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HIGH-TEMPERATURE VORTEX INCINERATOR

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HIGH-TEMPERATURE VORTEX INCINERATOR

By

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OFFICE OF RESEARCH AND DEVELOPMENT
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FOREWORD

Man and his environment must be protected from the adverse effects of pesticides, radiation, noise and other forms of pollution, and the unwise management of solid waste. Efforts to protect the environment require a focus that recognizes the interplay between the components of our physical environment--air, water, and land. The National Environmental Research Centers provide this multidisciplinary focus through programs engaged in

- studies on the effects of environmental contaminants on man and the biosphere, and
- a search for ways to prevent contamination and to recycle valuable resources.

The research efforts described herein represents a valiant attempt to advance the state-of-the-art of solid waste incineration. In addition to the goals of improved combustion efficiency, volume reduction, and mechanical reliability, this program sought to drastically reduce or eliminate completely the well-known environmental insults associated with many incineration practices.

Andrew W. Breidenbach, Ph.D.
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Although this report was written by Bob Thurnau and Don Oberacker, many others had a significant input into the concept, testing, or actual fabrication of the equipment. We acknowledge and thank, Russ Creager, Mark Dornhelm, Stan Graydon, Don King, Ken McHaffey, Boyd Riley, and John Sliter.

CONCLUSION

It was demonstrated that the experimental incinerator's design accomplished all of its anticipated goals except one. The main conclusion of this study was that efficient air pollution control devices are needed with incinerators, regardless of how well the combustion chamber is performing.

It was found that significant amounts of oxides of nitrogen were formed during the incinerators high temperature operation. These emissions could be controlled somewhat by allowing them to disintergrate automatically, and possibly be eliminated by installing a taller stack or extra duct work.

The feelings of those closely connected with this project indicate that the project was a significant step forward in advancing the art of incineration, particularly that of combustion chamber design.

INTRODUCTION

Problems of solid waste and its disposal are not new to mankind. When society was agrarian, the waste was simply stored out of the way or scattered about the landscape and nature took care of disposal.

As industrialization took over, however, and people began to concentrate in small geographical areas, the problems of waste management became quite pronounced. The move to the cities, coupled with a change in buying habits (hence disposal), magnified this problem to the point that it took political overtones.

Many communities followed earlier practices of letting nature take care of disposal and employed open-buring dumps as their answer to solid waste management. Communities with more foresight began to investigate composting, sanitary landfilling or incineration as better alternatives. These alternatives did not always live up to their expectations. Sanitary landfills began to resemple the old open dump, composting operations were expensive and an additional disposal method had to be used to account for the inorganic fraction of the waste, and incinerators produced a very poor quality residue, with associated smoke and odor problems. All in all, solid waste management techniques were quite poor.

The state-of-the-art for incineration progressed very little from its beginning in 1880 to the end of World War II. A short time after the war the age of one-way containers and other luxury items began in earnest. The character of the waste changed dramatically as did its volume. By the sixties, solid waste management had become a national problem as evidenced by the Solid Waste Act of 1965. Under the act, the disposal practices of the Nation were to be upgraded, and obviously one of the ways to accomplish this was to upgrade incineration practices. To help fill the gap between antiquated incinerators and the solid waste problem, work was initiated on a new type of incinerator--a high-temperature vortex incinerator. The project was sponsored by the U.S. Environmental Protection Agency, National Environmental Research Center-Cincinnati, Solid and Hazardous Waste Research Laboratory. Specifically, the incinerator was designed and built at the Center Hill Pilot Plant of SHWRL, and used only untreated municipal waste as its fuel. The project was initiated in 1967 and terminated in 1970.

INCINERATOR CONCEPT AND DESIGN

The power generating industry has explored the combustion of fossil fuel quite extensively. Although numerous texts and handbooks on fuels and combustion have been published, very little is published on using solid waste as a fuel or the characteristics of its combustion. Utilities use the heat derived from combustion to generate their product, and hence, they try to maximize the amount of heat that can be obtained from the fuel. Incinerators, on the other hand, are more interested in processing a prescribed amount of refuse per day without trying to maximize their heat release. In fact, many incinerators are designed to operate at relatively low temperatures, and efficient heat release would damage the combustion chamber. Thus, borrowing from the power companies, the intent of this project was to maximize the amount of heat released by the refuse while not damaging the combustion chamber, thus burning solid waste in an efficient manner with minimal air pollution.

If temperature is no longer a restraining force, then consideration must be given to other areas of the incinerator that will be affected by the increase in temperature. Changes in refractory type and design, elimination or modification of the grates, slag formation and removal, charging and stoking mechanisms, and air pollution control equipment would have to be made if the idea of improved incineration by increased heat release were to become reality.

The final concept envisioned a horizontal refractory-lined cylinder into which refuse was fed by a hydraulic ram. The stoking action would be accomplished by the incoming refuse pushing the burning refuse across the floor of the incinerator and finally out the other side into the residue pit. This kind of stoking would also eliminate the need for grates. Any slag that was formed would flow or be pushed into the residue pit. The combustion air would be delivered to the combustion chamber via a manifold, and distributed in such a manner as to set up a circular or vortex action. This, in addition to providing mixing and turbulence, would also aid the stoking mechanism by exposing more burning surface to combustion. Since high temperature was one of the design objectives, heating the incoming combustion air was necessary. This was accomplished by a counter-current heat exchanger where the hot exhaust gases pass through a refractory-lined cyclone and were finally delivered to the atmosphere by a 15-foot-high stack.

EXPERIMENTAL APPARATUS AND METHODS

Construction of the incinerator proceeded with very few changes in the original concept. The finished unit was a horizontal cylinder 3.66 m (12 ft) and 1.83 m (6 ft) in diameter. The inside diameter was 1.22 m (4 ft) with 0.3048 m (1 ft) of fire brick and castable refractory surrounding the combustion chamber. Refuse was stored in a 2.29 m^3 (3 $ft.^3$) hopper and was charged to the incinerator by a hydrolyic system through a rectangle opening whose cross sectional area was 0.372 m^2 (4 ft^2). The combustion air was supplied by two manifolds with 15 nozzels each. The manifolds were located on the incinerator to produce a cyclonic or vortexing action when suppling air. The nozzels were 1.27 cm (1/2"), 1.59 (5/8) and 1.91 (3/4) and were used to regulate velocity and volume of the preheated combustion air. A blower capable of suppling 42.48 standard cubic meters (1500 ft^3) of air per minute at a pressure of 1.397 m (55") of water was used as the source of the combustion air. A counter current heat exchanger of 12, 7.62 cm (3") tubes was over the exit of the incinerator and used to preheat the incoming air to about 260° C (500°F). The desired burning rate was 453.6 Kg/hr (1000 lbs/hr) with a 90% volume reduction and an 80% weight reduction. The cyclonic movement of the gases down the combustion chamber was to provide at least 1/2 second residence time at temperatures in excess of 1315°C (2400°F). Figure 1 shows the final design of the incinerator.

The main parameter measured was temperature. By viewing temperature profiles during operation one could observe how efficiently the unit was operating. Chromel-alumel thermocouples were used in all locations except for directly over the burning face. The extreme temperatures of the primary combustion area necessitated a Rodium type thermocouple. Temperatures cited during the text of the paper refer to this thermocouple unless stated otherwise.

Gas sampling for carbon monoxide, carbon dioxide, oxygen, nitrogen, oxides of nitrogen, and HCl were carried out using the proportion sampling techniques. A sample rate of about 1 l/min. was employed for both intregrated bag samples as well as on line infarred analyzers.

Particulate sampling was done in accord with the methods and techniques published in the Federal Register Volume 36, Number 247, December 23, 1971. This method is commonly known as the "EPA Method."

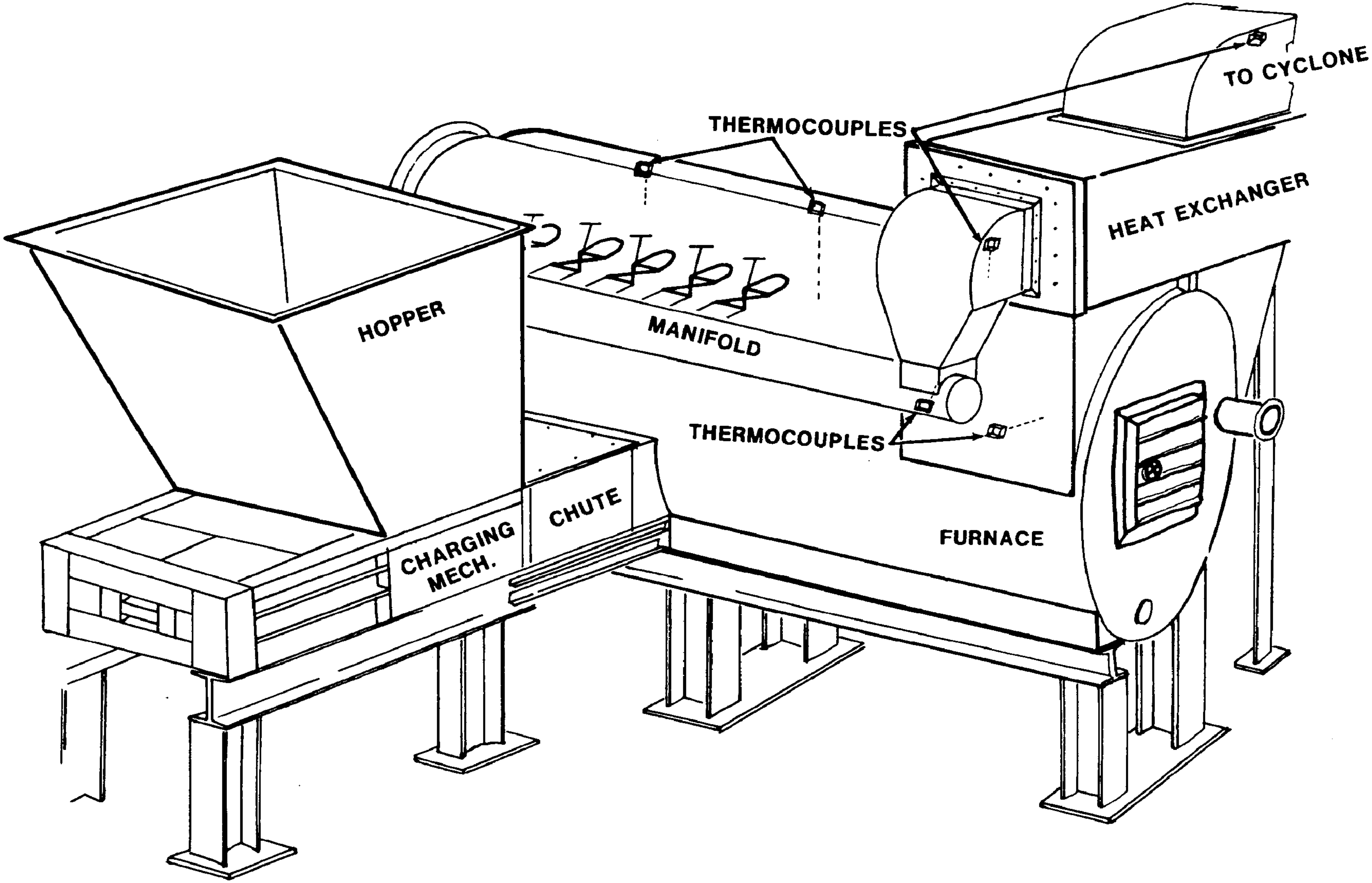

Figure 1. VORTEX INCINERATOR

EXPERIMENTAL RESULTS

The results observed in operating the experimental vortex incinerator will be discussed in two groups, conditions in the combustion chamber, and conditions in the stack.

I. Conditions in the Combustion Chamber:

A. Burning Rate:

Municipal incinerators are usually identified by the amount of waste they can burn during a twenty-four hour day. Typical municipal units are rated at about 226.8 m-tons/day (250 tons/day). Thus the identification of a unit is also its burning rate and this parameter becomes one of the standard criteria in incinerator design and construction. If the burning rate is overloaded, the combustion chamber cannot effectively handle the load resulting in poor combustion, excessive particulate entrainment, and poor residue quality. If the incinerator is underloaded, the pollution problems might not be as severe, but it may become uneconomical to run and could generate vaporous odors.

The experimental vortex incinerator was designed to burn about 454.6 Kg/hr (1000 lbs/(hr) of untreated municipal refuse. Table 1 is a summary of the burning rates for a typical run. After a warm-up period of about 3 to 4 hours, steady state conditions appear to exist and the incinerator burned on the average 616 Kg/hr (1240 lbs/hr) with a maximum of 757 Kg/hr (1730 lbs/hr) and a minimum of 494 Kg/hr (1090 lbs/hr). When compared with the designed burning rate, the actual burning rate is about 24 percent higher.

After preheating the unit, it was expected that the burning rate would be constant. This assumes, however, that the other operating parameters are reasonably constant, and that maximum heat is being released. However, as the temperature varies, so does the burning rate. If the data from Table 1 is plotted (Fig. 2), the burning increases as the temperature

Table 1. BURNING RATE FOR TYPICAL RUN

Hopper No.	Weight Charged Kg	Burning Time Min.	Average Temp. C^{C}	Burning Rate Kg/hr
8	174	20	1189	527
9	211	23	1239	550
10	251	22	1211	685
11	247	30	1244	494
12	283	25	1194	679
13	219	22	1250	597
14	227	18	1333	757
15	202	19	1319	638
16	162	19	1319	512
17	237	20	1341	718
		Average burning rate =		616

increases and levels off at about 650 Kg/hr (1430 lbs/hr). This is to be expected because at this point the amount of oxygen delivered to the combustion chamber becomes the limiting factor in this relationship. Using 1.293 g/l (0.0808 lbs/ft^3) as the density of air and assuming oxygen to be twenty percent of the air it is found that oxygen is being supplied at a rate of 660 Kg/hr (1454 lbs/hr) or being used as fast as it was supplied.

Once the burning rate has been established, the size of the combustion chamber, and hence the overall size of the incinerator will also be known. This is very important

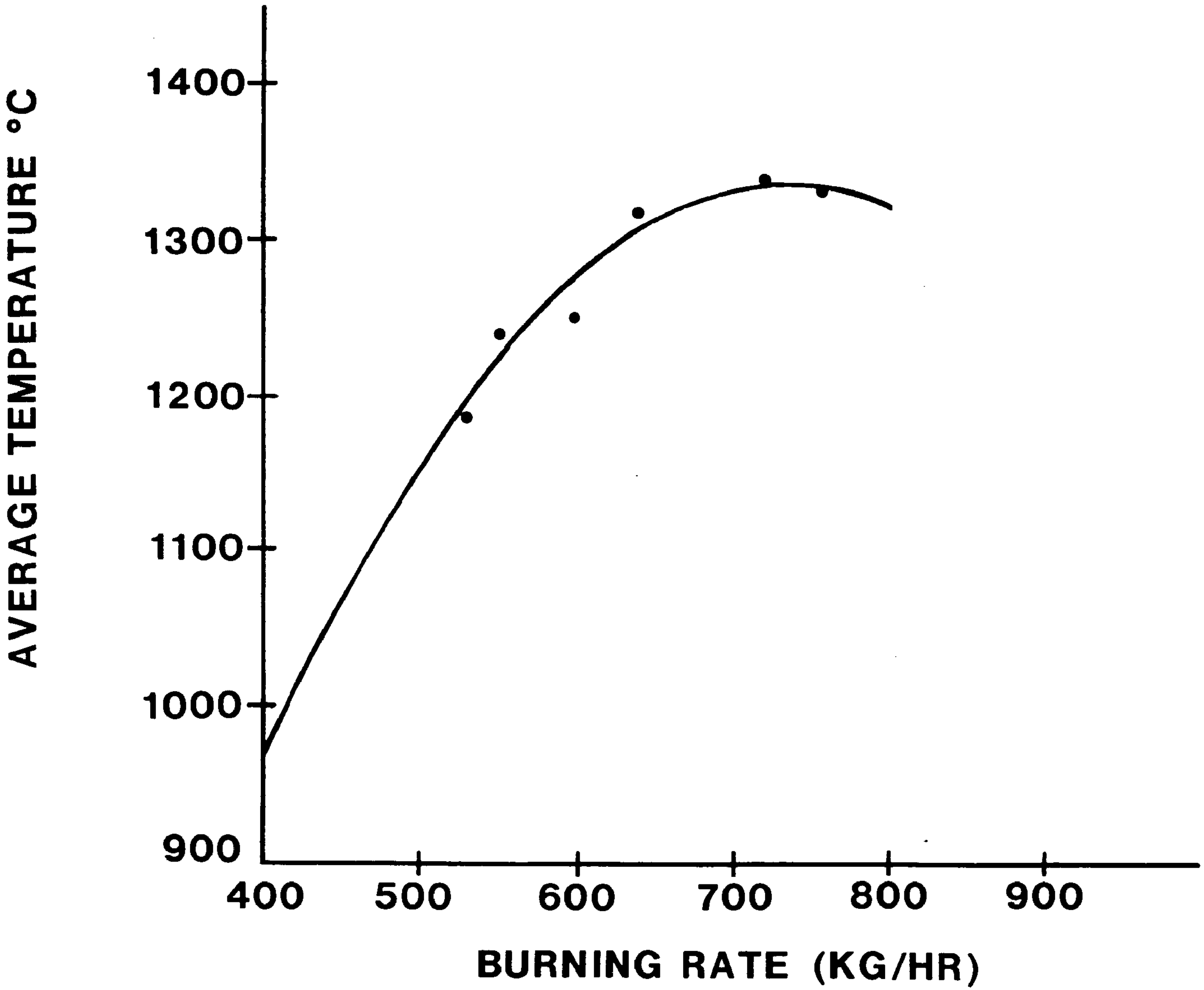

Figure 2. AVERAGE TEMPERATURE VS. BURNING RATE

especially since the costs seem to be exponentially related to the size. Presently, the guideline used by many grate designers is 293 Kg/hr/m^2 (60 lbs/hr/ft^2). The grate area of the vortex incinerator was 1.48 m^2 (16 ft^2) and if the average burning rate is used, the burning rate per square meter of grate was 413.7 Kg/hr (77.5 lbs/hr/ft^2).

B. Combustion Chamber Efficiency:

In addition to the burning rate, the design of the combustion chamber can greatly influence the efficiency of combustion. A poorly designed combustion chamber will allow particulates and gaseous combustion products a direct route to the atmosphere. To insure superior combustion, the experimental incinerator was specifically designed to increase turbulance in the combustion zones, increase the residence time of both solids and gases, and increase the agglomeration of the refuse while burning. The evaluation of combustion efficiency can be conducted in several ways.

One measurement of combustion efficiency is the concentration of carbon dioxide in the combustion chamber and throughout the incinerator system. Initially, the carbon dioxide, measured as percent by volume, was distributed in the incinerator as:

Combustion Chamber	..... 2.75
Midstack	.....10.3
Top stack	.....10.7

It appeared as though the oxidation of combustion gases to carbon dioxide was taking place outside the primary combustion chamber. This was not the design condition since some of the heat release was outside the primary chamber. To alleviate the incomplete combustion of carbon dioxide in the combustion chamber, a baffle wall that caused additional mixing and turbulence was added. After the baffle wall was added, carbon dioxide distribution improved:

Combustion Chamber	.....	10.2
Midstack	.....	11.5
Top stack	.....	11.7

These relatively high carbon dioxide levels indicate that the combination efficiency of the vortex incinerator's combustion chamber was quite good, and with the slight modification of a baffle wall meet the design specifications.

A second method for judging combustion efficiency is to observe the amount of unburned organic material in the exhaust gas. Poor combustion efficiency will result in high concentrations of organic pollutants, and usually reflect the inefficient design of the combustion chamber. Data taken from the vortex incinerator showed that the organic fraction varied between 1.1 and 2.0 weight percent of the total. Data presented at the 1970 National Incinerator Conference[1] showed that a pilot scale unit utilizing a scrubber and an afterburner had about a 10 percent by weight organic fraction, and full scale commercial units averaged about 14.6 percent by weight. These data clearly show that the vortex incinerator was efficiently burning municipal waste by its low output of organics.

A third method of judging combustion chamber efficiency is to observe the concentration of particulate being emitted from the furnace. It was found that the particulate loading for a typical run was 2.243 g/sm^3 (0.98 grains/sft^3). Furnace emissions for a 226.8 Kg/hr (500 lbs/hr) incinerator pilot plant[2] showed a somewhat larger value of 2.816 g/sm^3 (1.23 grains/5ft^3). Furnace emissions from three types of municipal incinerators are presented for comparative purposes. Because the data were not taken in the government-endorsed manner (i.e., the condensable fraction was not collected) only the dust loadings from the combustion chamber before entering any of the air pollution control devices are compared (Table 2).[3]

Table 2 Furnace Emissions Based on Design

Type	Gram Loading Per /5m^3
Experimental vortex incinerator	0.757
250 T/D traveling grate	1.265
250 T/D reciprocating grate	1.587
120 T/D rocking grate	0.778

The results indicate that the furnace emissions from the experimental incinerator are lower than either the pilot scale incinerator or full scale commercial units.

Another facet of furnace emissions is the size of the emitted particle. Under normal conditions the more complete the combustion the smaller the particulate. To better understand the overall combustion characteristics, the particle size of the particulate being emitted from the experimental incinerator were determined (Table 3).

Table 3. STACK PARTICULATE ANALYSIS

Source of particles (filter #)	Lab. sample no.	Wt. of particles analyzed (mg)	Percent by weight, in specified fraction				
			A (>125 μ)	B (<125 μ >105 μ)	C (<105 μ > 47 μ)	D (<47 μ >12 μ)	E (<12 μ)
0246	164	32.9	3.95	0.00	3.04	1.22	91.79
0153	160	89.2	2.58	0.67	6.06	4.37	86.32
0156	162	92.3	1.84	0.00	4.11	1.74	92.31
0158	163	6.8	0.00	4.41	7.35	0.00	88.24

It can be easily seen that most of the particulate was 12 μ or less. To understand the particle size of the 12 μ fraction its distribution was studied. (igure 3). At least 50 percent of the sample was less than 2 microns. It should be noted that the particle size distribution was carried out on material collected after the air pollution control device, and not on the dust emitted directly from the combustion chamber. It is believed that the data is representative and the vortex incinerator is responsible for the small particle size.

The more classical approach to evaluating incinerator combustion chambers revolved around volume and weight reductions of the fuel, and heat release rates.

Refuse is a bulky fuel with low density, and the volume reduction or densification is a standard criteria for measuring efficiency. When 50.5 cubic meters (66 yd^3) of refuse was burned in the vortex incinerator, the resulting residue occupied 2.29 cubic meters (3 yd^3), a 95 percent volume reduction. Conventional incinerators are usually designed for volume reduction of 80 to 90[4] percent. In comparison to conventional incinerators the volume reducing ability of the vortex incinerator was very good.

Weight reduction of the waste is also of interest to incinerator designers and operators. The weight of the residue is compared with the weight of the refuse, and the difference is the overall weight reduction. For the case sited above, the weight reduction was 70 percent; this compares favorably with published data on incinerator design.[5]

Another parameter used to design incinerators is the heat release rate per cubic meter (ft^3) of chamber volume. If too much heat is released,

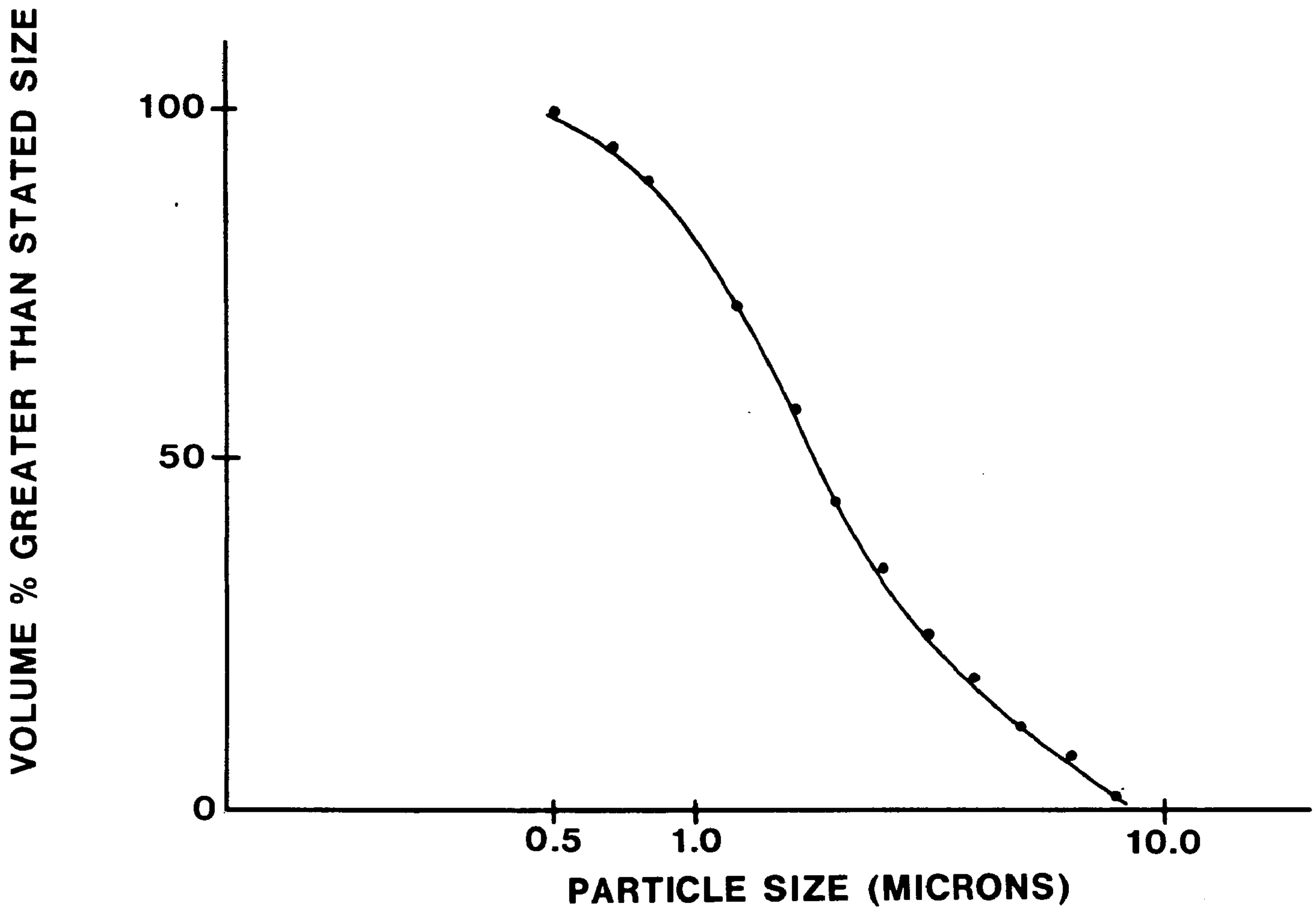

Figure 3. VOLUME PERCENT GREATER THAN STATED SIZE VS. PARTICLE DIAMETER

serious damage could be caused to the metal sections of the combustion chamber, and if too little heat is released, poor combustion will result. A common value employed as the heat release rate design standard is 106,855 K cal/hr/m^3 (12,000 BTU/hr/ft^3).(6) Using a calorific value of 3365 cal/g (6057 BTU/lb) for the refuse and 850 cal/g (1530 BTU/lb) for the residue, the heat release rate for the vortex incinerator was 384,000 K cal/hr/m^3 (43,132 BTU/hr/ft^3). This heat release rate is about 3 times the accepted value and demonstrated that high heat release rates could be used with municipal solid waste.

II. Conditions in the Stack:

The underlying aim of the vortex incinerator project was to develop and test an incinerator that would burn untreated municipal refuse efficiently at high temperatures with a minimum amount of air pollution. As discussed earlier the combustion chamber performed were, but oddly enough the efficient burning resulted in several emission problems.

Particulates:

An earlier point was that the better the combustion, the finer the resulting ash. This type of ash is desirable when considering combustion efficiency but undesirable from an air pollution control standpoint.

In Table 4, the data from two stack tests are presented so that the relative amounts of the solid, water soluble, and organic fraction of the total particulate can be observed. The emission rate endorsed by the Government at the time of the test was 0.458 grams per standard cubic meter corrected to 12 percent carbon dioxide (0.2 grains/scf at 12% CO_2). It can be seen that on both occasions the incinerator failed to meet the emission regulations with the best effort being 1.428 grams per standard cubic meter corrected to 12 percent carbon dioxide.

In conjunction with the second test, the removing efficiency of the cyclone was determined. The ratio of the amount of dust removed to the total incident dust loading is defined as efficiency. It was found that only 0.81 grams per standard cubic meter corrected to 12 percent carbon dioxide (0.35 grains/scf @ 12% CO_2) was collected out of 1.646 grams per standard cubic meter corrected to 12 percent carbon dioxide (0.709 grains/scf @ 12% CO_2) or 50 percent efficiency.

Gases:

In addition to the particulate problems originating in the combustion chamber, the elevated temperature and excellent oxidizing conditions

Table 4 STACK INVENTORY

	CONCENTRATION EXPRESSION	FRACTION PARTICULATE (PROBE & FILTER)	WATER SOLUBLE (CYCLONE & IMPINGERS)	ORGANIC CONDENSABLE (IMPINGERS)	TOTAL
July 1970	grams/scm (grains/set)	0.727 (0.313)	0.506 (0.218)	0.021 (0.009)	1.254 (0.540)
Jan. 1971	grams/scm (grains/scf)	0.834 (0.359)	0.625 (0.269)	0.019 (0.008)	1.477 0.636
July 1970	grams/scm @ (grains/scf @) 12% CO_2	0.873 (0.376)	0.601 (0.259)	0.030 (0.013)	1.483 (0.648)
Jan. 1971	grams/scm @ 12% CO_2 (grains/set @) 12% CO_2	0.817 (0.352)	0.615 (0.265)	0.016 (0.007)	1.428 (0.624)
July 1970	grams/scm @ 50% Excess Air (grains/scf @ 50% Excess Air	0.715 (0.308)	0.492 (0.212)	0.030 (0.013)	1.233 (0.531)
Jan. 1971	grams/scm @ 50% Excess Air grains/scf @	 0.887 (0.382)	 0.662 (0.285)	 0.019 (0.008)	 1.567 (0.675)

Table 4 (Continued)

	CONCENTRATION EXPRESSION	FRACTION PARTICULATE (PROBE & FILTER)	WATER SOLUBLE (CYCLONE & IMPINGERS)	ORGANIC CONDENSABLE (IMPINGERS)	TOTAL
July 1970	grams/cm @ stack conditions	0.176	0.121	0.023	0.320
	grains/cf @ stack conditions	(0.076)	(0.052)	(0.010)	(0.138)
Jan.1971	grams/cm @ stack conditions	0.239	0.183	0.005	0.427
	grains/cf @ stack conditions	(0.103)	(0.079)	(0.002)	(0.184)

produced several undesirable gaseous emissions.

Oxides of nitrogen occur in most combustion processes. The general belief is that they result from the direct fixation of atmospheric oxygen and nitrogen at elevated temperatures, and are monitored because they are quite toxic. The experimental incinerator attempted to control oxides of nitrogen by controlling the combustion. If refuse were burned stoichiometrically, there would be no oxygen left to be fixed with the nitrogen. The incinerator, however, was not consistently run at stoichiometric conditions and significant amounts of oxides of nitrogen were produced.

In Table 5, the oxide of nitrogen data are presently chronologically, and the results show a trend toward decreased emissions. The reason proposed for this trend is that better combustion conditions were achieved, i.e., closer to stoichiometric and less available oxygen for reaction with nitrogen. Initially, the incinerator ran at about 80 percent excess air, but as work continued on the unit this figure dropped to about 50 percent.

It was clear that oxides of nitrogen were not controllable by controlling the combustion, and therefore another method of control was employed. Oxides of nitrogen are unstable compounds and the reverse reaction (i.e., going to oxygen and nitrogen) is favored over the forward reaction. As long as the reaction is not quenched (sudden drop in temperature) the reverse reaction continues and lessens the nitrogen oxide concentration. A typical oxide of nitrogen profile for the vortex incinerator is shown below. The emissions from the combustion chamber were the highest, but dropped significantly as the gas passed through the system to the atmosphere.

Combustion chamber	.....	113 ppm
Midstack	.....	80 ppm
Top stack	.....	49 ppm

At the time of the project there were no oxides of nitrogen emission regulations, but if the project was to continue for a long period of time an alternate method of oxides of nitrogen control would be desired.

Hydrochloric acid was also determined with oxides of nitrogen. On the average, hydrochloric acid was found to be 150 parts per million by volume. No correlation was found between the operating parameters and the acid concentration, but it is suspected that relationship between fuel composition and acid concentration could be found if studied.

Table 5. OXIDES OF NITROGEN CONCENTRATIONS

Date	NO_x concentration	Date	NO_x concentration
1/29/70	142	5/26/70	158
	132		237
	125		182
	152		
		6/9/70	122
2/4/70	173		100
	216		193
			160
2/20/70	140		104
	177		
	128	7/14/70	102
	131		146
			86
3/4/70	146		
	128	9/24/70	93
	106		47
	132		43
4/2/70	129	10/1/70	58
	184		93
	158		21
4/7/70	240	10/10/70	94
	73		68
			79
5/16/70	171		
	184		
	266		

DISCUSSION

The data collected on the vortex incinerator's combustion chamber indicated that it did a very effective job in burning untreated municipal refuse. Low particulate concentration, small particle size, high heat release rates, and high carbon dioxide concentrations indicated the combustion chamber did the job for which it was designed. The burning rate was higher than the design specifications, but was necessary to sustain high combustion temperatures. The result of the elevated burning rate was a poorer quality residue even though the volume and weight reductions were acceptable.

Conditions in the stack are what led to the termination of the project. On the two occasions that a complete stack test was conducted, the concentration of particulate (as defined by EPA) was in excess of the established regulation. There are several reasons why the incinerator failed the particulate emission regulations. First, was the selection of a large diameter [1.37 m (4-1/2 ft] cyclone. This was initially selected because it could be refractory lined and withstand the hot temperatures [815°C, (1500°F]. It is common knowledge that the larger the diameter of a cyclone, the more inefficient it becomes. As stated earlier, the cyclone had an efficiency of about 50 percent and this is just not good enough to meet federal regulations.

The second reason why the incinerator failed to meet the emission regulations revolves around how particulate is defined. At the time of the test "Any material that was a solid or liquid at 760 mm @21.1°C (29.92 inches Hg @70°F) was considered particulate." Table 4 shows the breakdown of the data in relation to where it was caught, and how it is expressed. The particulate fraction refers to the actual solid material caught in the probe, in the cyclone and on the filter. The water soluble fraction is determined by what is left after evaporation of the water collected in the cyclone and impingers. The organic fraction is extracted from the collected water with chloroform and ether and evaporated. Total particulate is then (by definition) the sum of these three fractions. A close inspection of the data in Table 4 shows about 40 percent of the particulate to be present in the water of the combustion gas. Since the cyclone usually doesn't disintrain gases (for moisture), 40 percent of the accountable particulate is escaping untouched. Thus, this condition makes it almost impossible to meet any regulations.

A combination of poor cyclone efficiency and a large water soluble fraction of particulate led to unsatisfactory levels of particulate in the stack.

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6. Ibid

APPENDIX A

The concept of this vortex incinerator may seem straight forward, but its design, development, and fabrication was far from trouble free. It is not the intent of this report to belabor the project's mistakes and failures, but some of the larger problems and their solutions bear some mention.

Probably the biggest problem associated with the incinerator was the existence of a large, positive pressure in the combustion chamber. This positive pressure resulted from a combination of the high-velocity inflow of combustion air necessary for the stoking and vortex action and the frictional pressure losses of the heat exchanger and cyclone. The positive pressure forced a change from continuous operation to batch operation. For the incinerator to run at all, the combustion chamber had to be sealed off at the feed end. This was accomplished by a charging chute cover. Gaskets and clamps on this cover helped to seal the pressure in, but we found it impossible to prevent some smoke leakage from the charging chute. Leakage meant that whenever we wanted to add refuse to the charging chute, the pressure had to be reduced by (1) shutting the combustion air off and then (2) opening the charging chute cover. This interruption caused many problems, including the overheating of our heat exchanger and a severe, combustion-chamber temperature drop. This batch operation undoubtedly affected the stack samples that were taken during the various tests.

Problems were also experienced with the materials handling system. A plug of compacted refuse would not keep the smoke from backing out unless the plug was packed so tight that it jammed the chute. In addition, problems of insufficient stoking and unreliable residue removal were encountered. Materials such as cardboard and large pieces of plastic would not be sheared by the ram and would bind in the hopper. Every time a jam occurred, the operation had to be shutdown and the jam broken manually. Adding a system of blades, cables, and pulleys inside the hopper later solved this problem. Whenever the ram was pushed forward, a blade was pulled up the back of the hopper freeing up any materials that had a tendency to bridge. On the ram's back stroke, the blade would return downward forcing the refuse in front of the ram into the chute for charging. This technique was very effective and eliminated about 90 percent of the binding problems.

The residue and its removal from the combustion chamber presented another problem. Since there were no grates, we had to rely on the incoming fuel to push the residue out. As the temperature increased, the metal cans and glass bottles began to soften and fuse together. When pushed toward the residue pit, they began to bind and catch in the opening and thus, closed off the residue removal. To overcome this problem, an extension of the ram was added so that it would push any bridged material into the residue hopper. This extension was water cooled so that it could exist at the elevated temperatures. The ram extension performed quite well.

APPENDIX B. HEAT EXCHANGER DESIGN

I. Design Conditions

The principle of preheating combustion air is called either "recuperation" or "regeneration" in the coal-fired, boiler field. In the case of this incinerator, the principle is recuperation since the heat is transferred directly to the air. Regeneration, by contrast, involves an intermediate heat storage material such as pebbles or heat storage liquids.

The heat exchanger design was based on the following conditions:

- Combustion air flow rate: 71.22 kilograms per minute (157 pounds per minute) or 58.34 cubic meters per minute (2,060 cubic feet per minute) at standard conditions.
- Blower heating effect: ambient air is friction-heated to 65.6°C (150°F).
- Heat-exchanger air side-pressure drop: approximately 8.89 centimeters (3.5 inches) of water.
- Air temperature desired at heat exchanger outlet: 315°C (600°F) up to 426°C (800°F).

The conditions on the flue gas side of the heat exchanger are:

- Flue gas flow rate: 198.2 cubic meters per minute (7,000 cubic feet per minute).
- Flue gas temperature: 1,204°C (2,200°F), average.
- Allowable pressure drop: 0.51 centimeters (0.2 inches) of water.

Other considerations in the heat exchanger design were:

- Physical size: space approximately 40.6 centimeters (16 inches) x 48.3 centimeters (19 inches) x 182.9 centimeters (72 inches). The 182.9 centimeter dimention was a horizontal plane. A counterflow design for maximum recuperative heat transfer.
- Materials of Construction: mild, structural grade steel for reasons of minumum cost ana maximum availability. Future units would require a material with optimum high-temperature service qualities; for the experimental units, a short service life was considered acceptable.

II. Design Calculation, Round Tube Heat Exchanger

The first heat exchanger unit tried was a bank of 12 round tubes. Each tube was a 1.83 meter (6 feet) length and 7.62 centimeters (3 inches) black-iron pipe. Combustion air flowed on the inside of the 12 pipes while the flue gases flowed over the outside. The design calculations for this first unit are:

- Tube size: 1.83 meters (6 feet) length os 7.62 centimeters ! (3 inches) block-iron pipe; outside diameter 8.89 centimeters (3.5 inches): inside diameter 7.793 centimeters (3.068 inches).
- Combustion air velocity: 17.77 meters per second (58.3 feet per second) inside the tubes.
- Reynolds number inside tube: 36,600.
- Air-to-air heat transfer coefficient: 61.52 kilocalories per hour per square meter per degree Centigrade (10.7 BTU per hour per square feet degrees Fahrenheit) based on $Nu = 0.02 (Re)^{0.8}$.
- Flue gas velocity over outside of pipe: 51.56 kilometers per hour (47 feet per second).
- Flue gas Reynolds number: 24,300.
- Flue gas heat transfer coefficient: 87.98 kilocalories per hour per square meter per degree Centigrade (15.3 BTU per hour per square feet per degrees Fahrenheit) based on $Nu = 0.02 (Re)^{0.8}$
- Overall heat transfer coefficient 34.5 kilocalories per hour per square meter per degree Centigrade (6.0 BTU per hour per square feet degrees Fahrenheit).
- Heat transfer area: 145,152 kilocalories per hour (576,000 BTU's per hour) at approximately one-half of design air flow.
- Heat transfer area: 5.44 square meters (58.5 square feet) (actually, about 11.24 square meters (121 square feet) would be required at full design air flow).
- Combustion air outlet temperature: 315.5 degrees Centigrade (600 degrees Fahrenheit) predicted at half of design air flow.

This first heat exchanger with twelve 7.62 centimeters (3 inches) pieces was operated for approximately 50 hours at which time the pipe material disintegrated. The condition of the pipes is shown in the following pictures. Metallurgical analysis determined that the disintegration was caused by high-temperature oxidation.

The thermal performance of the first heat exchanger was unsatisfactory. The combustion air temperatures leaving the heat exchanger were only 148.9 to 204.4°C (300 to 400°F) for air flows between 42.48 and 56.64 cubic meters per minute (1500 to 2000 cubic feet per minute). The 12-pipe configuration lacked sufficient heat transfer area, 5.44 square meters (58.5 square feet) compared with the required 11.24 square meters (121 square feet) needed when full air flow exists.

The design selected for the second heat exchanger was also a bank of tubes with the combustion air flowing inside the tubes. Flue gases passed over the outside of the tubes in counterflow fashion. This time, the tubes were 3.81 centimeters (1-1/2 inches) (outside dimension) square tubes with a wall thickness of 0.476 centimeters (3/16 inches). Seventy tubes were stacked in seven vertical columns, 10 tubes hich with a 3.81 centimeters (1-1/2 inches) spacing between each column. This design, shown in the following pictures, effectively increased the air preheating. The air-side heat transfer area increased by a factor of 3 and the flue gas-side area increased by a factor of 2. In addition, this design effectively lowered the tube material operating temperature, and thereby increased the heat exchanger life.

Some representative design calculations for the 70-tube heat exchanger are:

- Heat exchanger tubes: quantity 70; square; 3.81 centimeters (1-1/2-inch) outside diameter, 0.478 centimeter (0.188 inch) wall thickness, 182.9 centimeters (72 inches) long.
- Combustion air flow area: 8.162 square centimeters (1.265 square inches) per tube, 571 square centimeters (88.5 square inches) total (0.0571 square inches).
- Air flow velocity: 28.13 meters per second (9.13 feet per second).
- Air Reynolds number 23,600, average.
- Air pressure drop: 6,655 centimeters (2.62 inches) of water (tube only).
- Air side heat transfer area: 14.63 square meters (157.5 square feet).

$$\frac{h}{C_p G} \frac{C_p \mu}{k}^{2/3} = \frac{.023}{\left(\frac{DG}{\mu}\right)^{0.2}}$$

h = 64.407 kilocalories per hour per square meter per degree Centigrade (11.2 BTU per hour per square feet of degree Fahrenheit).

- Flue gas-side calculations: gas-side heat exchanger aara 9.755 square meters (105 square feet).
- Flue gas heat transfer coefficient: $h = 0.30 \frac{C_p G^{0.6}}{D^{0.4}}$
- h = 71.883 kilocalories per hour per square meter per degree Centigrade (12.5 BTU per hour per square feet degrees Fahrenheit).
- Flue gas temperature entering heat exchanger: 1,204°C (2,200°F).
- Flue gas temperature leaving heat exchanger: 782°C (1,440°F).

- Log mean temperature: 793°C (1,460°F).
- Quantity of heat transferred: 277,200 kilocalories per hour (1,100,000 BTU's per hour).
- Overall heat conductance coefficient 401.5 kilocalories per hour per degree Centigrade (752 BTU's per hour per degree Fahrenheit).
- Flue gas flow area: 0.116 square meters (1.25 square feet).
- Calculated combustion air preheat temperature: 343.3°C (640°F).

The upper four pictures (Views A-1 show the incinerator's cyclone and stack area during a typical stack sampling test. View E shows the incinerator feed hopper and air manifold. View F, inside the feed hopper, shows the ram blade.

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(Please read Instructions on the reverse before completing)

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16. ABSTRACT

This study was designed to help fill the gap between antiquated incinerators and the solid waste problem. Work was initiated on a new type of incinerator--a high-temperature vortex incinerator. The project was sponsored by the U.S. Environmental Protection Agency, National Environmental Research Center-Cincinnati, Solid and Hazardous Waste Research Laboratory. Specifically, the incinerator was designed and built at the Center Hill Pilot Plant of SHWRL and used only untreated municipal waste as its fuel.

17. KEY WORDS AND DOCUMENT ANALYSIS

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