means and control means including means adapted to be responsive to said torque sensing means and said means for indicating chain means torque changes for controlling the heat input to the kiln to maintain the remainder of the total torque constant.

2. A rotary cement wet kiln control system as recited in claim 1 wherein said feed temperature determining means comprises means for measuring conditions at the chain means and means for performing a heat balance for the chain means to thereby indicate the temperature of feed leaving the chains.

3. A rotary cement wet kiln control system as recited in claim 2 wherein said means for measuring conditions at the chain means comprises second and third sensing means for measuring gas temperature entering the chain means and leaving the chain means, respectively, fourth sensing means for measuring the rate of material feed into the kiln, fifth sensing

means for measuring the rate dust is introduced into the kiln and sixth sensing means for measuring the rate of flow gas through the kiln and wherein said feed temperature determining means additionally comprises means responsive to said second through sixth sensing means for determining the feed temperature.

4. A rotary cement wet kiln as recited in claim 3 wherein said control system additionally comprises means for storing information concerning past control actions initiated by said control means for inhibiting variations of heat input to the kiln by said control means in response to variations in the torque developed by the drive means directly caused by such past control actions, said information storage means also being responsive to said means for indicating chain means torque changes to directly and immediately inhibit variations of heat input in response to variations in the torque developed by the drive means.

5. A rotary cement wet kiln as recited in claim 4 wherein said means for indicating chain means torque includes means responsive to successive feed temperatures from said feed temperature determining means for generating a trended feed temperature, means responsive to said feed temperature determining means and said trended feed temperature generating means for generating a feed temperature error and filter means responsive to said feed temperature error generating means for generating the chain means torque indication.

6. A method for controlling a rotary cement wet kiln including chain means for contacting wet feed entering the kiln and driving moisture therefrom, drive means for rotating the kiln at a constant speed and heating means for causing a material transformation in the kiln at a burning zone including the steps of measuring the total torque developed by the drive means to rotate the kiln, said total torque measurement representing, in part, conditions in the chain means, determining the temperature of feed leaving the chain means, generating a signal variable in accordance with torque changes resulting from conditions in the chain means in response to said determination of feed temperature and controlling the heat input to the kiln so as to maintain the total torque minus the chain means torque at a constant value.

7. A method for controlling a rotary cement wet kiln as recited in claim 6 wherein said determination of feed temperature is made by measuring conditions at the chain means and performing a heat balance for the chain means based upon those measured conditions to thereby obtain the feed temperature.

8. A method for controlling a rotary cement wet kiln as recited in claim 7 wherein said chain means condition measurement includes measuring the gas temperature entering the chain means, the temperature of gas leaving the chain means, the rate of material fed into the kiln, the rate at which dust is introduced into the kiln, and in response to said measurements determining the feed temperature.

9. A method for controlling a rotary cement kiln as recited in claim 8 additionally comprising the step of storing information concerning past control actions initiated by said control method for inhibiting variations of heat input to the kiln by said control method in response to said measured torque variations developed by the drive means directly caused by past actions of said control method, said information storage step additionally including step of directly and immediately inhibiting variations of input in response to variations of the torque developed by the drive means in response to said chain means torque determination.

10. A method for controlling a rotary cement wet kiln as recited in claim 9 wherein said determination of chain means torque includes the steps of generating a trended feed temperature based on said feed temperature determination, generating an error function based on said feed temperature determination and said trended feed temperature determination and filtering the error from said error generation to obtain the chain means torque indication.