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nt emissions from fluidized bed ...wage sludge incinerators

10.1.4.2.0
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Gaseous emissions from a properly operated fluidized bed sewage sludge incinerator appear well below any current pollutant emission standards; particulate matter is the significant pollutant.

10.4.0.2.5
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LIAO, P. B.

By Paul B. Liao and Michael J. Pilat*

As sludge production by United States sewage treatments plants increases, the problem of its disposal will become more serious. A recent federal report pointed to incineration as potentially the most feasible sludge disposal method.[1]

A problem connected with sludge incineration methods, which include fluidized bed, multiple hearth, flash drying and incineration, atomized suspension firing and wet air oxidation,[2] is air pollution. This paper deals with the air pollutant emissions produced by a fluidized bed sewage sludge incinerator.

Fluidized bed incinerator. A fluidized bed sewage sludge incinerator system consists of a sludge thickener, centrifuge or equivalent, sludge feeder, preheat burner, air distribution box (fluidized sand supporter), air blower, combustion chamber, exhaust pipe (chimney), air pollution control facility (usually scrubber), cyclone (solid separator) and an ash pit (Fig. 1). Silica sand is placed in the combustion chamber. Air is applied underneath and goes through the air box to force the sand into suspension, creating a fluid-like mixture of sand and gases. The fluidized bed is preheated to operating temperature, and dewatered sludge fed into it. The combustion products, inert ashes and finer fluidizing sand are carried out of the combustion chamber by the exhaust gases, which are treated by a scrubber before emission into the atmosphere.

Test program. Air pollutant emissions from fluidized bed incineration include particulates, CO, CO_2, SO_2, NO_x, hydrocarbons and water vapor. A test program was designed to measure these emissions and to determine whether or not they varied with variable conditions. Samples to be tested were taken upstream of air pollution control systems so that the measurements would be accurate.

Two fluidized bed incinerators, located at Lynnwood and Edmonds in Washington, were used in the test program. The Lynnwood incinerator, 4 ft in diameter and about 17 ft high, was the first commercial unit installed (1961) in the United States. It was designed with a capacity of 220 lb dry sludge/hr. The Edmonds incinerator was constructed in 1967 to handle 500 lb. dry sludge/hr. It is 6 ft in diameter and approximately 22 ft high.

The flow diagrams of both plants are identical, and they are similar to that in Fig. 1. Sewage sludges collected in the primary clarifiers are pumped to a sludge thickener for concentration and then to a centrifuge for further dewatering. The dewatered sludges which are 65 to 75 percent moisture, are injected by means of a screw feeder into the reactor. In the reactor sludge is rapidly mixed with fluidized sand, dried and burned, leaving inert ashes in the exhaust stream. A scrubber treats the exhaust gases before emission to the atmosphere.

Sampling procedures. Sampling trains (Fig. 2) were used to collect exhaust gas and particulate samples at various operating conditions and different sludge loadings before and after the scrubber, at both the Lynnwood and Edmonds incinerators. Tests were made on the samples collected to determine particulate mass concentration (grain loading), size distribution and concentrations of SO_2, NO_x, CO, CO_2, O_2, N_2 and water vapor.

Particulate mass concentration and size distribution were measured using an alundum thimble[3] and University of Washington cascade impactor[4]

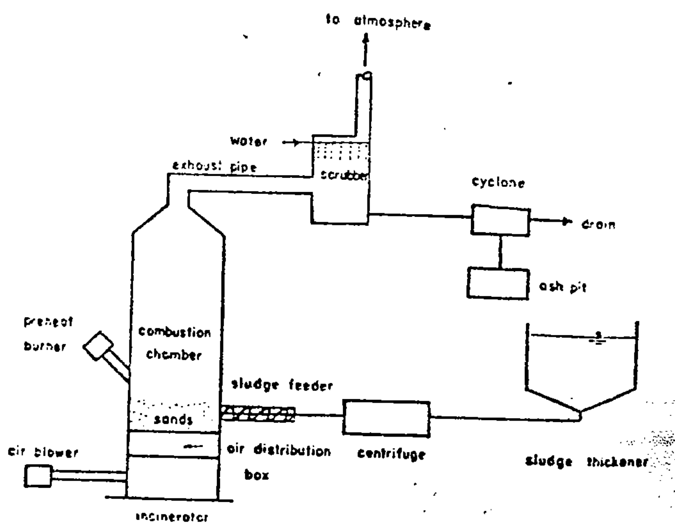

FIGURE I. FLUIDIZED BED SEWAGE SLUDGE INCINERATION SYSTEM

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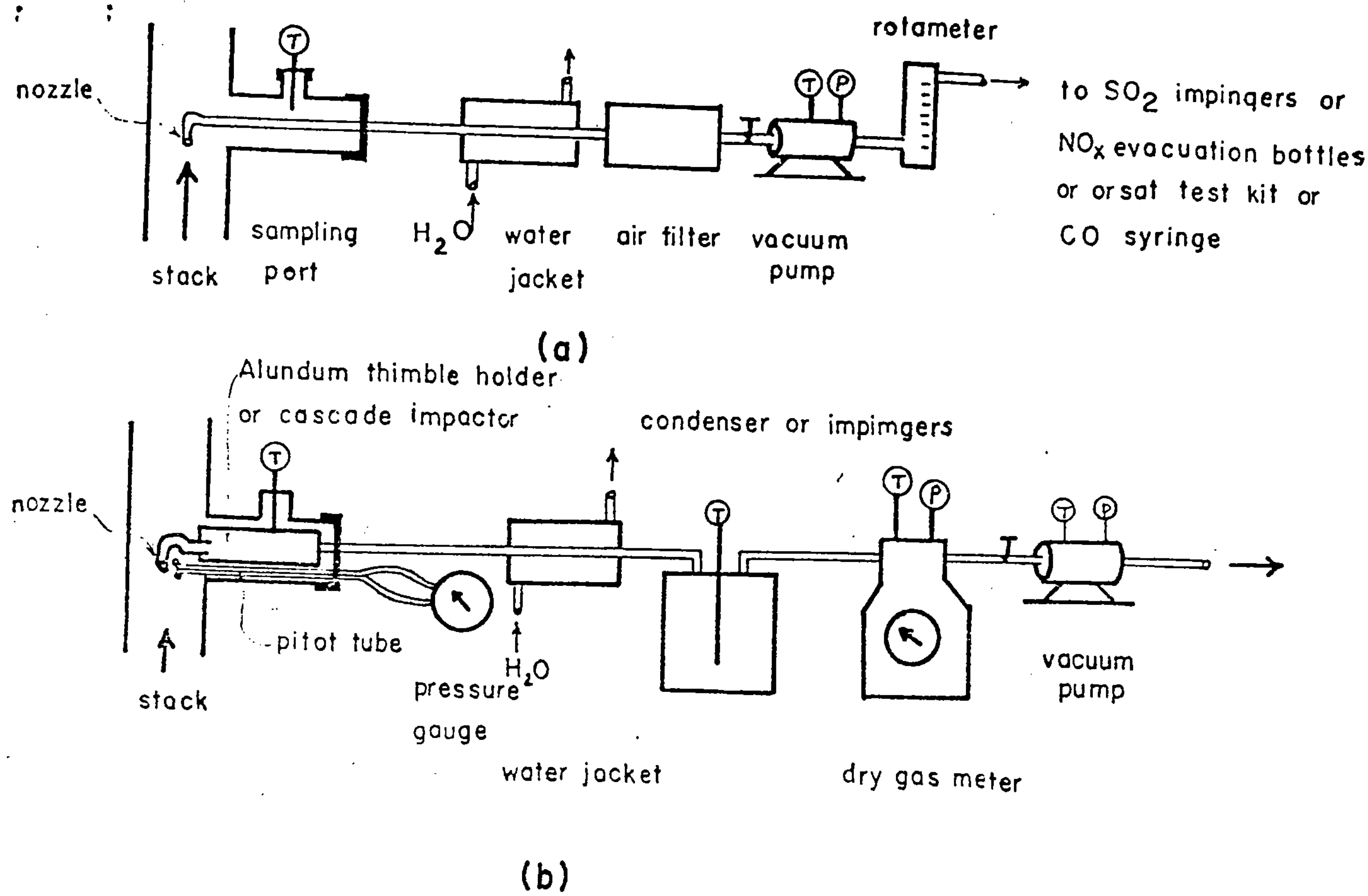

FIGURE 2. (a) GASES SAMPLING TRAIN

(b) PARTICULATE MATTER SAMPLING TRAIN

respectively. O_2, CO_2, CO and N_2 were determined by Orsat test kit. CO was also determined by industrial hygiene indicator. The Phenoldisulfonic acid method and the iodine method were used to measure NO_x, and SO_2, respectively.

For particulate analysis, the fractions of ash and sand in the exhaust particulate matter were determined by washing. Because sand is much heavier than the ashes, water is used to wash away the ashes. The separated sands are then dried and weighed.

Sewage sludge samples were collected at the reactor to determine moisture, volatile contents and heat value. The size distribution of the fluidizing sand was determined. Operating conditions, including combustion temperatures, pressures, auxiliary oil supply rate, sludge feeding rate, amount of sand in bed, etc., were recorded for each pollutant sampling test.

The results of tests on exhaust gas compositions and particulate mass concentrations at various operating conditions and sludge loadings were summarized (Table 1). Gaseous pollutant emissions were plotted against sludge loading rates (Fig. 3). A typical set of the particulate size distributions of samples collected before and after the scrubber is shown (Fig. 4). Also, the relationships between air and auxiliary oil requirements at various burning rates are presented (Fig. 5). The test results of air pollutant emissions after the scrubber are averaged and listed together with the pertinent data collected (Table 2).

Predicted emissions. Given the empirical formulas of sewage sludge and auxiliary fuel, the ratios of air/sludge and auxiliary fuel/sludge and the moisture and ash contents of sludge, the amount of air pollutants emitted during sludge incineration may be calculated.

Based on data available, the empirical chemical formula of raw sewage sludge (ash and moisture free) is $C_{482.5}H_{847.5}O_{276.5}N_{22.9}S$ and of auxiliary fuel (No. 2 oil) is $C_{1290}H_{2230}S$. For a sludge loading rate of about 11.5 lb dry/sq ft-hr. combustion of one dry pound of raw sewage sludge requires 23.75 lb of air and 0.0545 gal (0.4246 lb) of residual oil (Fig. 5). The corresponding moisture and ash contents of sludge are 74.9 and 14 percent respectively (Table 1). Given the empirical chemical formulas and data mentioned above, the quantities of the constituent elements of one dry pound of sludge and 0.4246 pound of No. 2 oil can be calculated (Table 3).

Assuming that combustion is complete, the amount of CO_2, water vapor and SO_2 produced by burning one pound of dry sludge can be computed with

Table 1. Air Pollutants Emitted From Fluidized Bed Sewage Sludge Incinerator

Sludge Loading Rates		Air Pollutant Emissions							
		Particulate Matter			Gaseous Pollutants				
lb/hr	lb/ft²-hr	grains/scf*	lb/hr	lb/ton	CO mg/l	CO_2 Percent	SO_2 mg/l	NO_x mg/l	H_2O Percent by volume
100	6.60	1.180	9.35	187.00	0	3.0	27.1	7	10.3
134	8.84	0.170	1.43	21.30	0	14.2	11.2	30.6	12.5
172	11.36	3.430	29.50	342.00	0	6.4	18.3	0	12.6
175	11.53	0.936	7.53	85.80	10	9.4	30.5	2	18.4
179	11.80	0.732	6.07	67.80	0	7.0	29.2	4	17.7
183	12.10	0.555	5.11	55.60	5	7.4	22.5	0	15.3
189	12.46	0.446	4.39	46.40	0	8.7	24.7	8	17.8
213	14.10	0.233	1.95	18.34	0	12.6	33.4	6	17.7
236	15.50	0.883	7.79	66.00	0	11.6	24.3	21.6	20.3
280	18.45	0.803	7.72	55.20	10	4.5	35.7	26.0	19.9

Remarks: 1. The volatile and moisture contents of sludge are 85.7-87.5 percent and 73.5-78.3 percent. respectively.

2. The combustion temperature ranges from 1290 to 1380 °F.

3. The exhaust gas flow ranges from 928 to 1151 scfm.

* Corrected to 12 percent CO_2.

the aid of the following combustion equations:

C	+	O_2	CO_2
1 lb		2.67 lb	3.67 lb
2 H_2	+	O_2	2 H_2O
1 lb		7.94 lb	8.94 lb
S	+	O_2	SO_2
1 lb		1 lb	2.0 lb

The values of CO_2, water vapor and SO_2 calculated are 2.955 lb, 1.043 lb and 0.0064 lb, respectively.

The moisture content of sludge is 74.9 percent. Therefore, 2.984 lb of water evaporate when one dry pound of sludge is incinerated. The total water vapor produced upon ignition of one dry pound of sludge is 1.043 lb water from combustion products and 2.984 lb water evaporated, or 4.027 lb. Using the combusion equations, the amount of oxygen consumed for complete combustion of one dry pound of sewage sludge can be calculated, 2.149 lb, 0.928 lb and 0.0032 lb for converting carbon to CO_2, hydrogen to water vapor and sulfur to SO_2, respectively (totaling 3.0802 lb required). Based on the above calculations a material balance for sludge incineration is illustrated (Fig. 6).

As illustrated on the mass balance diagram the total volume of exhaust gases at a temperature of 60 °F may be computed as follows:

$$
\begin{aligned}
CO_2 &= 2.955 \text{ lb} \times 8.63 \text{ scf/lb} &&= 25.51 \text{ scf} \\
SO_2 &= 0.0064 \text{ lb} \times 5.93 \text{ scf/lb} &&= 0.038 \text{ scf} \\
H_2O &= 4.027 \text{ lb} \times 20.00 \text{ scf/lb} &&= 80.540 \text{ scf} \\
N_2 &= 18.3116 \text{ lb} \times 13.55 \text{ scf/lb} &&= 248.00 \text{ scf} \\
O_2 &= 2.7140 \text{ lb} \times 11.85 \text{ scf/lb} &&= 32.20 \text{ scf} \\
\hline
\text{Total} & && 386.288 \text{ scf}
\end{aligned}
$$

scf = (standard cubic feet)

The concentrations of CO_2, water vapor, SO_2 and particulate in the exhaust gases can be calculated as follows:

Table 2. Fluidized Bed Sludge Incinerator Effluent Quality After Scrubber

Incinerator Plants	Air Pollutant Concentrations							
	particulate (grains/scf[1])	CO (mg/l)	CO_2 (percent)	SO_2 (mg/l)	NO_x (mg/l)	Hydrocarbon (mg/l)	Water Vapor Percent	References
Lynnwood, Wash.	0.096	—	13.5	28	4.7	—	21.0	
Edmonds, Wash.	0.011	0	7.3	22	7.0	—	18.5	authors
East-Cliff Capitola, Calif.	0.039	0	9.8	186	7.0	none	—	8
Lynnwood, Wash.	0.050	0	15.5	none	none	none	—	9
Foster City, Calif.	0.059	0	14.3	200	0	0	11.25	10
Edmonds, Wash.	0.058	0	14.9	0	0	0	25.6	10
Barstow, Calif.	0.025	0	14.8	0	0	0	2.9	10
Douglas County, Nev.	0.055	0	15.1	0	0	0	11.9	10
Port Washington	0.025	0	15.5	0	0	0	12.0	10
Average	0.046	0	13.4	48.2	2.1	0	11.46	
Emission standards[2]	0.200[3] 0.100	—	—	2000	—	—	—	

1. Corrected to 12 percent CO_2.
2. Established by the Puget Sound Air Pollution Control Agency, State of Washington, March 13, 1968.
3. Standard for incinerators installed prior to March 13, 1968; 0.10 grains/scf for incinerators installed after March 13, 1968.

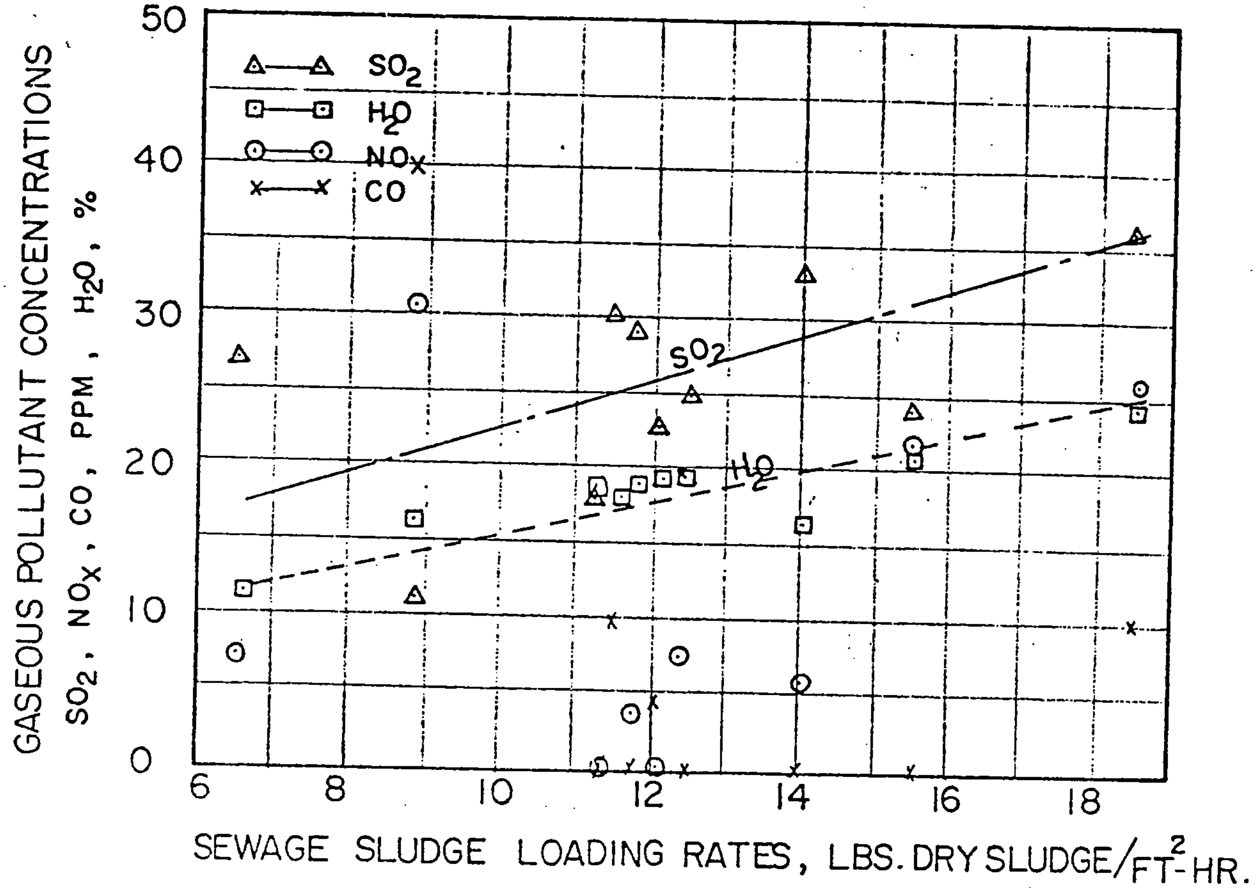

FIGURE 3. GASEOUS POLLUTANT EMISSIONS AT VARIOUS SLUDGE LOADINGS

$$CO_2 = \frac{25.51 \text{ scf}}{386.288 \text{ scf}} \times 100 = 6.62 \text{ percent by volume (8.35 percent dry basis)}$$

$$H_2O = \frac{80.54 \text{ scf}}{356.288 \text{ scf}} \times 100 = 20.6 \text{ percent by volume}$$

$$SO_2 = \frac{0.038 \text{ scf} \times 10^6}{386.288 \text{ scf}} = 98 \text{ mg/l by volume}$$

$$\text{particulate} = \frac{0.14 \text{ lb} \times 453.6 \text{ gm/lb} \times 15.43 \text{ grains/gm}}{386.288 \text{ scf}}$$

$$= 2.53 \text{ grains/scf}$$

Some nitrogen oxides are formed during combustion, but, because the formation of NO_x is a function of temperature, time and air, the quantity of NO_x produced is fairly complicated and has not been calculated.

Measured emissions. Air pollutants discharged from a fluidized bed sludge incinerator may be classified as gases (CO_2, CO, SO_2, NO_x, and water vapor) and particle matter (Table 1).

The maximum CO concentration measured at the Edmonds fluidized bed sewage sludge incinerator upstream of the scrubber was only 10 mg/l. In most cases CO was not detected in the exhaust gases, indicating that combustion was complete most of the time. NO_x concentrations ranged from 0 to 30.6 mg/l during the tests, with an average of 10.5 mg/l. The average concentration of SO_2 was 25.7 mg/l with a range of 11.2 to 35.7 mg/l. The amount of water vapor present in the exhaust gases ranged from 10.3 to 20.3 percent by volume with an average of 16.3 percent. The water vapor concentrations were affected by sludge moisture content and amount of fluidizing air (combustion air).

Based on these test results gaseous emissions except water vapor from a fluidized bed sewage sludge incinerator appear well below any pollutant emission standards. Water vapor is usually not considered a pollutant.

Rather, particulate matter is the significant pollutant from a fluidized bed sewage sludge incinerator. The particle mass concentration measured ranged from 0.17 to 3.43 grains/scf (comparable to calculated value of 2.53 grains/scf) with an average of 0.986. This value is fairly comparable to that from other types of incinerators burning municipal refuse or pathological wastes.[5]

However, the particulate emission rate in terms of pounds particulate per ton dry sludge burned ranged from 18.3 to 342 with an average of 94.5. This rate is much higher than that from a refuse incinerator, in which about 1.5 to 35 has been reported.[5]

Measurement of the bulk densities of fluidized bed incinerator emissions indicated that finer sand

Table 3. Calculated Elemental Composition of Sewage Sludge and oil

Elements	C lb	H lb	S lb	O_2 lb	N_2 lb	Ash lb
Dry Sludge 1 lb	0.4363	0.0637	0.0024	0.3335	0.0241	0.140
No. 2 oil 0.4246 lb	0.3705	0.0533	0.0008	0	0	0
Total	0.8068	0.1170	0.0032	0.3335	0.0241	0.140

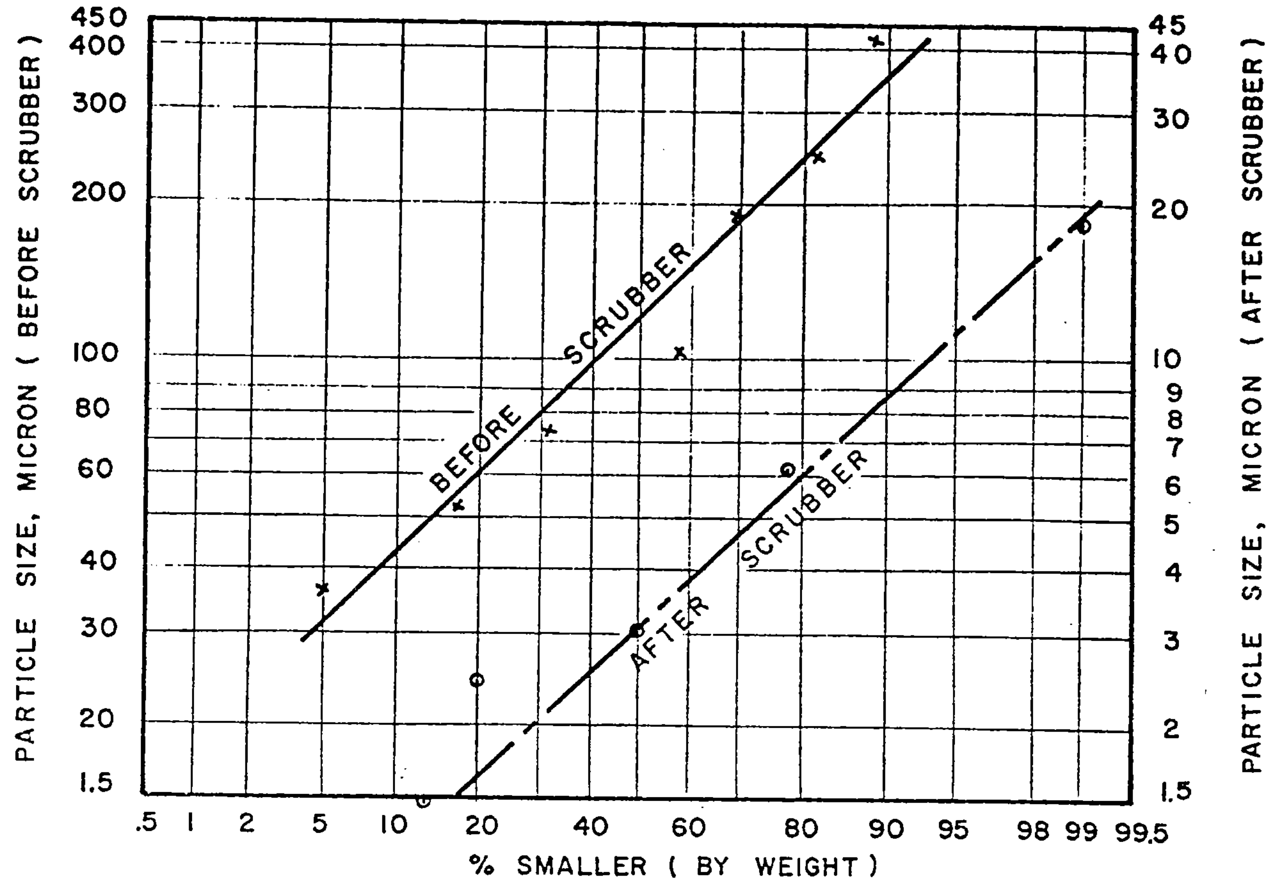

FIGURE 4. EXHAUST PARTICLE SIZE DISTRIBUTION

granules were emitted in addition to inert ash. The bulk densities of the particulates exhausted and bed sand were 1.43 and 1.8 g/cm^3 respectively. In most cases, the density of inert ash of sludge is less than 1 g/cm^3. The measured value of 1.43 g/cm^3 for particulates indicates that the exhaust particulate matter of sand granules and ashes.

Comparison. The calculated air pollutant emissions using material balance relationship were tabulated together with those measured (Table 4).

Table 4. Air Pollutant Emissions from Fluidized Bed Sewage Sludge Incinerator

Air Pollutant Emissions	Calculated	Measured Average	Measured Range
Particulate:			
grains/scf	2.53	2.19	0.94 to 3.43
lb/lb sludge	0.14*	0.11	0.043 to 0.171
CO_2, percent	8.35	7.90	6.400 to 9.400
SO_2, mg/l	98	25	18.30 to 30.50
H_2O, percent	20.6	15.5	12.6 to 18.40

*The results of recent measurements indicate that the average ash content is about 0.1 lb ash/lb sludge.

In general, the calculated values are well in the range of that measured. Sulfur dioxide and water vapor are exceptions.

The sources of sulfur are sludge and auxiliary fuel oil. The sulfur content of Edmonds sewage sludge and No. 2 oil are approximately 0.28 and 0.18 percent by weight, respectively. The concentration of SO_2 measured is lower than that calculated, probably reflecting a lower sulfur content in both sludge and oil than that proposed in the equations, or sulfur trapped in the ashes. Also, some SO_2 may have been converted to SO_3 or sulfuric acid prior to sampling.

The difference in quantity of water vapor calculated and measured may be attributed to condensation. Water vapor condensation may also have occurred in the exhaust pipe and in the sampling tube. For the above reason the measured water vapor concentration was lower than that calculated.

Based on the above comparison, it appears that in the absence of measured data air pollutant emissions from a fluidized bed sewage sludge incinerator may be predicted using the combustion equations and material balance data.

Sludge loading rates. The relationships between the gaseous pollutant emissions and sludge feeding rates obtained at the Edmonds fluidized bed sewage sludge incinerator appear somewhat irregular (Fig. 3).

Average concentrations of SO_2 and water vapor do increase slightly with an increase in the sludge loading rates. Irregularity of SO_2 and water vapor emissions reflects the slight variations of sulfur and water contents in sewage sludges and the change of auxiliary fuel oil feeding rates. If the sulfur and

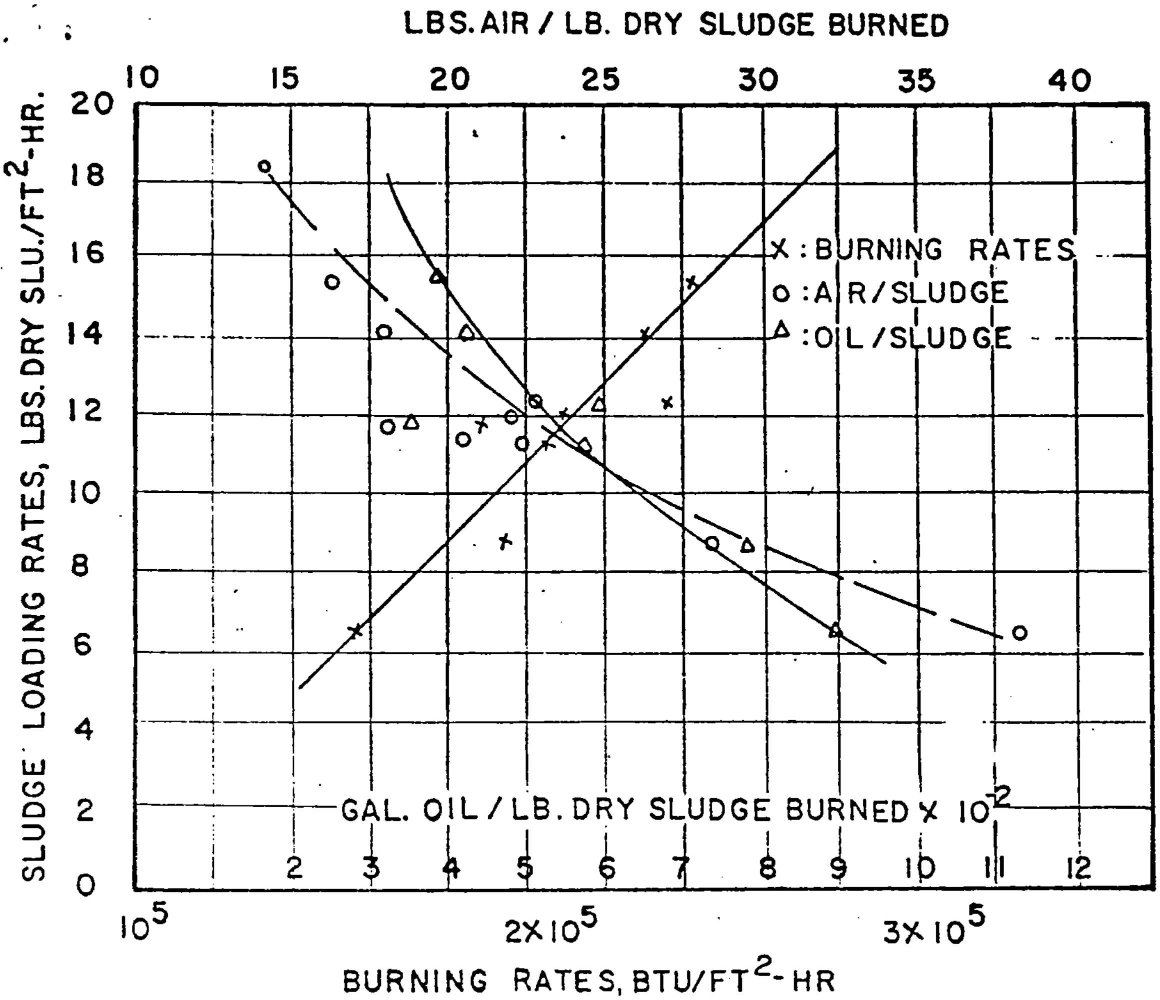

FIGURE 5. AUXILIARY FUEL AND AIR REQUIREMENTS AT DIFFERENT SLUDGE LOADINGS

water contents in sludges were uniform, the increase in sludge load would result in a higher emission of SO_2 and water vapor, since the amount of fluidized air remained fairly constant. Existing plants are designed with very narrow ranges of air supplies-automatic control.

Relationships between particulate mass concentrations and sludge loading rates were also irregular. The fluctuation in particulate emission probably reflects the variation in fluidization. Sands and sludges in the combustion zone are forced up and down by the fluidizing air. This action tends to break coarser sand particles into smaller ones. When these smaller and lighter sand particles return to the bottom of the bed they are instantaneously rejected by the air jets. Because the smaller sand particles are lighter, their upward trajectory path is higher than the bed height, and they are emitted.

The particulate mass concentration measured under normal operating conditions was about 1 grain/scf or less, disregarding the sludge loading rates. This value is lower than that calculated using mass balance diagram. Ash may have been trapped in the bed or the inert ash content of sludge may have been lower than measured.

Particulate size distribution. More than 85 percent by weight of the particles exhausted had sizes greater than 30 microns. Particles of diameter greater than 30 microns can be separated from the gaseous stream by a number of methods including water scrubbing.[6] This is proved by the results of size distributions measured on samples collected downstream of the scrubber (Fig. 4) where the largest particle sizes measured were about 20 microns.

Odor. Usually odor is considered the major air pollution problem associated with sewerage systems.[7] Odors in sewerage systems are mainly developed from the reduction of proteins to amines or from anaerobic decomposition of organic compounds. Sewage sludge incinerators oxidize odors. In addition the sludge conveying and feeding systems at the Edmonds plant are completely enclosed, further reducing odors. During the field study at Edmonds plant odor was detected in the sludge thickener room. However, no odor was detected in the incineration room or in the exhaust stack.

Conclusions. The amounts of gaseous pollutants (except water vapor) emitted from a fluid bed sewage sludge incinerator are quite small: 2.79 lb SO_2, 0.022 lb CO, and 1.14 lb NO_x per ton dry sewage sludge burned. Thus, with the present emission standards, controls for these pollutants are not required.

Field test results indicate that more than 95 percent of the exhaust solids has particle sizes greater than 30 microns and that particle density is about 1.5 grams/cm^3. Under normal operating conditions the suspended particulates emitted are of 1 grain or less per standard cubic foot mass concentration and of size distribution with a mean diameter of 123 microns with a geometric standard deviation of 2.82. The uncontrolled particulate emission rate is about 94.5 lb particulate per ton dry sludge burned. Therefore, control of particulate matter emissions is necessary. However, test results (Table 2) indicate that a water scrubber or equivalent is adequate for particulate removal. All the pollutant concentrations in samples collected downstream of the control facility-water scrubber met the local air pollution control codes which are $SO_2 \leq$ 2,000 mg/l and particulate mass concentration $\leq$ .02 grain/scf (0.10 grain/scf for new installation).

Water vapor emitted from a fluidized bed sewage sludge reactor may be objectionable, although the State of Washington currently does not consider it as a pollutant and requires no control. Sewage sludges injected into the reactor contain more than 65 percent of water by weight resulting in a white plume from the exhaust stack. When the local meteorological conditions are not favorable for plume dispersion and the relative humidity is high, a water vapor plume may sweep residential or business areas near the plant. Complaints against the plume have been received by the cities operating this type of incinerator. Should water vapor control become necessary a demister in the exhaust pipe will remove water from the gas stream. If dilution is acceptable as a pollution control method, a taller stack could be installed. Another method involves condensing the water vapor from the gas stream.

The amounts of SO_2 and water vapor emitted from a fluidized bed sewage sludge incinerator increase slightly with an increase in the sludge loading rates. ■

Acknowledgments. This research was partially financed by the Office of Engineering Research of the University of Washington; the city of Bremerton, Wash.; and Kramer, Chin and Mayo Consulting Engineers, Seattle, Wash. The assistance of Professor August T. Rossano; the cooperation of Ronald Whaley and the plant personnel of Edmonds; and Daryl Bruchsen of Lynnwood, Wash., are also acknowledged.

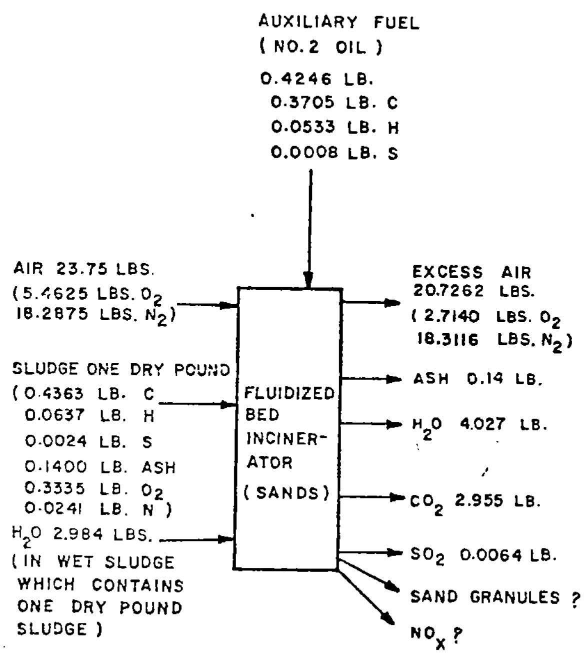

FIGURE 6. MATERIAL BALANCE FOR FLUIDIZED BED SEWAGE SLUDGE INCINERATION.

References

1. Burd, R. S. A Study of Sludge Handling and Disposal. Federal Water Pollution Control Administration Publication WP-20-4 (May 1968).
2. Balakrishnan, S., Williamson, D. E. and Okey, R. E. State of The Art Review on Sludge Incineration Practice. U. S. Department of Interior, Federal Water Quality Administration (April 1970).
3. Methods for Determination of Velocity, Volume, Dust and Mist Content of Gases, Bulletin WP-50, Western Precipitation Division, Joy Manufacturing Co., Los Angeles, Calif.
4. Pilat, M. J., Ensor, D. C. and Bosch, J. C. Source Test Cascade Impactor. Atmospheric Environment, 4:671-679 (1970).
5. Air Pollution Engineering Manual. U. S. Department of Health, Education, and Welfare, Public Health Service 999-AP-40, 421-461 (1967).
6. Strauss, W. Industrial Gas Cleaning. Pergamon Press, New York (1966).
7. Stone, R. Sewage Treatment System Odors and Air Pollutants. Jour. of Sanitary Engineering Division, Proceedings of the American Society of Civil Engineer, SA4, 905-909 (Aug. 1970).
8. Sohr, W. H., Ott, R. and Albertson, O. E. Fluidized Bed Sewage Sludge Combustion. Water Works and Waste Engineering (Sept. 1965).
9. Darby, W. A. and Millard, R. S. Fluidized Bed Combustion. Presented at the 13th Annual Waste Engineering Conference, University of Minnesota, Minneapolis, Minn. (Dec. 1966).
10. Albertson, O. E. Personal communication. The Dorr-Oliver Co., Inc., Stamford, Conn. (June 1970).
11. Liao, P. B. Design Method For Fluidized Bed Sewage Sludge Incinerators. Ph.D. Dissertation Submitted to the Department of Civil Engineering, University of Washington, Seattle, Washington (1971).