FIELD TESTING AND COMPUTER MODELING OF AN OXYGEN COMBUSTION SYSTEM AT THE EPA MOBILE INCINERATOR

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ABSTRACT

The Oxygen Combustion System has been demonstrated successfully at the EPA Denney Farm site as part of the modified EPA Mobile Incinerator. This paper describes the field testing results and computer modeling of the Linde System. The oxygen system enables the EPA unit to incinerate dioxin and PCB contaminated soil at a consistent rate of 4000 lb/hr—200% of the original maximum capacity. The pure oxygen combustion system improved the thermal efficiency of the incinerator by over 60% and reduced the flue gas volume dramatically. Therefore, the dust carryover problem was mitigated. The destruction and removal efficiencies of hazardous wastes exceeded EPA requirements.

The unique design of the proprietary burner allows the use of up to 100% oxygen in place of air for incineration with improvements over conventional oxy-fuel burners. As a result, the temperature distributions in the rotary kiln are very uniform and NO_x emissions are low.

The oxygen combustion system, controlled by a programmable controller, provided much better response and flexibility than conventional air-based systems. The system generated an extremely stable flame and responded very well to the transient conditions of the rotary kiln. Kiln puff occurrence was virtually eliminated in the operation of the Mobile Incinerator.

A computer model of the incinerator was developed and used for process design. The model predicted the test results reasonably well. This model can be a useful tool in the design and operation of rotary kiln incineration systems.

INTRODUCTION

The objective of this paper is to describe the field testing results and computer modeling of the Oxygen Combustion System (OCS). The system was retrofitted to the EPA's mobile incineration system (MIS) as part of the EPA's overall modifications. The EPA confirms that the modified MIS has passed all compliance tests using Denney Farm material at a solids feedrate of 4000 lb/hr [1]. The successful demonstration of the OCS in the EPA/MIS represents a significant technical advancement in the field of chemical waste incineration.

The MIS was designed and built by the EPA to provide a mobile facility to demonstrate on-site thermal destruction and detoxification of hazardous and toxic organic substances collected from clean-up operations at spills or at uncontrolled hazardous waste sites. The system is designed to provide highly efficient thermal destruction of all organic contaminants fed to the system.

The EPA/MIS was in operation at the Denney Farm site in McDowell, Missouri, between July, 1985 and February, 1986 with a trial burn on dioxin-contaminated solids and liquids and subsequent field demonstration. During this field demonstration the MIS demonstrated the ability to destroy liquid and solid hazardous wastes and toxic organic wastes. However, its relatively low capacity and low on-stream factor limited the direct application of this technology for the massive task of cleaning up the myriad abandoned hazardous waste sites.

The throughput of the MIS in decontamination of soil had been limited by the required gas residence time in the secondary combustion chamber (SCC). The MIS had shown that only 2000 lb/hr of soil with relatively low moisture content could be incinerated. Higher moisture content feeds further reduced the system capacity. The low on-stream factor had been caused mainly by excessive dust carryover which required frequent SCC clean out. A detailed discussion of the problems encountered during the 1985–1986 operation and the system modifications thereafter can be found in Refs. [1] and [2].

System modifications were undertaken to increase the MIS throughput and its on-stream factor. The modified system consists principally of: *(a)* a rotary kiln; *(b)* an added refractory lined cyclone; *(c)* a secondary combustion chamber (SCC); *(d)* a wetted throat quench elbow with sump; *(e)* a wet electrostatic precipitator (WEP) to replace the particulate filter; *(f)* a mass transfer (MX) scrubber; and *(g)* an induced draft (ID) fan. Ancillary support equipment consists of bulk fuel storage; waste blending, and feed equipment for both liquids and solids; scrubber solution feed equipment; ash receiving drums; and an auxiliary diesel power generator.

As part of the system modifications, the conventional air burner system in the kiln was replaced by the Oxygen Combustion System. The OCS consists of the patented "A" Burner [3, 4], an oxygen flow control piping skid and a control console. The control console utilizes a programmable controller to optimally integrate all system components into a flexible combustion package while providing for easy operator interfacing and safety interlocking. The unique design of the proprietary "A" Burner allows the use of up to 100% oxygen in place of air for incineration without creating high flame temperature, high NO_x, poor mixing, and nonuniform heat distribution. However, for incinerators under even a slight vacuum, close to 100% oxygen enrichment would be very difficult to achieve due to the inevitable air infiltration.

BENEFITS AND TECHNICAL CONSTRAINTS OF USING OXYGEN

The use of oxygen or oxygen enriched air in place of air for incineration can improve the overall performance and efficiency of chemical waste incinerators, increasing throughput, improving DRE, and overall, reducing the cost of the system. As oxygen replaces part or all of the air for incineration, the nitrogen portion is reduced in both the oxidant and the flue gas. Hence, the volume of the oxidant and the flue gas are reduced per unit of waste processed. In addition, the concentration of oxygen in the fuel-oxidant mixture is increased.

The main advantages accrued from these changes are: *(a)* the throughput of the incinerator, which is normally limited by the air blower capacity, the gas residence time and the size of the flue gas cleaning system when using air, can be significantly increased; *(b)* the fuel consumption, if supplemental fuel is required, is lowered primarily due to the reduced sensible heat loss to the flue; *(c)* the DRE should be improved due to the higher oxygen concentration in the fuel-oxidant mixture and longer residence time; and *(d)* pollution control of the reduced flue gas is less costly and more effective. A summary and detailed discussion of these benefits were provided in a previous presentation [5].

Unfortunately, the use of oxygen in conventional burners for hazardous waste incineration applications suffers the disadvantages of: *(a)* high flame temperature, resulting in high NO_x and local overheating; and *(b)* poor mixing and poor recirculation of the gases within the combustion chamber. These technical constraints restricted most people to the use of oxygen at only modest enrichment level.

In order to overcome the disadvantages noted above, the Aspirator Burner or "A" Burner was developed [3,4]. The key feature of the "A" Burner is that the furnace gases are aspirated into the oxidant jets prior to mixing with the fuel, as indicated in Refs. [4] and [5]. By maintaining sufficient distance between the oxygen jets and fuel supply, enough of the furnace gases can be aspirated into the oxygen jet prior to mixing with the fuel so that the resulting flame temperature can be reduced to a value equivalent to an air flame temperature. Gas mixing and recirculation within the furnace is accomplished with the "A" Burner by using very high velocity oxygen jets, which result in a uniform temperature distribution within the incinerator.

OPERATING RESULTS AND DISCUSSION

Operation of the modified MIS, from early June to mid-September 1987, confirmed that the system had achieved the following:

(a) throughput increase,
(b) kiln puff reduction,
(c) specific fuel savings over 60%,
(d) NO_x emission comparable to air systems, and
(e) good flame stability and operational flexibility.

Each of these achievements is described below.

Throughput Increase

The maximum contaminated soil throughput of the Mobile Incineration System during its operation with air burners had been 2000 lb/hr. However, this maximum rate was not sustainable. For example, the average throughput rate of four test runs in the Spring of 1985 had been only 1478 lb/hr of dry soil (< 10% moisture). With the Oxygen Combustion System, the MIS achieved a sustainable soil throughput rate of 4000 lb/hr with moisture content up to 20%, as confirmed by certified verification tests and trial burn runs. The comparison of the two sustainable conditions is shown in Table 1.

With normal and relatively dry (about 20% moisture) soil, it was found quite easy to feed up to 5000 lb/hr. Although the ram feed system had trouble processing muddy soil, the kiln and SCC operated well with it. Due to the significant reduction in kiln combustion gas velocity, as shown in Table 1, and the addition of a cyclone, the dust carryover problem was totally eliminated. It has been demonstrated that very light (4 lb/cu ft) vermiculite can be processed through the system at a capacity up to 7.4 cu yd/hr (800 lb/hr). The particulate carryover was less than 15% of the feed rate and it was easily removed by the cyclone.

It should be noted that the current capacity limitation of the MIS is about 5000 lb/hr of soil, mainly due to the mechanical limitations of the rotary kiln (which could be upgraded). It is not due to heat transfer or flue gas volume limitations. The kiln limitation can be solved by, for example, using two or more transportable rotary kilns to feed the common downstream equipment. It is estimated that up to 10 TPH of soil can be handled by such an upgraded system. Such a throughput increase would make mobile incineration technology more economically attractive.

This impact of using oxygen for throughput increase would be substantial in any system. In the case of a mobile or transportable incineration system which is restricted in size, a higher throughput is even more important. With comparable capital investments, the oxygen system can potentially process several times the throughput of an air system. Fixed operating costs can be spread out over a much larger quantity of wastes processed per year. In addition, the oxygen-based system will offer the benefit of a much shorter cleanup time, which is very desirable from the point of view of the public.

For existing stationary incinerators, it is also technically feasible and economically attractive to utilize an oxygen-based combustion system to increase the throughput. It could not only cut down the lead time to achieve a capacity increase, but also negate the need for the large capital expenditure of entirely new incinerators.

Kiln Puff Reduction

When high-Btu wastes are fed into rotary kiln incinerators in an intermittent mode, the transient combustion behaviors of these materials create unsteady releases of combustible gases which may momentarily deplete the oxygen supply to the incinerators. These temporary oxygen-deficient conditions could cause the release of products of incomplete combustion (PICs) and often called kiln "puffs". These "puff" phenomena have raised public concerns recently and have been the subject of research projects sponsored by the EPA [6, 7].

In the field operation of the EPA/MIS, large quantities of plastic materials were burned periodically [1]. These materials were ram-fed in the rotary kiln every 1–2 mins. To respond to the transient oxygen demand as a result of burning these materials, a unique oxygen feedforward-feedback control logic was designed into the system. Automatic water spray was used to modulate kiln temperature when required.

Before the implementation of this O_2 control feature, the MIS had difficulty in burning these plastic materials smoothly, partly due to its relatively small capacity. Shown in Fig. 1 are examples obtained during the early shakedown period. Even though the normal excess oxygen level was high, occasional feeding practice upsets caused puffs to occur as evidenced by the drop in the O_2 concentration close to 0% and the CO spikes. Although the MIS is designed so that the waste feed is automatically cut-off whenever the O_2 level is below 4% and/or the CO level is above 100 ppm, the waste materials already in the kiln can continue to release combustible gases for a few minutes, during which time the complete destruction of hazardous materials may not be assured. Extreme caution by operators to limit the waste feed rate and to adjust the air flow rate was

TABLE 1 EPA MOBILE INCINERATION SYSTEM OXYGEN DEMONSTRATION RESULT SUMMARY

	AIR CASE+	OXYGEN CASE	PERCENT CHANGE
Contaminated Soil (Lb/Hr)	1478	4000	+171%
Firing Rate (MMBTU/Hr)			
Kiln	4.9	3.9	
SCC	3.9	5.4	
Total	8.8	9.3	+6%
Specific Fuel Use (MMBTU/Ton Soil)	11.9	4.7	-61%
Pure Oxygen Input (Lb/Hr)			
Kiln*		574	
SCC		0	
Total		574	
Specific Oxygen Consumption ($Ton\ O_2/Ton\ Soil$)		0.14	
Fuel Savings (MMBTU/Ton O_2)		50	
Kiln Superficial Velocity** (Ft/Sec)	8.1	3.3	-59%
SCC Residence Time** (sec)	2.6	3.2	+21%
Quenched Gas Volume (DSCFM)	3250	2250	-31%

NOTE:

+From Reference 2, average of four runs. Maximum throughput during the four runs was 2000 lb/hr.

*58% of total oxygen entering the kiln supplied by pure oxygen. (Equivalent to 40% O_2 Enrichment)

**Calculated data

used to avoid these upset conditions. This was a significant operational constraint.

Immediately after the implementation of the oxygen control feature, the transient upset conditions associated with the release of the combustible gases were virtually eliminated in the operation of the MIS. As shown in Fig. 2, the oxygen level of the gas entering the SCC was controlled to be within ±1% from the setpoint of 9% O_2, while the O_2 level at the SCC is maintained at about 6% (dry). Carbon monoxide spikes were not detected. Note also in Fig. 2, the oxygen flow rate responded promptly to the transient oxygen demand. This can be attributed to the fast response (short lag time) of the pure oxygen system and the in situ O_2 analyzer. In addition, the high-momentum oxygen jets in the Linde burner also enhanced mixed in the kiln to eliminate any pockets of unburnt combustibles.

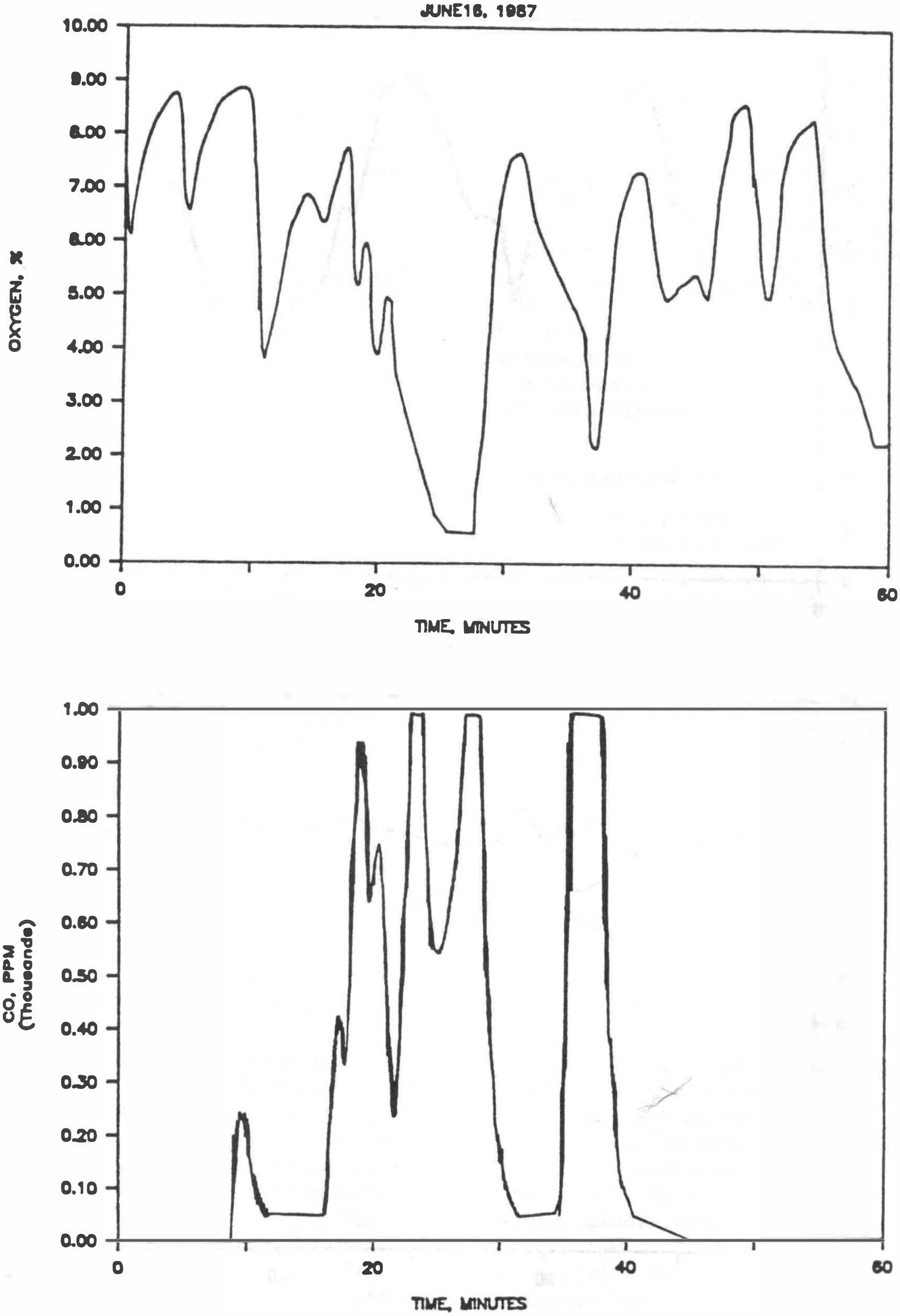


FIG. 1 KILN PUFFS

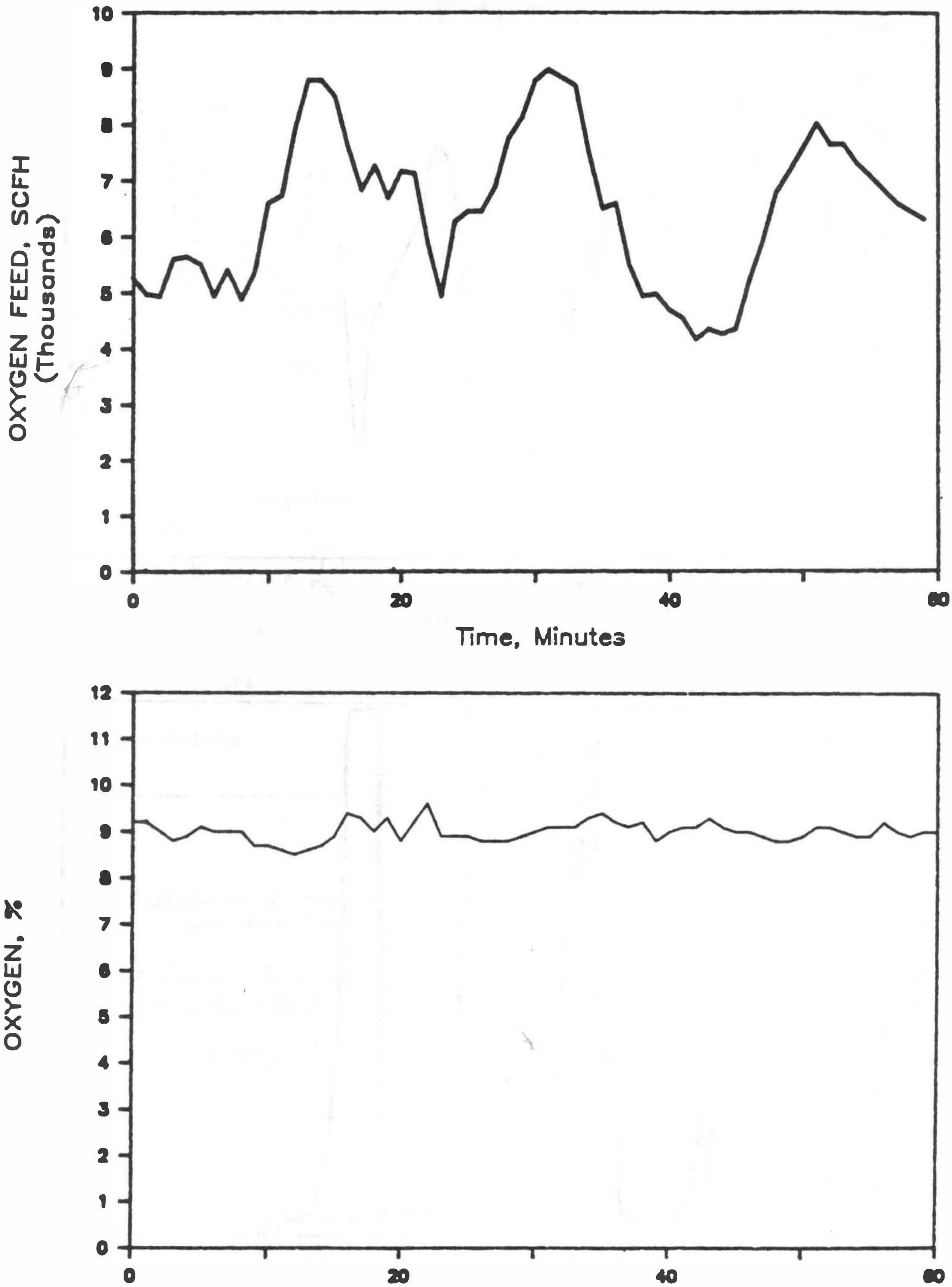


FIG. 2 EFFECTS OF OXYGEN CONTROL

Of course, no control scheme is a substitute for good operational discipline, including batch size reduction, avoidance of large containers of bulk liquid, etc. However, oxygen feedback flow control was shown to alleviate the common kiln upset conditions effectively. This is an important achievement for the system in the full scale operation of a hazardous waste incinerator.

Fuel Savings

Supplemental fuel was required to provide the heat required to operate the rotary kiln at 1500–1600°F and secondary combustion chamber at about 2100°F, because the waste materials did not have a sufficient heating value to sustain self-combustion.

Specific fuel savings of over 60% was achieved during operation of the EPA/MIS with the OCS system. This result can also be expressed as 50 MMBTU saved per ton of oxygen used, as shown in Table 1.

The economics of using oxygen to save fuel, of course, depend on the relative cost of fuel and oxygen. With No. 2 fuel oil costing $0.70 per gallon (or $5.50 per million Btu) and a fuel savings of about 50 million Btu for every ton of oxygen used, the breakeven oxygen cost is $275 per ton oxygen. The cost of oxygen depends on methods of oxygen generation, size of plant, and location. For example, it ranges from about $50 per ton of oxygen produced by a large on-site facility to about $120 per ton for delivered liquid.

NO_x Emissions

As previously stated, the "A" Burner design overcomes the problems associated with conventional oxygen combustion, such as high flame temperature and high NO_x emissions. A recent study sponsored by the Department of Energy (DOE) [8] obtained extensive NO_x data on various oxygen-enriched combustion conditions using natural gas. The burners tested represent both conventional air-fired designs and oxygen/fuel burners designed primarily for very high oxygen levels. As shown in Fig. 3, the NO_x emissions peak between 35 and 50% O_2 levels for all test conditions. The absolute levels of the NO_x emissions also depended on both the furnace temperature and burner design. With pure oxygen, the "A" Burner produced its lowest NO_x emissions: less than 0.05 lb NO_x/MMBtu. This compares to 0.10 lb NO_x/MMBtu for air burners.

In the Denney Farm field demonstration, NO_x level was continuously monitored and recorded. Due to the air infiltration, which is discussed in a later section, the effective O_2 enrichment levels were about 40–50% O_2 in the rotary kiln. The mean NO_x emission level reported in the 1987 trial burns was between 54.6 and 138.3 ppm at 15% CO_2 (or 0.07–0.18 lb NO_x/MMBtu), which compares favorably with the previous air system levels obtained in the 1985 trial burns (between 126–166 PPM at 11% CO_2 or 0.19–0.235 lb NO_x/MMBtu). Furthermore, since the specific fuel consumption of the modified MIS was reduced by 60%, the NO_x emission per ton of contaminated soil was further reduced based on these trial burn data. It should be noted, however, that the NO_x emission level from the Linde system was more sensitive to the operating conditions than the air system. It is anticipated that additional NO_x reduction can be achieved by: *(a)* reducing air into the kiln; *(b)* using steam instead of air as an oil atomization fluid for the oxygen burner; and *(c)* reducing excess oxygen level in the rotary kiln.

Flame Stability and Operational Flexibility

During operation of the EPA/MIS, good flame stability and operational flexibility were also achieved with the Oxygen Combustion System. A number of system stability tests were conducted with various feed materials at different feed rates. Disturbances were generated to test the dynamic response of the burner system, such as by cycling liquid waste feed and water spray. Satisfactory system response and flame stability were demonstrated in all the tests conducted [1]. It has also been demonstrated that very light vermiculite can be processed through the system with very little particulate carryover. Tests with mixtures of brominated sludge, soil and sodium sulfate have also been successful. During the entire 14-week demonstration period, no system downtime was attributed to the OCS System.

COMPUTER MODELING

Different types of industrial furnaces have been successfully modeled in the past. A mathematical model for a rotary kiln based incineration system was developed in this case to aid the design and optimization of oxygen firing. This model performs both heat and mass balances and heat transfer analyses.

As shown in Fig. 4, the heat transfer mechanism includes radiative, convective and conductive heat transfer among combustion gases, the kiln wall and the solid bed. A two-sink model is used to calculate the radiative heat transfer within the freeboard. The radiative heat transfer between the solid bed and the covered inner wall is modeled as radiation between two infinite parallel plates [9]. Convective heat transfer

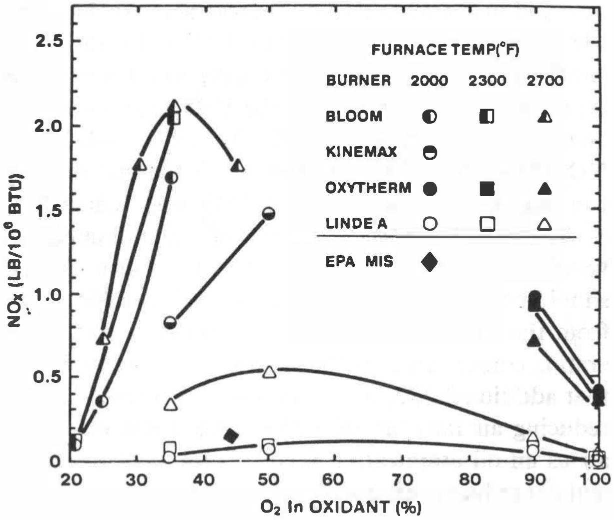
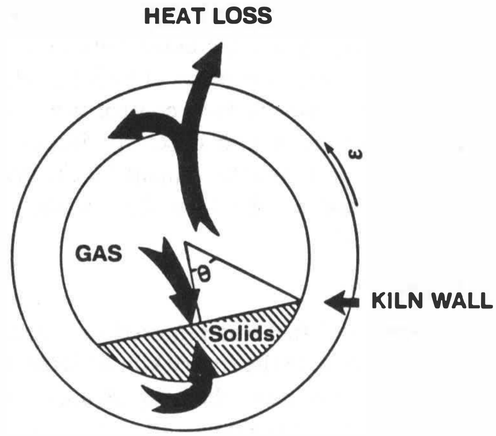


FIG. 3 SUMMARY OF NO_x EMISSIONS: FUEL: NATURAL GAS EXCESS O_2=2% (Dry) SOURCE: DOE STUDY



MECHANISM OF HEAT TRANSFER IN ROTARY KILN			
Radiation:	Gas-Solid	Gas-Wall	Solid-Wall
Convection:	Gas-Solid	Gas-Wall	Solid Bed
Conduction:	Wall-Solid		

FIGURE 4

coefficients at the exposed and covered areas are adopted from Gorog, et al. [10]. The solid bed is considered to be well-mixed at any cross section, which is a reasonable assumption for this operation [11]. The combustion gas temperature is also considered uniform, which is a good approximation for the flame characteristics of the "A" Burner [5,8]. The gas is taken to be radiatively gray in the calculation of gas emissivity.

The model can be used to predict the fuel requirement, flue gas properties, and axial temperature profiles of the solid bed, the kiln inner wall and the outer skin. Figure 5 shows temperature profile predictions which indicates that heat transfer is not a limitation for the MIS at a 4000 lb/hr throughput.

Projected Performance

Appropriate heat and mass balances for the EPA/MIS were calculated before the Denney Farm tests using the aforementioned computer model [5]. The air case with a throughput of 2000 lb/hr of contaminated solid with 20% moisture was chosen as the basis for comparison. A comparable calculation for an oxygen-fired rotary kiln was also made to predict the impact of using the OCS. This comparison, summarized in Table 2, projected the following benefits using oxygen:

(a) A throughput increase of 100%, i.e., a processing rate of 4000 lb/hr is feasible.

(b) Such a throughput increase achievable with the oxygen system can reduce the incineration cost per ton of soil.

Comparison of Calculated and Actual Results

In the field demonstration of the EPA/MIS, the air leakage rate into the rotary kiln was estimated to be about 8000 SCFH at a vacuum level of 0.2–0.3 in. of water column. The air leaked partially through the kiln seals between the stationary and rotary components and partially through the ram feed chute. In addition, 4000 CFH of compressed air was used for the waste and water atomization nozzles. The backup air burner also needed 1000 CFH of air flow to avoid overheating. The oxygen burner required only 400 SCFH of atomizing air. Altogether there was about 13,000 SCFH of air entering the kiln.

The actual oxygen usage was lower than originally expected, mainly due to the higher than expected air infiltration into the kiln. Therefore, only 58% of the oxygen entering the kiln is supplied by pure oxygen (equivalent to a 40% oxygen enrichment level), instead of the planned 95%. There are other factors affecting the oxygen and fuel consumptions. The rotary kiln was operated at a lower temperature (around 1550°F) than the originally anticipated 1800°F. Also, the heat loss from the secondary combustion chamber of about one million of Btu/hr was underestimated by 40% in the

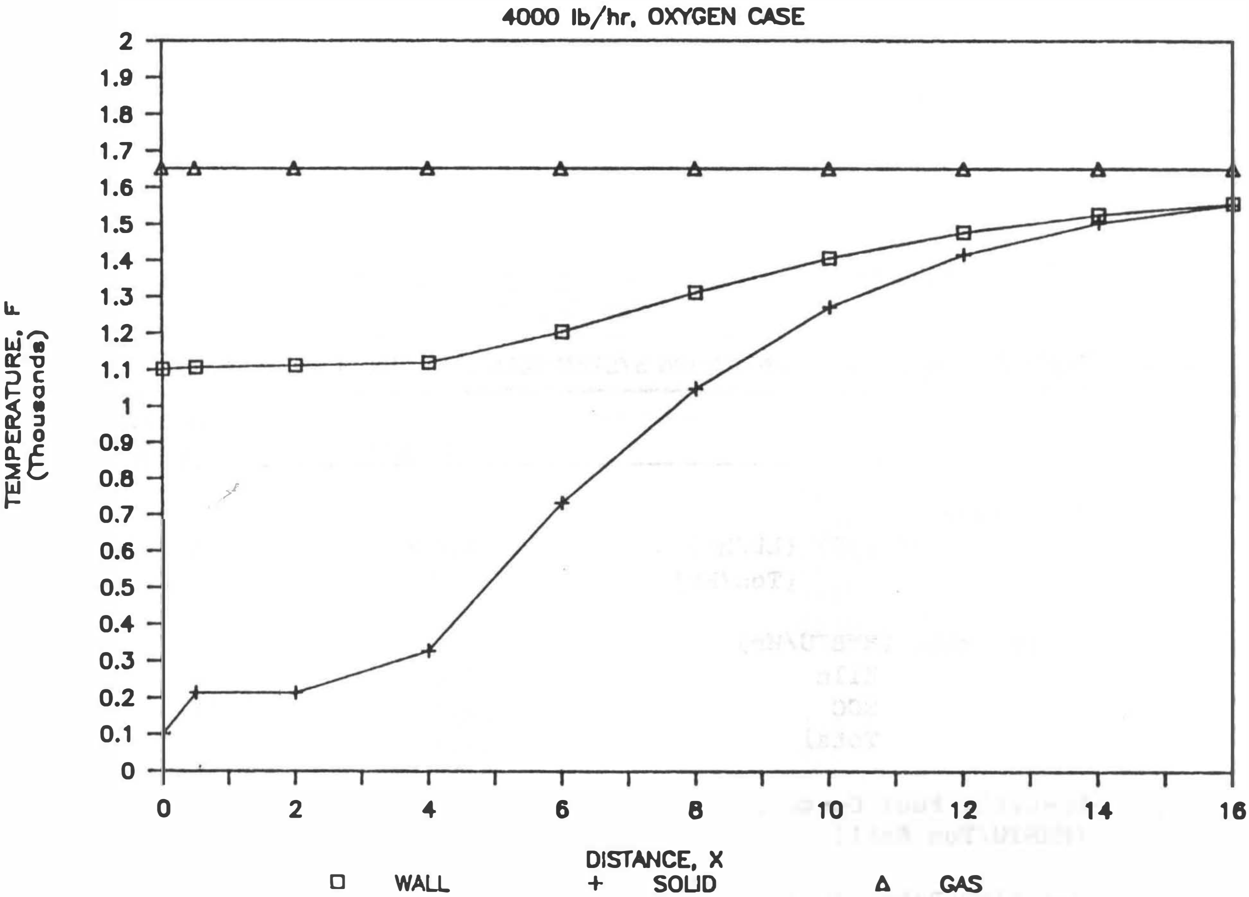


FIG. 5 PREDICTED TEMPERATURE PROFILES

original estimation. Futhermore, it was previously unknown to the authors that the majority of excess air was supplied to the kiln rather than the SCC in the prior operation. Such practice was discontinued after the process modifications. Once corrected for these actual operating parameters, the model calculated results are quite consistent with actual operating data, as shown in Tables 3 and 4.

The measurement of kiln ash dropout temperature was very difficult, because the ash started losing heat immediately upon discharge from the exit chute into a metal drum. The ash temperature was taken with a thermocouple inserted into the ash drum once it had been filled, and it was presumably lower than the true temperature. It was found that the measured ash temperatures increased as the kiln throughput increased, with the same kiln control temperature. Apparently, this was due to the shorter heat loss duration before ash temperature measurement at the higher throughput. The conclusion of the test was that heat transfer was not a limitation for the MIS up to a 5000 lb/hr throughput, as predicted by the model.

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TABLE 2 EPA MOBILE INCINERATION SYSTEM COMPUTER MODEL PROJECTION

	AIR CASE	OXYGEN CASE*
Throughput:		
Soil (20% H_2O) (Lb/Hr)	2,000	4,000
(Ton/Hr)	1.0	2.0
Firing Rate (MMBTU/Hr)		
Kiln	5.6	4.4
SCC	4.8	3.3
Total	10.4	7.7
Specific Fuel Consumption (MMBTU/Ton Soil)	10.4	3.85
Gas Flow Rate (ACFM)		
Kiln	7,100	2,400
SCC	14,000	6,800
APC	6,200	3,200
Kiln Superficial Velocity (Ft/Sec)	8.2	2.7
SCC Residence Time (Sec)	2.3	4.6

TABLE 3 EPA MOBILE INCINERATION SYSTEM MODEL VERIFICATION OXYGEN CASE FOR CONTAMINATED SOIL AT 4000 lb/hr

	Projection model	Actual Results
Temperature (°F)		
Kiln Gas	1650	1640
Kiln Wall	1530	1540
Kiln Ash	1540	>1450
SCC Gas	2250	-
SCC Wall	2150	2120
Firing Rate (MMBTU/HR)		
Kiln	3.9	3.9
SCC	5.3	5.4
Total	9.2	9.3
Specific Fuel Consumption (MMBTU/Ton)	4.7	4.7
Pure Oxygen Input (LB/HR)		
Kiln*	579	574
SCC	0	0
Total	579	574
Specific Oxygen Consumption ($Ton\ O_2$/Ton Soil)	0.14	0.14
Fuel Savings (MMBTU/TON O_2)	54.82	50.58

NOTE: *58% of total oxygen entering the kiln (Equivalent to 40% O_2 Enrichment)

TABLE 4 EPA MOBILE INCINERATION SYSTEM MODEL VERIFICATION AIR CASE FOR CONTAMINATED SOIL AT 1478 lb/hr

	Model Projection	Actual Results
Temperature (°F)		
Kiln Gas	1700	1700
Kiln Wall	1640	-
SCC Gas	2200	2200
SCC Wall	2100	-
Fuel Input (MMBTU/HR)		
Kiln	4.9	4.9
SCC	4.4	3.9
Total	9.3	8.8
Specific Fuel Use (MMBTU/Ton)	12.6	11.9

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