OXYGEN ENRICHMENT OF COMBUSTION AIR IN A 360 TPD MASS BURN REFUSE-FIRED WATERWALL FURNACE

WILLIAM S. STRAUSS AND JOHN A. LUKENS
Harrisburg Steam Generating Facility
Harrisburg, Pennsylvania

FLORIO K. YOUNG AND FRANK B. BINGHAM
Air Products and Chemicals, Inc.
Allentown, Pennsylvania

ABSTRACT

The Harrisburg Waste-to-Energy Facility is one of the oldest operating waste-to-energy facilities in the Western Hemisphere. Since entering commercial operations on October 10, 1972, this facility has processed almost two and a half million tons of municipal solid waste.

Harrisburg was a learning center for many engineering firms and equipment vendors in the early 1970s as a source of design considerations in a new and untried field of technology. Now as the facility enters "old age," ironically it is, once again, the pioneer for the nation.

A series of experiments were completed in August and September of 1987 that have explored the effects of enriching the combustion air with pure oxygen in a medium sized refuse-fired waterwall combustor using Martin grates.

INTRODUCTION

In mid 1986, the Director of the City of Harrisburg's 720 waste-to-energy facility was approached with the concept of replacing some small percentage of the inert fraction of atmospheric air with oxygen; thereby increasing the percentage of oxygen in the combustion air from about 21% to about 23–25%.

The calculations that were presented in the early discussions suggested that the cost of the oxygen would be outweighed by the increased revenues from better combustion efficiency, higher tonnage throughput, and reduced ash volume and weight.

The preliminary calculations assumed that the total mass flow of hot gasses could not be increased. This assumption is based on the fact that this furnace is operated at its maximum heat release and, at that level, the induced draft fan is moving as much gas as possible (the motor amperage is at the upper limit for continuous operation). At that level, a slight increase in heat release causes the furnace to "go positive." The improvement in performance, based on that assumption, would be in better burn out of the fuel and better throughput due to the replacement of about 2% of the inert nitrogen in atmospheric air with pure oxygen; thereby allowing more combustion with the same mass flow. The increase in available oxygen from 21% to 23% is an increase of 9.5%. Assuming that all of that increase is used (no increase on oxygen concentrations in the exhaust), the same mass of fuel should require a smaller mass of air for combustion by a factor of 9.5%. A 9.5% decrease in combustion air mass should result in a decreased quantity of gas passing through the induced draft fan even though a similar amount of garbage is being burned and the same amount of heat is being released. The decrease in mass flow to the induced draft fan should allow "room" to increase the throughput in tons per hour of garbage in order to utilize the induced draft fan at its maximum capacity. Based on the fan capacities of system in Harrisburg [62,500 acfm (29.24 m^3) forced draft, 16,800 acfm (7.92 m^3) overfire, and 122,500 acfm (57.78 m^3) induced draft], 11,600 acfm (5.41 m^3) of "room," before reaching capacity, represents the extra by-products of combustion of 0.941 tons (854 kg) per hour of garbage; which is an increase of 6.3% capacity.

A 6.3% increase in capacity represents a daily throughput increase of 45 TPD.

Current furnace efficiency without oxygen enrichment is about 54% [assuming 4500 Btu/lb (10.46×10^6 J/kg)]. Furnace efficiency is calculated simply by multiplying the number of pounds of waste processed by the assumed energy per pound and dividing that number into the total energy in the exported steam. At the Harrisburg facility, numerous problems associated with age, many years of poor management, and some inadequate original design deficiencies cause rather low efficiencies. Main contributors to the rather low efficiency include no preheating of the combustion air or the boiler feedwater, a deaerator that is ready for major overhaul, heat losses around the waterwall and some of the main steam header, and combustion of 35 TPD of 15% solid sewage sludge. In the two years since the current plant management has been in charge, the efficiency has steadily improved from 44% to around 58%. Installation of air and feedwater preheaters and implementation of automated combustion control in early 1988 will result in more improvement. Also, the sewage treatment facility is currently installing belt presses; the sludge will then enter the furnaces at about 23% solids.

Historically, oxygen enrichment in traditional fuel fired combustors results in a significant increase in combustion efficiency. Based on data presented by Air Products and Chemicals, Inc. (see footnotes), about a 10% improvement was expected. Without oxygen enrichment, a total tonnage throughput of 720 tons (653,760 kg) per day will produce 3,500,000 lb (1,589,000 kg) of steam at 54% efficiency. With oxygen enrichment, at 64% efficiency, 765 TPD will produce 4,406,000 lb (2,000,000 kg) of steam.

A further motivation to go forward with this experiment was the fact that the City of Harrisburg's Advanced Wastewater Treatment Plant generates liquid oxygen which is used as a part of the sewage treatment process. The Treatment Plant's cryogenic system was built in 1979 from design criteria generated in 1972. The quality of influent has improved steadily thus requiring less than expected quantities of oxygen. The quantity of unneeded oxygen produced is about 25 tons (27,700 kg) per day. The cost of the electricity to produce the unneeded oxygen (in excess of \$200,000/year) had precipitated a decision by the Sewerage Authority to downsize the operation (at a considerable cost). Discussions with the top management at the Treatment Plant suggested that it may be feasible to defer the downsizing if the Waste-to-Energy Facility could purchase and use the excess oxygen at a price that would at least cover the power usage. Currently, the downsizing is on hold pending the outcome of these experiments.

The discussions with the oxygen supplier combined with the excess oxygen situation at the sewage treatment plant finally led to an agreement between the supplier and the City that would fund a full scale experiment.

THE OXYGEN ENRICHMENT SYSTEM

The system consists of a liquid oxygen storage tank (11,000 gal), steam vaporizers to convert the liquid to gas, flow control valving, safety interlocks to the furnace controls, gas flow metering equipment, a system of piping and lances to mix the oxygen with the underfire air, and dedicated inconel lances to inject pure oxygen into the overfire area.

The system was installed in one of the two IBW-Martin 360 TPD furnace/boilers.

THE TEST PROTOCOL

It was decided that several runs of data gathering under each condition (with or without oxygen) would be required in order to enhance the statistical reliability of the numbers recorded. The tests were run in ten (10) day intervals; five days operation with oxygen enrichment and five days without the enrichment. Three tests were run for a total of 30 days of data.

As much as possible, certain parameters were controlled within very narrow bands: the furnace temperature setpoint remained unchanged throughout the experiment; the underfire air static pressure was maintained at 15 in. (3.733 kPa); the furnace negative pressure was maintained at −0.2 in. (49.8 Pa); and the oxygen concentration in the exhaust was maintained at about 11%. Prolonged excursions by any of the above parameters caused the data gathered during those excursions to be discounted.

All of those involved in setting up this experiment agreed that the most dramatic benefits would probably be gained where the refuse was entering the furnaces with a very high moisture content (as it arrives at the

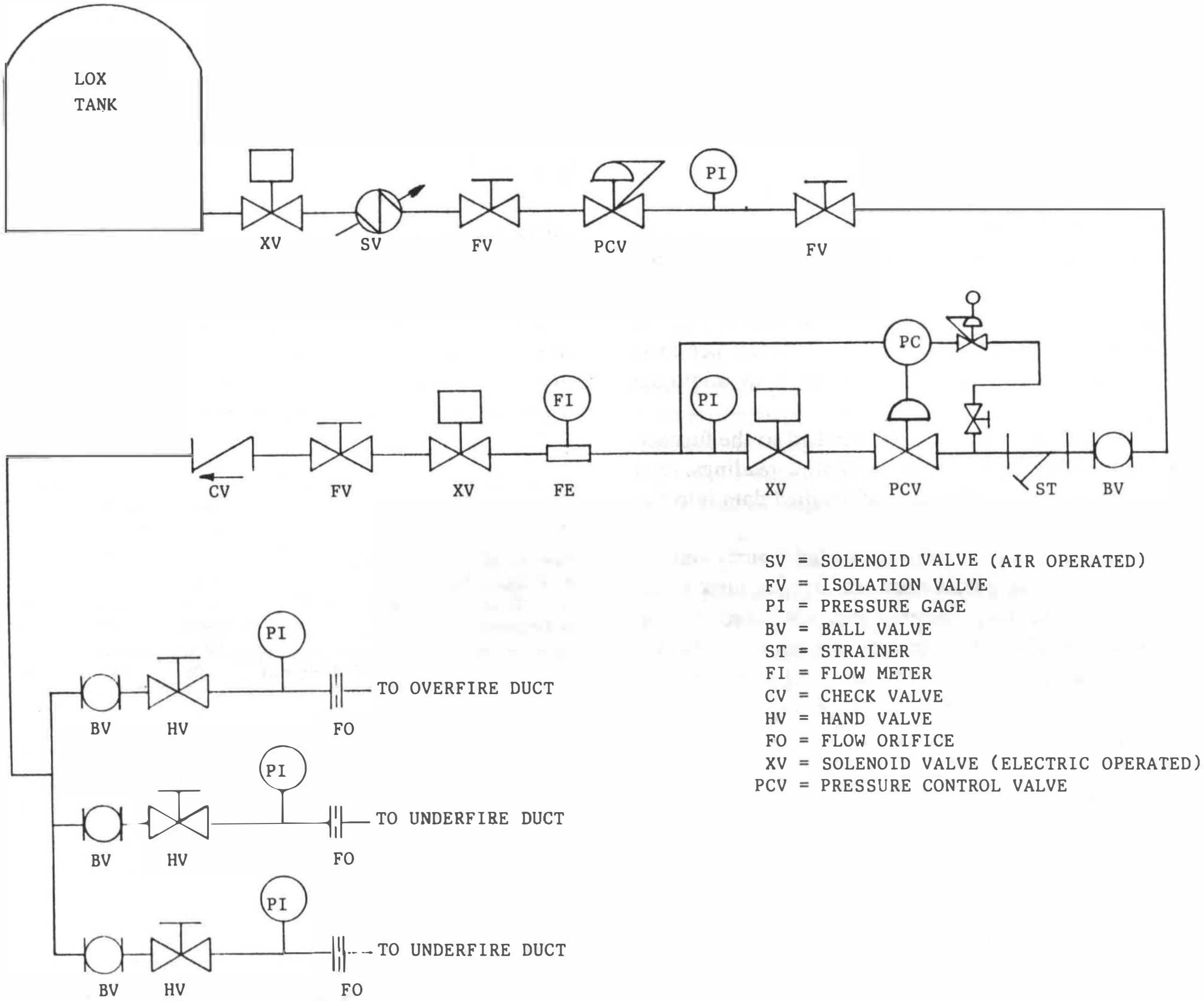

FIG. 1 VALVING AND PIPING ARRANGEMENT

facility after a soaking rain storm or a heavy snow storm). Very wet refuse is one of the operator's biggest challenges. Very wet refuse has a significantly lower average energy content per given mass. When the furnace is running at the maximum heat release with very wet refuse, the amount of refuse on the grates must be increased in order to maintain the same heat release. This results in "high beds" (a depth of garbage on the grates that is in excess of normal) which can cause the quality of the ash to degrade, will cause excessive wear on the grate drives, and, in extreme situations, due to the height of the bed, can block off the lower end of the furnace at the arch causing serious gas flow problems. The expectation was a thinner bed of waste resulting in better burnout; the ability to direct oxygen-enriched air to the lower end of the underfire system, also for better burnout; and, the fact that less volume of air was needed for the same combustion would "make room" for the extra water in the exhaust gas, allowing sustained mass flow. (Unless a good supply of high energy waste such as tires is available for mixing, the units must be turned down somewhat when very wet refuse is being fed into the furnace. The expectation was that the amount of "turn down" would be less.) Therefore, a special test was run with very high moisture waste.

The operators of the facility received extensive safety training in the handling and use of pure oxygen. The training also focused on the desire to gather consistent data throughout the month of experimentation. To help reinforce the consistency of operation during the test, the equipment suppliers were present in the control room throughout the data gathering portion of the experiment.

As those familiar with the waste-to-energy field understand, measuring the exact quantity of tonnage passing through a 360 TPD furnace is almost impossible. In the absence of a load cell attached to the bridge crane, we simply counted the number of grapple loads per hour (again, stressing consistency per load with the crane operators in an attempt to minimize error).

Dedicated data loggers were attached to the furnace temperature readings and the steam flow readings, thus allowing a direct downloading of detailed data into the computer.

All other parameters were recorded hourly onto a spreadsheet. These parameters are: oxygen tank level, oxygen tank inventory, metered and calculated O_2 flow rate, steam production, number of grapple loads, O_2 level in exhaust, furnace temperature setpoint, furnace pressure (draft), underfire air pressure, superheater outlet temperature, and economizer inlet and outlet temperatures. The regular hourly shift logs also provided significant data such as the amperage on the induced draft fan.

Ash samples were randomly pulled from the discharger after several days of operation in each of the test runs. The ash samples were taken "as discharged," meaning that the fly ash and bottom ash are combined. The samples were composited into six packages; three taken while oxygen was used and three from normal operation. The ash was tested for percent combustibles, Btu/lb (J/kg), and density after the water was removed.

A series of stack samplings were taken to test the exhaust gas for total volatile organic compounds, carbon monoxide, and oxides of nitrogen. Half of the samples were gathered during the use of oxygen and half during normal operation.

SUMMARY OF DATA

The test was accomplished during the month of September 1987. Runs of 5 days on oxygen and 5 days off were conducted twice. A third run of 48 hr was conducted specifically for the stack gas testing. A fourth run of 48 hr was conducted in late September specifically to test the difference in operation using large inputs of sewage sludge. Several problems, unrelated to the oxygen testing, developed during the testing that required bringing the unit down for maintenance. These periods were not recorded. Several hours were allowed to pass after the unit was up and running before data were recorded to let the system gain stability.

The ten days on oxygen compared to the ten days off have produced some interesting results. During the tests approximately 30,000 ft^3 (849 m^3) per hour (which is about 1.24 tons (1125 kg) per hour of liquid oxygen) was mixed with the underfire air and directly injected into the overfire area. The split was two-thirds to under fire and one-third to overfire. The following comparisons are based on a summation of all of the valid data:

	Without Oxygen	With Oxygen	% diff.
Number of buckets Per Hour	8.5	8.9	+ 5%
lb of Steam Per Bucket	8000	8510	+ 6%
kg of Steam Per Bucket	3630	3860	+ 6%
lb/hr Steam	67980	75700	+11%
kg/h Steam	30800	34370	+11%
Amperage on the Induced Draft Fan	205	185	−9.8%

Assuming that over a period of 20 days the weight of garbage carried per bucket is more or less averaged, and using measured values of about 1.65 tons (1498 kg) per bucket load, an efficiency calculation can be made. Following are the efficiencies with and without oxygen:

	Without Oxygen	With Oxygen	% diff.
Boiler Efficiency	53.8%	57.2%	+6.3%

The difference in ash quality was dramatic. Following are the significant comparisons:

	Without Oxygen	With Oxygen	% diff.
Heating Value (Moisture Free)	545 Btu/lb	286 Btu/lb	−48%
	(1.26 × 10^6 J/kg)	(0.67 × 10^6 J/kg)	
% Combustibles	5.33	1.23	−76.9%
Density	2.19	2.37	+ 8.2%
% Moisture	34.22%	21.89%	−36.0%

The difference in gaseous emissions indicates a need for further research. Due to budgetary constraints, only three runs were made under each condition. Each run lasted 1 hr. The wide swings in numbers suggest a poor data base from which to draw conclusions.

		Without Oxygen		
		High	Low	Average
NO_x	(ppm at 7% O_2)	78.56	26.5	43.2
VOC	(ppm at 7% O_2)	14.01	13.97	13.99
SO_2	(ppm at 7% O_2)	178.5	122.9	155.1
CO	(ppm at 7% O_2)	15	11	12

		With Oxygen		
		High	Low	Average
NO_x	(ppm at 7% O_2)	64.6	60.1	61.3
VOC	(ppm at 7% O_2)	0.25	0.08	0.13
SO_2	(ppm at 7% O_2)	205.5	155.4	176.4
CO	(ppm at 7% O_2)	11	9	10

Comparisons of data with and without oxygen during the high moisture run of 48 hr are difficult. The plan was to run the sludge pumping system at maximum [3 tons (2724 kg) per hour] with oxygen and record significant data, and then to run the system similarly without oxygen. The difficulty arises because the system cannot be run with maximum sludge pumping without oxygen. Without oxygen, the bed level became very high causing transference problems due to the grate system being overloaded, and, furthermore, the quality of the ash degraded significantly due to an increased concentration of unburned waste.

Due to the difficulty with reaching the maximum sludge output without oxygen, this portion of the comparison is not based on a set furnace temperature, but is based on maintaining a relatively constant steam flow output. The plan then was to see how much sludge the unit could take with and without oxygen before the quality of performance (steam production and ash quality) was significantly degraded.

	Without Oxygen	With Oxygen	% diff.
Tons Per Hour of Sewerage Sludge (14% Solids)	0.5 (454 kg)	2.25 (2043 kg)	+350%

Several points were noted by the operators that are significant:

(a) The depth of waste on the stoker was generally much less with the oxygen.

(b) The flame pattern as observed in the firebox appeared to improve. By that, the operator observed that no flame was seen to move above the overfire air ports when oxygen was used. Without oxygen, the flame occasionally will move all the way to the top of the firebox and sometimes impinge upon the superheater tubes. It should be noted that this facility does not modulate any of the combustion air dampers. (Installation of new dampers, damper actuators, and appropriate controls including continuous monitoring of O_2 and CO with feedback to the dampers is planned in 1988.)

(c) The furnace temperature remains closer to setpoint.

CONCLUSIONS

The age and condition of the refuse fired boilers combined with the limited money available for this experiment makes any conclusions suspect. There is no question that a modern plant and a comprehensive test program would produce better data. However, in spite of a limited budget and relatively primitive furnaces, boilers, support systems, and controls, the data does indicate the probability of a positive effect.

The most significant positive aspects are as follows:

(a) The quantity of steam produced per given mass of waste is increased by 6%.

(b) The quantity of waste processed with major furnace operating parameters identical is increased by 5%.

(c) The total steam production with major furnace operating parameters identical is increased by 11%.

(d) The amount of current needed to turn the induced draft fan motor was reduced by 9.8%.

(e) The amount of energy remaining in the ash was reduced by 47.5%.

(f) The amount of high moisture sludge that can be run through the system without significant degradation of the steam production and ash quality is much greater (350%) with the oxygen. This represents a variation per day from 12 tons (10896 kg) to 42 tons (37,800 kg).

(g) The thinner bed of burning waste on the grate system creates a decreased power demand on the grate drive system. It should be noted that the grate drive system at Harrisburg is due for a major rebuild in March of 1988 (the first in seven years). It should also be noted that the German manufacturer of the grate system expressed concern when informed of this experiment. The concern centered around the potential of too thin a bed of waste on the grates and the possibility of high temperatures on the grates combined with the oxygen rich environment causing damage to the grates. Understanding their concern, the depth of waste was carefully watched and never allowed to be less than 2 ft. Furthermore, visual inspections of the grate sections before and after the test noted no change in appearance.

In general, the benefits add up to a significant improvement in overall plant performance in terms of tonnage throughput, sludge throughput, and steam production. The impact of these improvements in performance is further enhanced by a significant reduction in the volume of the ash residue and a reduction in the electricity required to run the furnace/boiler.

The observations of an improved flame pattern are indications that the use of oxygen may reduce the frequency of waterwall tube failures.

The observations of a thinner bed of refuse on the grates may indicate reduced wear and tear on the grates, the grate drive system, and the hydraulic system that powers the grate drives.

It should be noted that this was a "first time" test, and therefore a great deal of refinement most probably can be done. This test was somewhat limited and of a short duration. There is a potential that similar percentage variations may be achieved with the use of less oxygen. This is based on the fact that during the test, the quantity of oxygen being mixed was reduced for about 5 hr by about 15%. There was no observed change in performance. In the future, we intend to further refine the usage of oxygen in the 360 TPD furnace/boiler with the intent of optimizing the balance between performance improvement and quantities of oxygen used. Several improvements to the system were incorporated after the test. These changes promoted better mixing in the underfire plenum and better resistance to particulate blockage in the mixing lances.

As noted above, the condition of the equipment and the limited time and money spent on the experiment prevent conclusive deductions. It would appear that oxygen enrichment of the combustion air can be beneficial to the operation of a waste-to-energy plant. A cost/benefit analysis may or may not support the usage of commercially delivered liquid oxygen. However, the situation at the Harrisburg Waste-to-Energy facility suggests an overall benefit due to the existing excess liquid oxygen that is produced by the advance wastewater treatment plant at a cost of about one-fifth the price of commercially delivered liquid oxygen.

The results of this limited experiment suggest that further investigation in a modern facility is merited.

REFERENCES

[1] Reuther, James J. and Hansel, James G. "Oxygen Enriched Coal and Coal-Water Slurry Combustion." Presented at American Flame Research Committee 1984 Symposium on Alternative Fuels and Hazardous Wastes, Tulsa, Oklahoma, October 9–11, 1984.

[2] Endicott, Wayne A. "Oxygen Boosts Plant Output." Brick and Clay Record, August 1985.

[3] Rappe, C., and Buser, H. R. "Formation and Degradation of Polychlorinated Dibenzo-*p*-dioxins (PCDDs) and Dibenzofurans (PCDFs) by Thermal Process." Presented at 178th National American Chemical Society Meeting, Washington, D.C., September 3–14, 1979.

[4] Westbrook, C. K., and Dryer, F. L. "Simplified Reaction Mechanism for the Oxidation of Hydrocarbon Fuels in Flames." Presented at Spring Technical Meeting, Central States Section, The Combustion Institute, Warren, Michigan, 1981.

[5] Hottel, H. C. and Williams, C. G. *Proceedings of the Tenth Symposium (International) on Combustion.* The Combustion Institute (1965) III.