Design and construction of a rotary kiln simulator for use in studying the incineration of hazardous waste

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(Received 28 December 1988; accepted for publication 8 April 1989)

Rotary kiln systems are widely used in industrial applications to transfer energy from high temperature flames to irregular solids. Recently these systems have been shown to be suitable for the incineration of hazardous solid waste materials and the thermal treatment of contaminated soils. Destruction and removal efficiencies in excess of 99.99% have been reported for hazardous species, but the rate controlling steps of the incineration process are not well understood. This article describes the design, construction, and operation of a laboratory scale simulator which was developed to investigate the fundamentals of hazardous incineration in a rotary kiln environment. This 2 ft × 2 ft refractory-lined kiln allows time-resolved characterization of contaminant evolution and destruction. Continuous thermal and exhaust concentration measurements are used to characterize the fate of the solid charge as a function of residence time within the kiln. Overall destruction efficiency can be measured by subsequent analysis of the solid phase. The initial performance of this facility has been demonstrated by studying the combustion of waste zirconium metal and by characterizing the thermal clean up of solid sorbent contaminated with toluene. The rotary kiln simulator has been shown suitable for investigation of parameters such as amount of charge, contaminate loading, rotation speed, temperature, excess oxygen, and particle size.

INTRODUCTION

Rotary kilns have been used extensively in the cement industry to calcine limestone. In the past few years, the technology has been viewed as a possible option for the incineration of hazardous waste materials, especially for the disposal of solid wastes and the cleanup of contaminated soils and transformers.[1] The technology is promising for incineration of hazardous waste for several reasons. First, it is flexible,[2] i.e., many different types of solids and liquids can be fed into a single facility. Second, in some cases, incineration greatly reduces the volume of solid waste streams. Finally, there are many existing facilities that could be retrofitted for use in hazardous waste incineration. The kiln is used to drive the hazardous compounds into the gas phase, and an afterburner is used to destroy the gaseous compounds by exposing them to the required time/temperature history.

Incineration success is measured by the destruction and removal efficiency (DRE), for each toxic component, which is defined as

$$\mathrm{DRE} = (\mathrm{Mass}_{\mathrm{in}} - \mathrm{Mass}_{\mathrm{out}})/\mathrm{Mass}_{\mathrm{in}} \times 100\% . \qquad (1)$$

Generally, a DRE of at least 99.99% is required by the EPA. Facilities have been determined to be successful as long as these criteria are been satisfied. Whether a smaller or lower temperature facility could have produced the same results is generally not known, because the tests are often done on already existing facilities. The ambiguous nature of DRE also prevents success from being accurately measured; 99.99% DRE of a component with a high initial concentration in a waste is considerably easier to measure accurately than 99.99% DRE of a compound initially present in small amounts. Because of the rising costs and legal liabilities associated with hazardous waste disposal, there is now considerable interest in optimizing the disposal options. In order to mitigate the costs involved in hazardous waste incineration, it is necessary to define the temporal and thermal requirement for a particular application by testing the specific waste stream to establish its suitability for rotary kiln incineration.

Each waste stream has its own particular properties and thus its own particular problems associated with incineration.[3] Small-scale testing is desirable to determine the feasibility of incinerating a particular waste stream in a rotary kiln. Such testing can aid in the design and sizing of the kiln, in defining the optimum operating conditions, and determining whether or not rotary kiln incineration is appropriate for that particular waste stream.

I. BACKGROUND

A typical rotary kiln incineration facility consists of two elements: the rotary kiln and the afterburner, as shown in Fig. 1. The rotary kiln is a long, hollow, firebrick-lined cylinder mounted at a slight inclination from the horizontal. The kiln typically rotates at speeds of approximately 1 rpm. Depending on the rotation and the inclination of the kiln, the solids move down the length of the kiln in a time interval on the order of hours. The kiln contains a burner which is fired axially either in the same direction as the solids flow (co-flow) or counter to the solids flow (counter-flow). The afterburner is usually a refractory-lined chamber with a burner, designed to maintain a temperature of 2000 °F (1100 °C) for a minimum time of 2 s; this time/temperature combination has been found to adequately destroy even the more stable hazardous species, such as PCBs or dioxins.[4]

The basic concept behind the rotary kiln simulator[5,6] is that by studying the fate of a control volume of solids in the

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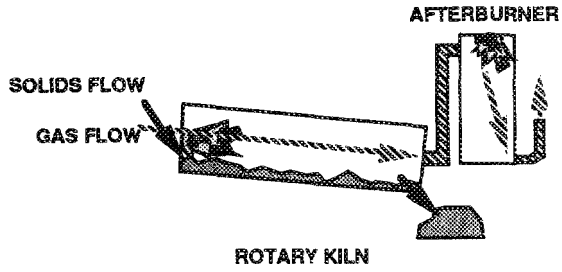

FIG. 1. Diagram of a typical rotary kiln incinerator.

rotary kiln simulator, it is possible to predict what would happen in a full-scale rotary kiln. In an actual kiln an element of charge progressively moves from one end of the kiln to the other as illustrated by the dotted lines in Fig. 2. In the simulator, the control volume is studied in a batch mode; the charge rotates but does not move axially. Time is exchanged for distance as the independent variable. A movable burner can be positioned to vary the amount of flame that is directly exposed to the bed. A schematic of this concept is also shown in Fig. 2. By measuring the gas phase component concentrations and other parameters such as temperature as a function of time, it is possible to calculate the fate of a particular volume of feed. Using the molar gas flow rate through the simulator, the instantaneous rates of desorption and/or reaction of various components can be determined, and by integration of the resulting traces, the total amount of material released from the solid phase can be calculated. Periodic solid phase grab samples can be used to verify the results.

The results from the simulator experiments can be used to predict the performance of a full-scale facility by using mathematical modeling. A mathematical model is first used to extract key empirical kinetic and diffusion rate constants based on the results of burning the sample in the simulator at various conditions. Subsequently, a mathematical model describing the incineration process in a full-scale continuous rotary kiln is used to evaluate the fate of the waste when it is fed into a real kiln. Thus a simulator experiment can be used to obtain information about full-scale performance without the expense and time delays involved in testing in a large facility. This article describes the details of the rotary kiln simulator designed and fabricated by the authors at the University of Utah. It also summarizes the associated analytical measurement equipment, data-acquisition system, and experimental procedures.

II. EXPERIMENTAL FACILITY

A. General description

The University of Utah Rotary Kiln Simulator is a bench scale, batch mode rotary kiln as shown in Figs. 3 and 4. The kiln has a cylindrical inner core which is 2 ft (0.6096 m) long $\times$ 2 ft in diameter, and is refractory lined. A movable burner assembly is attached at one end, with both the burner section and the main section rotating. A stationary exhaust section is positioned at the other end. The gap between the main (rotating) sections and the stationary exhaust section is bridged by a rotary seal based on a design by IT Corporation. The burner is equipped with a carbon-faced mechanical seal designed by the Anchor Packing Co. A slip collar on this seal enables the burner to be manually pulled back into a recess in the burner section of the kiln. UV peepers are mounted on the exhaust section of the kiln, facing toward the flame along the kiln center line. The kiln exhaust flue leads to an afterburner.

There are two windows in the kiln. The first window is along the center line of the kiln, at the back end of the exhaust section. This window allows axial viewing of the flame. The second window is on the airlock attachment that replaces the loading chute after the kiln is charged. This window provides a direct view of the bed, and allows bed and wall temperature measurements via optical pyrometry.

B. Kiln shell

The shell of the kiln was rolled out of 3/16-in (0.476 cm) mild steel plate to the specifications shown in Fig. 5. Steel tires were rolled out of 1/2-in. (1.27 cm) mild steel and welded to the shell. Stainless-steel refractory anchors were welded on a 5-in. (12.7 cm) pitch inside the shell. Cooling coils were cast into the outside layer of refractory at the shell, and at the interface between the middle and the outside layers. The kiln is mounted on a frame made from 1 $\frac{5}{8}$-in. (4.128 cm) channel and driven by a 1-hp dc motor using a 200:1

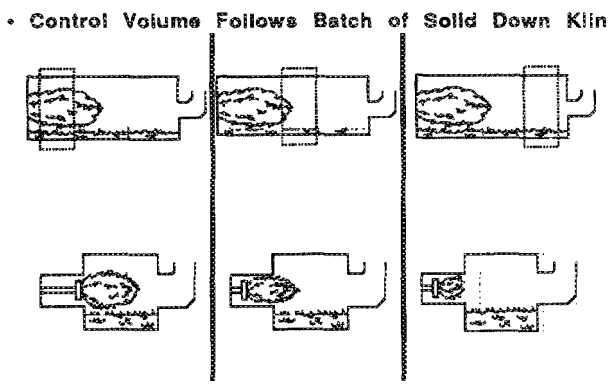

FIG. 2. Rotary kiln simulator concept.

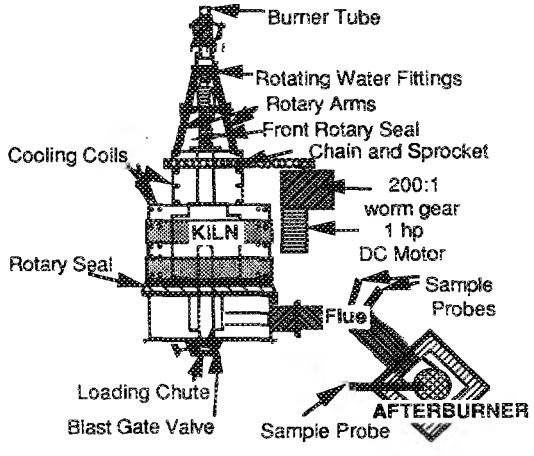

FIG. 3. Rotary kiln simulator—top view.

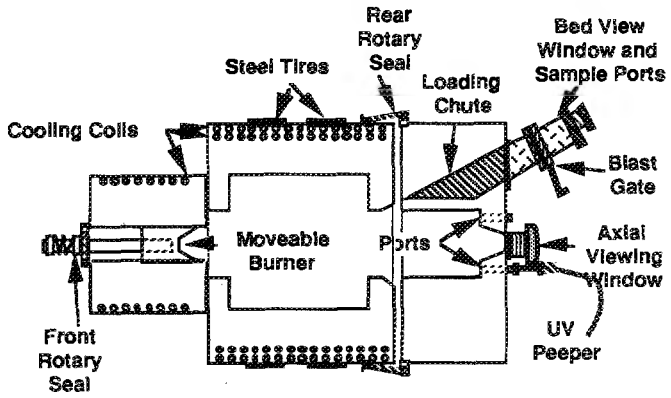

FIG. 4. Rotary kiln simulator—side view.

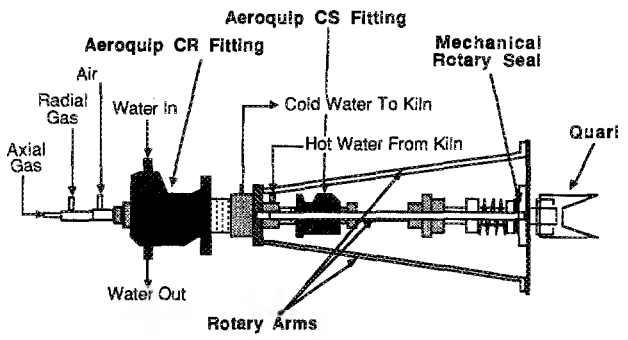

FIG. 6. Rotary kiln simulator moveable burner.

worm reduction gear. The kiln drive surface allows rotational speeds between 0.2 and 2.0 rpm. Experimental residence times vary from 30 min to 8 h.

The kiln rotates on heavy duty casters. The sprocket was welded on the burner section and the motor and worm gear assembly was bolted to the frame. The walls are composed of three 3-in. (7.62 cm) layers of refractory: A.P. Green MC-30 dense castable, and B&W Kaolite 25 and Kaolite 22 insulating castables, with water lines cast in the outside two layers. The refractory walls of the core of the kiln are rated at 3000 °F (1650 °C). The refractory lining in the flue is rated at 2200 °F (1370 °C).

C. Kiln burner

The movable burner shown in Fig. 6 is equipped with variable axial and radial gas. Air flows through the outside of a 2-in-diam annular region, and the natural gas flows through another annulus, inside the first, with 3/4-in. (1.9 cm) o.d. and 1/2-in. (1.27 cm) i.d. The radial gas flows through six 11/64 in. holes in the 3/4-in. tube drilled normal to the air flow at a 60° pitch. The axial gas flows through the 1/2-in. tube. The burner has detachable swirl vanes[7] allowing swirl numbers to vary from 0 to 1. With this arrangement, flame types ranging from short, intense highly recirculating flames to long axial flames can be achieved. The burner assembly can be pulled back 10 in. (25.4 cm) into the burner section to vary the radiant heat to the bed. Average gas temperatures measured in the core are normally in the range of 1400–3000 °F (750–1650 °C).

The kiln is designed to operate at a maximum firing rate of 250 000 Btu/h (2.635×10^5 kJ/h) using natural gas as fuel. The burner, rotary water fittings, and burner section endpiece are installed as a unit, with the help of a floor jack and specially designed cradle. The rotary arms are bolted to the burner section of the kiln and slipped through the slots on the rotary fitting assembly. Ignition is achieved by directly sparking the main burner with an ignitor inserted axially through a port on the opposite end of the kiln.

D. Kiln cooling coils

The kiln is equipped with two separate sets of cooling coils: one set at the outside shell and one set 3 in. (7.62 cm) into the refractory lining. The coils can be run separately, together, or not at all, and thus different wall heat removal

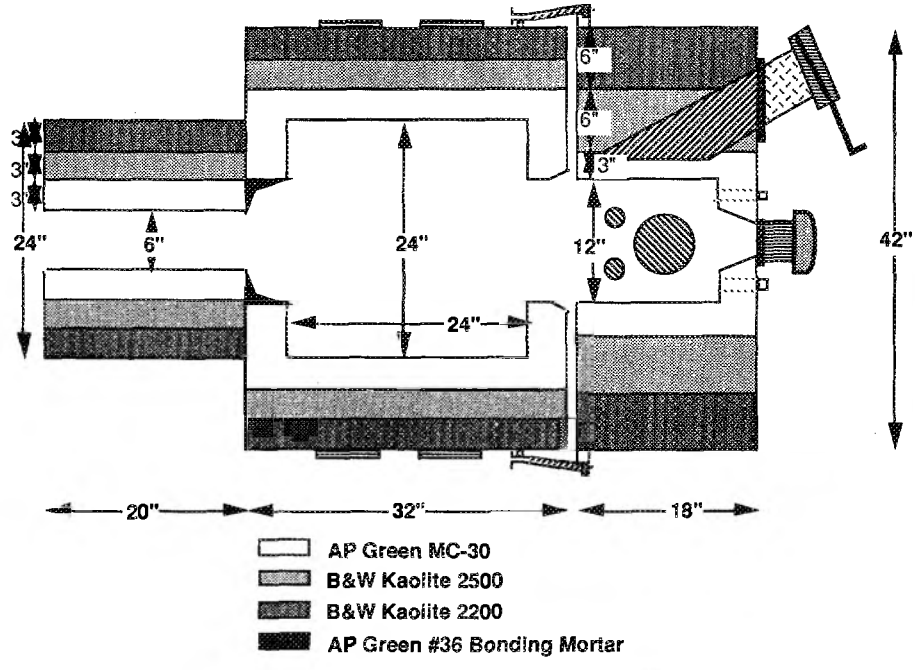

FIG. 5. Rotary kiln simulator dimensions.

rates are obtainable. The cooling water is transported through a rotating fitting assembly as shown in Fig. 7. Two Aeroquip rotary fittings, type CR and CS, are mounted opposite each other, and are connected by galvanized pipe fittings. The 2-in. burner tube carrying the gas and air runs up the center of the Aeroquip fittings. The back ferrules in the Swagelok® male connectors at the ends of the rotary fitting assembly have been replaced with rubber O-Rings to ensure quick disassembly. Safety is not sacrificed, however, because of the low-pressure nature of the water supply.

E. Charge introduction and removal

Charge introduction and removal is through the stationary exhaust section. A retractable chute 6 in. (15.24 cm) in diameter and 5 ft (152.4 cm) long, is lowered through the kiln airlock. After charging the kiln, the loading chute is removed and the airlock is closed. A 6 in. (15.24 cm) diameter assembly containing a 3-in. (7.62 cm) quartz window and three sample ports, is then attached to the airlock of the kiln. This window allows direct viewing of the bed and bed temperature measurements by optical pyrometry. Probes can be inserted through the sample ports to measure gas concentrations and temperatures in the core of the kiln.

While the kiln is still hot, the burned charge is removed by the charge removal system illustrated in Fig. 8, utilizing a wet/dry industrial vacuum and a separate stainless-steel bin. Ice is used as the heat exchange medium to cool the hot gases prior to entering the vacuum cleaner. The charge removal bin is continuously purged with argon or nitrogen to quench any possible reactions in the bin. This arrangement allows evacuation of the kiln while hot, without resorting to a refractory plug in the wall, which greatly reduces the structural integrity of the refractory.

F. Sampling procedure

Gas concentration and temperature measurements are made with the exhuast gas sampling system[8] shown in Fig. 9, utilizing water-jacketed gas sample probes and suction pyrometers.[9] Solid grab samples can also be withdrawn from the bed. Gas samples are passed through a refrigerated water trap and glass wool filters to remove any water and particulates from the sample stream. All lines are TFE or 304 stainless steel. Measurements are made while the kiln is rotating.

Several samples are taken during an experimental run. A suction pyrometer is used to measure the gas temperature just prior to the kiln exit. A second suction pyrometer, inserted through the airlock, can be used to measure the temperature inside the core of the kiln. The gas sample probe is placed near the flue entrance to withdraw samples for O_2, CO, CO_2, NO_x analysis. Table I lists the gas analysis instruments used in this facility. A similar probe can be inserted into the kiln through the airlock. This probe would be used to measure gas concentrations at various points in the core of the kiln. Finally, the solids sample probe can be lowered into the kiln through the airlock to allow grab sampling of the bed solids at various points during the run.

G. Data-acquisition system

The experimental data are acquired and analyzed using an Apple Macintosh microcomputer based system, shown in

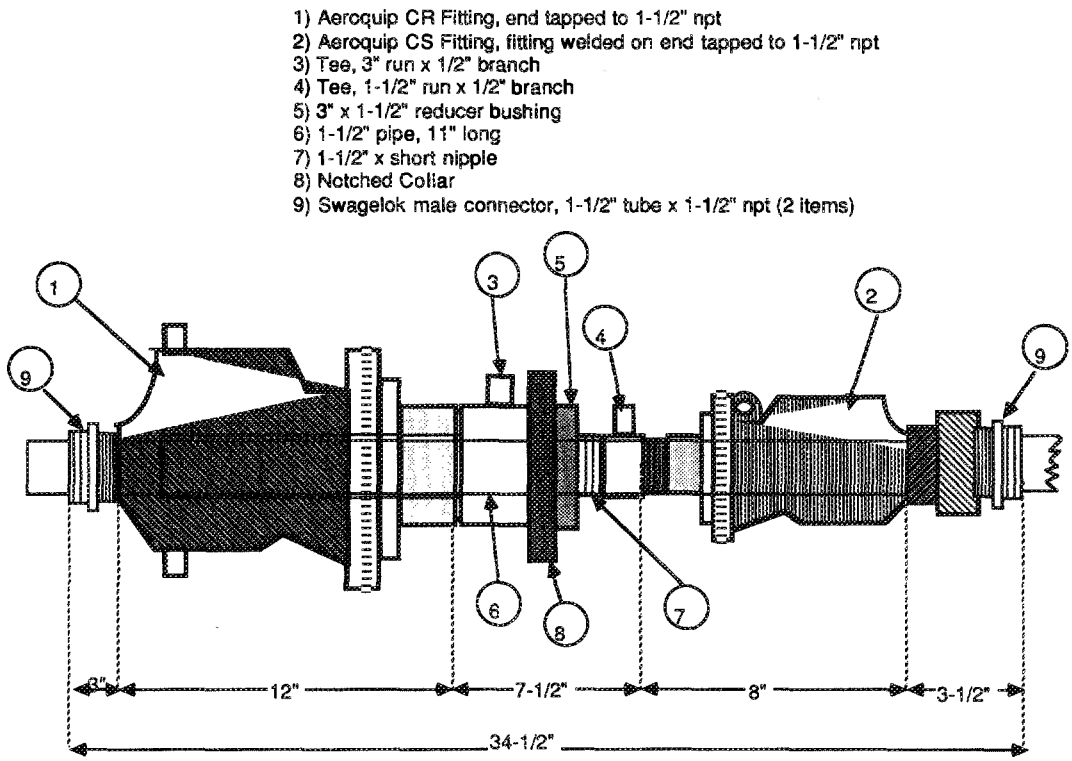

FIG. 7. Rotary water fitting assembly.

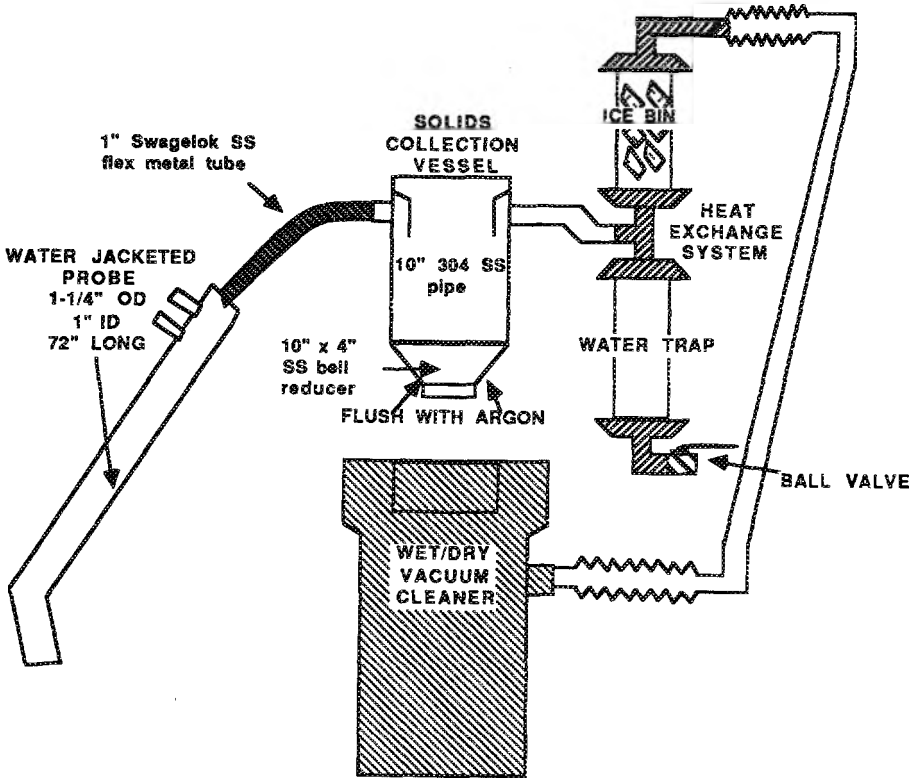

FIG. 8. Charge removal system.

Fig. 10. The system used is the Macquisition® software package obtained from IDAC in Amherst, NH. This system uses a Taurus One/05A data-acquisition peripheral to convert the signals from the gas analyzers and thermocouples into voltages. The data-acquisition parameters, i.e., number of samples, frequency of sampling, etc., are defined using a Microsoft Multiplan® or Excel® spreadsheet template. The raw data are outputted to a blank spreadsheet, and the data are reduced and analyzed by a user-defined spreadsheet. The resultant sets of data can then be copied and pasted into a plotting diagram such as Cricket Graph®. Large amounts of data can be examined, manipulated, and plotted without cumbersome and time-consuming hand copying and graphing.

H. Safety system

The rotary kiln simulator is monitored by a flame safety interlock system[10] which cuts off the natural gas under a variety of abortive conditions, such as low air pressure, low water pressure, power interrupts, and low UV emissions from the flame. The flame safety interlock system is shown in Fig. 11. The safety system reduces the danger of possible explosions due to buildup of natural gas in the reacting chamber or flue. There is also an inert purge system connected to the main burner air which allows the entire kiln to be filled with nitrogen or argon in the event of a runaway reaction inside the core of the kiln. A manually activated three-way ball valve switches the flow from air to inert gas. Due to the small size of the batch charges fed to the kiln, and the fact that any organic emissions leaving the afterburner are of such a small quantity and short duration, no additional air pollution control equipment is required.

III. EXPERIMENTAL PROCEDURES

The rotary kiln simulator is relatively simple to prepare for experiments. Three procedures must be performed in order to take data: preparation of the kiln, preparation of the gas analysis system, and preparation of the data-acquisition system.

The kiln is prepared by setting the gas and air rotameters to the required settings, and allowing the kiln to come to steady state overnight while keeping the internal kiln pressure slightly positive [+ 0.05 in. H_2O (0.0125 kPa)]. By keeping the kiln pressure greater than atmospheric, air leaks cannot cool the kiln below the steady-state temperature.

The gas analysis instruments are prepared by zeroing with nitrogen and calibrating with a primary standard quality gas mixture of known concentration. The sample lines are blown out with air to remove any water, ice, and particulates that have accumulated. New glass wool filters are installed into the filter tubes.

The data-acquisition system is prepared by setting up application templates in the spreadsheet program. These templates tell the data-acquisition system how many channels to use, how many samples to take, and the frequency of sampling. Separate application templates are used for the baseline determination with an empty kiln, generally a 5-min run with the kiln turning, and the actual run, usually consisting of 6 h of sampling at 1-min intervals.

After the systems are prepared, and the baseline template is executed, the kiln is set to slightly negative pressure (for safety reasons) and a preweighed charge of known composition is introduced to the reaction chamber in the rotary kiln, while the kiln is turning. Once the charge has been fed, the kiln is returned to slightly positive pressure and the sam-

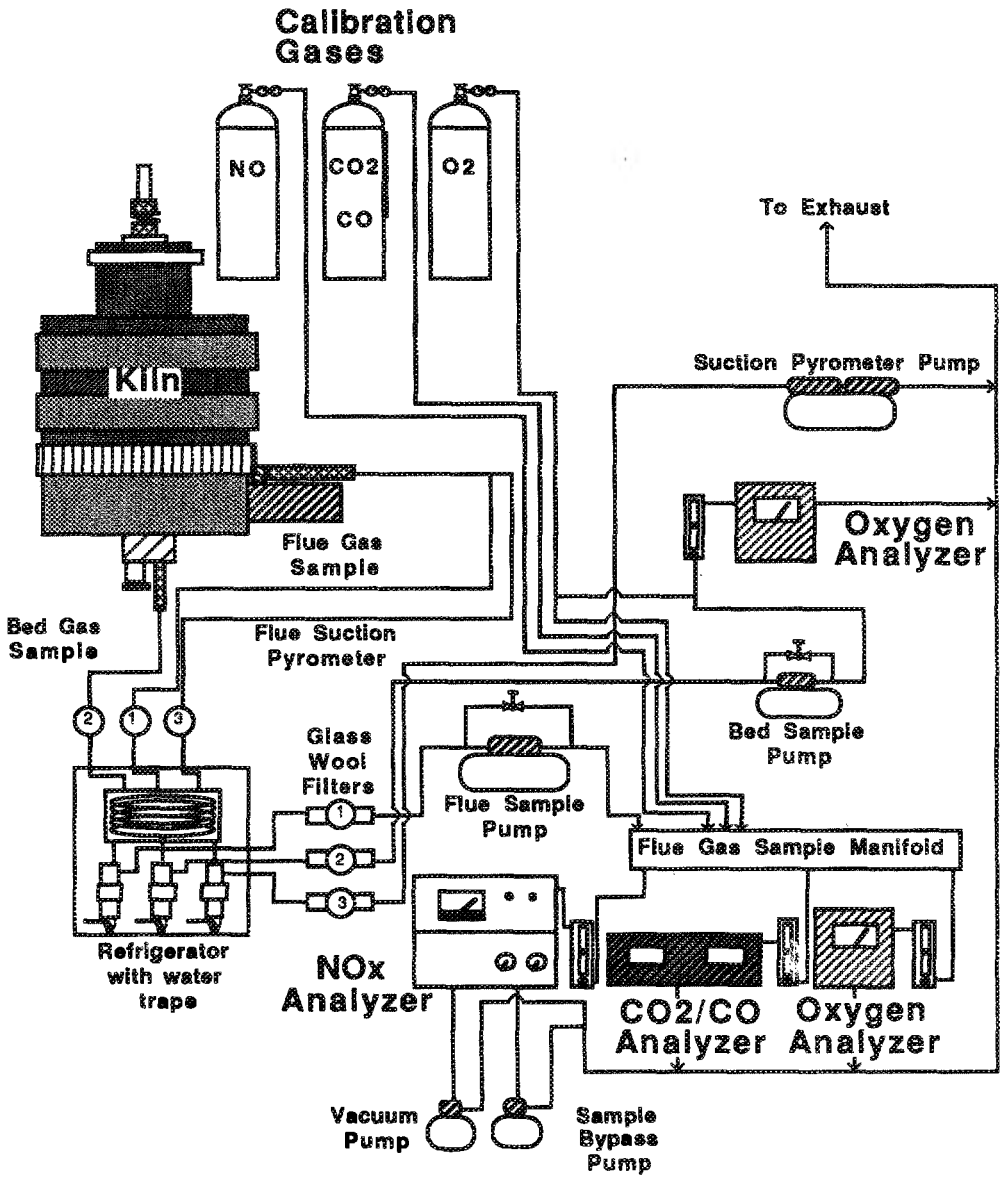

FIG. 9. Kiln simulator sample system.

pling begins. Sampling continues throughout the duration of the run as defined by the application template.

IV. DATA ANALYSIS

The data are recorded into templates that are readable by any spreadsheet that can read files in the SYLK format, such as Multiplan or Excel. The data are placed in rows and columns as defined in the application template. Gas analyzer data are in units defined by the 12 bit resolution of the Taurus data-acquisition peripheral, with values ranging from 0 to 2047. Thermocouple data are in units of 0.1 °C, and no ice point calculations are necessary. The instrument readings are converted into gas concentrations by the formula:

$$\text{Gas Concentration} = \frac{\text{Cal Gas Concentration} \times \text{Taurus Reading}}{\text{Taurus Reading @ Cal Gas Concentration}}. \quad (2)$$

The data, already in spreadsheet form, can be reduced, manipulated, and integrated[11] very easily. By calculating the gas flow rate through the kiln, based on the air and gas rotameter settings, and using the baseline (empty kiln) gas concentrations, it is possible to calculate the rate at which the bed reacts and this value, when integrated, gives the total amount of material reacted. For example, when burning zirconium waste sponge in the kiln, the burning rate of the zirconium can be calculated:

$$R_{\text{burn}} = 100\% \times \frac{(O_{\text{base}} - O_{@\ \text{time}}) \times N_{O_2} \times M_{Zr}}{O_{\text{base}} \times m_{\text{charge}}}, \quad (3)$$

where O_{base} is the concentration of O_2 at the baseline conditions, $O_{@\ \text{time}}$ is the concentration of O_2 at the time that the burning rate is being calculated, N_{O_2} is the molar flow rate of oxygen through the kiln, as calculated by the material balance in lb mol/h, M_{Zr} is the molecular weight of zirconium, which is 91.22, and m_{charge} is the initial mass of the charge introduced into the kiln. This equation gives the burning rate in units of (% of initial charge/h). This equation can then be integrated using a numerical integration technique such as the trapezoidal rule, to give the fractional conversion:

TABLE I. Analytical instruments.

Instrument	Range	Analog voltage output
Anarad Model AR-600 Dual gas analyzer	CO_2 ranges 0–6% 0%–30%	0–100 mV
CO/CO_2 (NDIR)	CO ranges 0%–1% 0%–10%	0–100 mV
Beckman Model 766 Paramagnetic Oxygen analyzer	Four range selections 0%–5% 0%–10% 0%–25% 0%–50%	0–100 mV
ThermoElectric Series 10 Chemiluminescent NO NO_2 NO_x	Eight range selections 0–2.5 ppm 0–10 ppm 0–25 ppm 0–100 ppm 0–150 ppm 0–1000 ppm 0–2500 ppm 0–10 000 ppm	0–10 mV

$$X_{Zr} = \sum_{i=1}^{n} 0.5(R_{burn,i} + R_{burn,i-1})\Delta t , \qquad (4)$$

where X_{Zr} is the fractional conversion to ZrO_2, $R_{burn,i}$ is the burning rate at time i, (or $i-1$) and Δt is the time interval between samples.

V. RESULTS

The rotary kiln simulator is a reliable facility able to generate reproducible data. The multiple windows and sample ports allow many different samples, both physical and visual (e.g., videotape) to be taken to fully study the bed of a rotary kiln as time progresses. The microcomputer-based data-acquisition system makes the acquisition, storage, and analysis of large amounts of data possible.

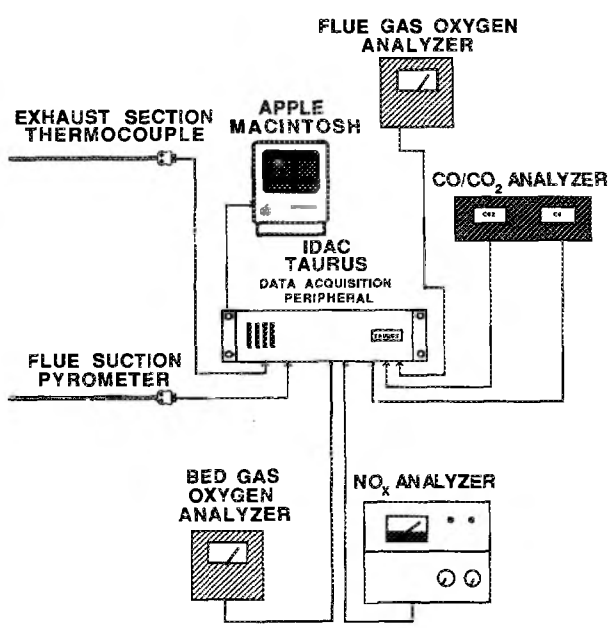

FIG. 10. Data-acquisition system.

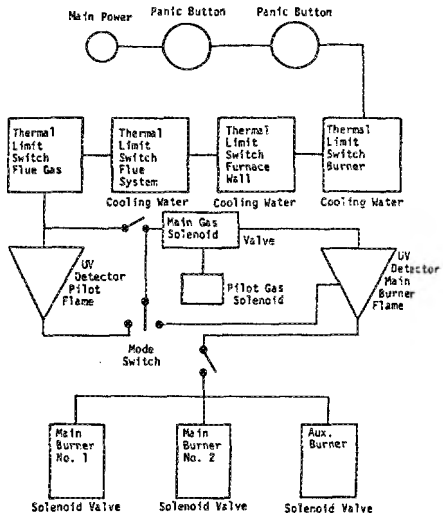

FIG. 11. Overall logic diagram for the flame-safety interlock system.

Figure 12 illustrates typical experimental results on exhaust O_2 and temperature obtained while burning waste zirconium sponge in the rotary kiln simulator. Prior to run initiation, the bulk oxygen concentration at the kiln exhaust was approximately 6%. Immediately after the zirconium was charged into the kiln, the exhaust oxygen dropped to approximately 4% because the zirconium was being oxidized according to the reaction:

$$Zr(s) + O_2(g) \rightarrow ZrO_2(s) .$$

As the zirconium is consumed, the overall burning rate decreases and, therefore, the oxygen concentration in the exhaust gradually returns to its base-line value. Figure 12 shows O_2 measurements made directly above the burning zirconium bed and indicates the local oxygen at the bed surface is somewhat lower than that measured in the exhaust. This behavior is believed to be typical of normal rotary kiln operation because the solid charge does not fully surround the flame zone, but rather covers a small portion of the kiln bottom. Figure 12 also shows typical thermal characterization data which indicate that after an initial transient associated with a very high local burning rate, the temperature of the zirconium bed (as measured with an optical pyrometer) rapidly equilibrates with the temperature of the kiln gases (as measured with a suction pyrometer).

Figure 13 summarizes typical burning rate and fractional conversion results which were calculated from the deviation of the measured oxygen concentration during the test burn relative to the oxygen concentration measured in the empty kiln prior to the test burn. In this experiment the fractional conversion increases steadily until essentially total conversion of the zirconium to zirconium oxide was achieved, approximately 4 h. The solid symbols in Fig. 13 indicate the results of actual direct measurements of the fractional conversion based on the ultimate analysis of solid sam-

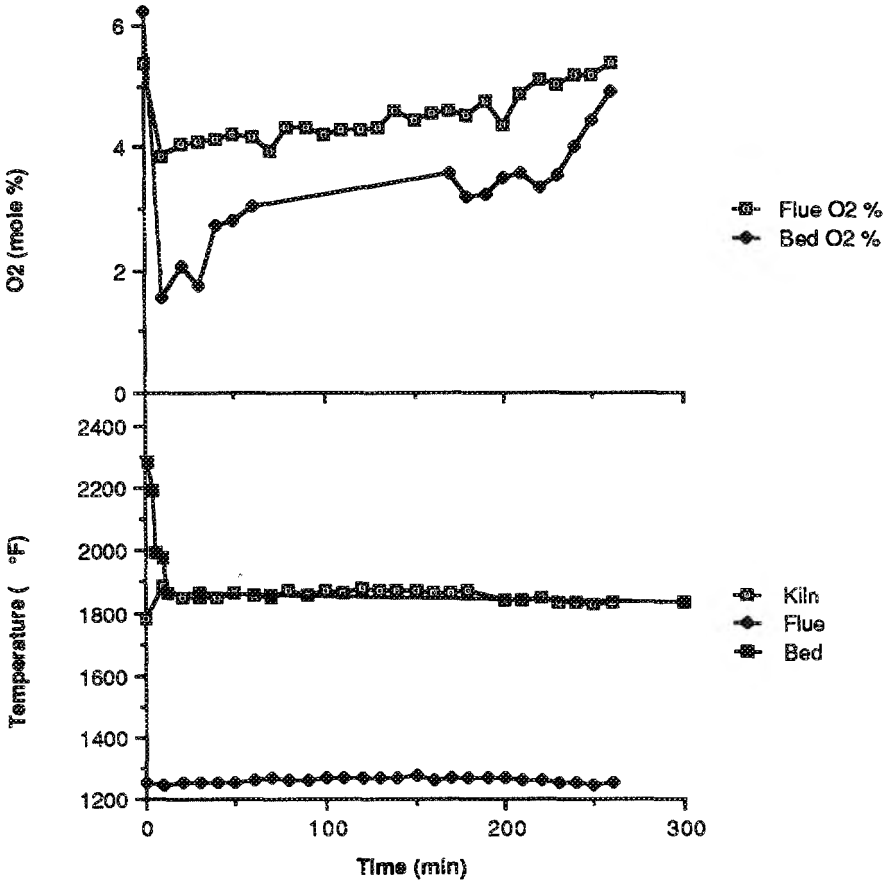

FIG. 12. Sample oxygen and temperature trace, zirconium sponge.

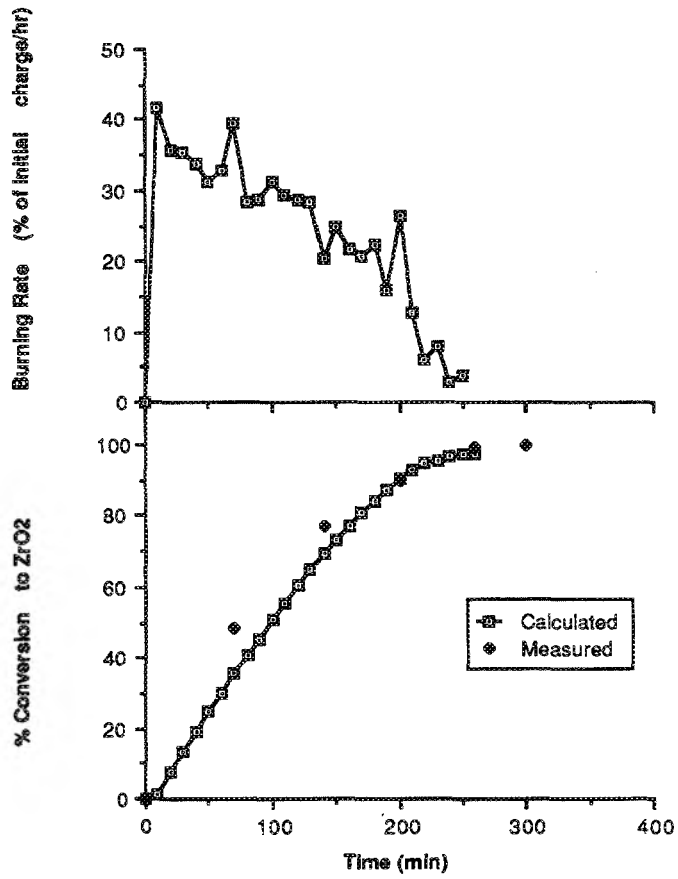

FIG. 13. Sample burning rate and conversion trace, zirconium sponge.

ples withdrawn from the kiln bed at the indicated times. The agreement between the measured conversion and that calculated based on the local burning rate helps confirm the accuracy of the burning rate calculation and the subsequent integration to estimate the cumulative fractional conversion.

In the zirconium sponge studies, a major fraction of the heat release in the kiln occurs in the solid bed phase and the principal product is a dry powder. Figure 14 illustrates results from a completely different type of experimental test sequence in which the fate of trace hydrocarbons found in typical hazardous waste is being characterized. In this experiment the sorbent originally contained 1.0 mass % toluene. Five pounds (2.27 kg) of this contaminated solid was incinerated in the rotary kiln simulator at a temperature of 1000 °F and mean kiln oxygen approximately 10% by volume. The evolution data shown in Fig. 14 are typical of the hydrocarbon concentrations which would enter the afterburner as a function of time. The initial spike corresponds to a rapid release of toluene during the first 10 min of the run. The subsequent low level hydrocarbon concentration results from unburned hydrocarbons from the burner gas (due to the low operation temperature) and the slower desorption of the final remaining traces of toluene in the solid phase after the initial burning regime.

These results are typical of the type of data which can be obtained with the rotary kiln simulator. In addition to quantifying the burning and evolution rates, detailed GC and GC/MS analysis of the exhaust gases allow specific chemical

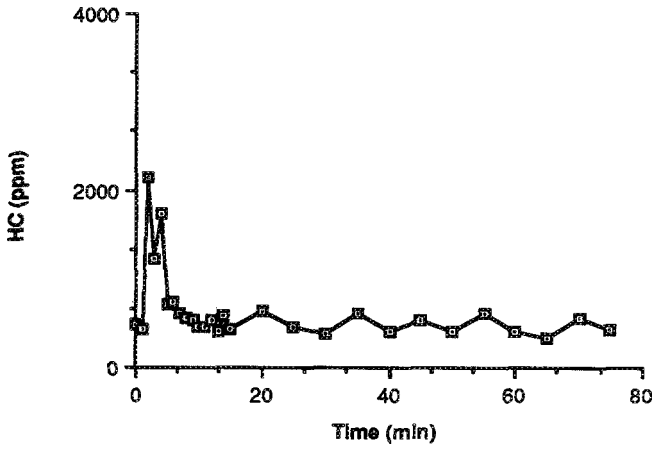

FIG. 14. Sample hydrocarbon trace, 5 lb absorbent, 1% toluene.

quantification of products of incomplete combustion. In the example shown in Fig. 14, toluene was the primary species measured, but significant amounts of benzene and lower alkanes were noted. The cyclic nature of the trace near the end of the plot is probably due to cycling of the air compressor. The fact that the THC reading does not drop to zero is due to the low operating temperature for that particular experiment.

ACKNOWLEDGMENTS

The authors would like to thank the following people for their invaluable help in the development and operation of this facility: Dr. Vic Cundy, for his useful input in the field of hazardous waste incineration; JoAnn Lighty, for her help in getting the facility up and running, Ray Cayias, for his advice and machining work, without which none of this would have been built; Western Zirconium, for funding the zirconium sponge experiments, Patti Case, for her expert guidance in the handling and behavior of zirconium and in providing direction for the research, and Brad Overmoe, who did the original zirconium sponge experiments in the EER kiln in Irvine, CA.

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