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VARIABILITY OF METALS AND DIOXINS IN STACK EMISSIONS OVER FIVE YEARS: HOW MUCH IS CONTRIBUTED BY THE WASTE AND HOW MUCH BY THE TECHNOLOGY?

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ABSTRACT

The environmental impact of emissions from planned new and upgraded waste-to-energy facilities have been predicted based on the variable emissions reported for tests of existing facilities having apparently similar technologies. These emissions reflect seasonal and other variations in the waste as well as in the operating and performance characteristics of different furnace and air pollution control technologies. Conservative estimates of health risk and environmental impact, based on this data and manufacturers' and operators' guarantees, necessarily including safety factors so that when compliance tests are performed, the owner can reasonably anticipate that the facility will meet emission limits. Since many state-of-the art waste-to-energy (WTE) plants have now been tested at least annually for several years, a large database has been developed which can be used to characterize the variability of stack emissions. This paper looks at data from facilities burning municipal solid waste (MSW), having refractory furnaces with dry-lime sorbent injection (DI) and baghouses, wall furnaces with spray dryer absorbers (SDA) and baghouses, and shredded MSW-fired water-wall furnaces with SDA and electrostatic precipitator (ESP) emission controls. The range of emission factors for particulate matter, heavy metals and dioxins from these individual facility over a three to five year period and test data from another 20 WTE facilities with SDA/baghouse combinations is found in EPA's AP-42 and follow lognormal distributions. The percentage of metals in the particulate matter (PM) varies with PM concentration and air pollution control technology. Methods are presented for estimating probable annual averages and the maximum emissions level likely to be measured in future tests. The testing limit which is not expected to be exceeded by 95% of future tests exceeded three times the average using this data set. These findings are significant from the standpoint of the Maximum Available Control Technology (MACT) regulations in the Clean Air Act (CAA) since they point out that simple arithmetic averaging produces emissions limitations that do not consider real world variability.

INTRODUCTION

In order to obtain State and local permits for WTE facilities, environmental impact statements had to be prepared and permit limits set based on the projected emissions from the facility. These projections are based on test data from facilities having similar or similar-performing technology. The EPA and literature emissions database were used to obtain emissions estimates for the pollutants such as particulate matter and the regulated heavy metals, cadmium, lead and mercury, as well as dioxins.

The primary purpose of making emissions estimates was to set permit limits which protect the public and to use as a conservative basis for the environmental impact statements and health risk assessments. Another purpose was to set limits which vendors and operators of the facility could reasonably expect to meet each time a stack test is performed. It was often understood that when the facility was first operated and tested, if one or more of the original permit levels was exceeded, the permit level could be adjusted after efforts were made to reduce emissions as much as possible. This might occasionally happen because the MSW in a given locality, or at a given time, was very different than the waste burned by the facilities included in the database. Permit limits are usually set at a level significantly higher than normal performance, providing a reasonable factor of safety for the guarantees which developers and vendors of combustion and emission control equipment have to make, but not at a level which would trigger non-compliance and prevent building the facility. The mean plus two standard deviations is a generally used rule of thumb for emission limits used in permits and upper limit health risk estimates.

The EPA's Emissions Guidelines (EG) and New Source Performance Standards (NSPS) published on December 19, 1995 require that all new waste-to-energy (WTE) facilities burning municipal solid waste (MSW) obtain permits to construct and permits to operate containing numerical limits on emissions. The Clean Air Act (CAA) requires that a Maximum Available Control Technology (MACT) floor be established for new units taking into account the cost of achieving such emissions and non-air-quality health and environment impacts. EGs for existing units may not be less stringent than the average emission limitations achieved by the best-performing 12% of units in a category (MACT Floor).

While the USEPA was in the process of developing the guidelines and new plant emission standards, new facilities continued to be built and permitted by the States using Best Available Control Technology (BACT). These plants have environmental impacts far below the levels of concern established by authorities from the standpoint of health and the environment. These facilities are now the basis for the MACT floor.

While the EPA pondered over how to implement the CAA, permits for some new facilities were delayed, and owners and operators of existing facilities were frozen into a waiting strategy. Without actual regulatory, there is a large risk in embarking on retrofit activities, or even in making plant improvements, since the effort could all be wasted.

The EPA's Administrator signed the EG and NSPS limits on October 31, 1995 and published them in the December 19, 1995 Federal Register. They are summarized in Table 1. The EPA Administrator has established capacity categories for small (38.6 ton/day to 248 ton/day) and large (greater than 248 ton/day) plants. The emissions limits are shown in Table 1. Even though these emissions limitations have been published, there remains concern that the whole procedure contains flaws which may haunt us in the future. In accordance with this approach, as additional new facilities are built exhibiting lower emission levels, these levels might in the future be "ratcheted down" under the auspices of Prevention of Significant Deterioration. Permits for existing facilities could also be revised downward over time as they come up for periodic renewal, and

these facilities might be required to be upgraded or retrofitted to meet increasingly stringent requirements.

Table 1. U.S. EPA Municipal Waste Combustor Guidelines and NSPS Limits

Pollutant	Small mg/dscm	Large mg/dscm	NSPS mg/dscm	Small lb/MT	Large lb/MT	NSPS lb/MT
Cadmium	0.1	0.04	0.02	800	320	160
Lead	1.0	0.49	0.2	12,800	4,000	1,600
Mercury	80	80	80	640	640	640
PM, gr/dscf	0.03	0.012	0.010			
D+F, ng/dscm	125	60	30			
TEQ, ng/dscm	2	1	0.5			

Since most of the permit conditions, on which the regulatory limits were based, were negotiated between State regulators and guarantors of the emission levels based on test data from other facilities, with unknown, but undoubtedly different, safety factors, they vary widely and do not necessarily characterize what actually happens when the facility is operated.

The EPA database, which has been developed for the purpose of making predictions of emissions, reveals a wide range for many regulated pollutants. It was not possible to determine how much of the variability results from individual plant design and what comes from the operating differences and changes in waste composition.

One of the ways used in the past to obtain predictions of emissions likely to be seen during testing was to add two standard deviations to the average of emissions test data from appropriate facilities. In general, the standard deviation of data for each pollutant is equal or somewhat larger than the mean. The maximum reported emission level is often roughly the same as the mean plus two standard deviations, which should include roughly 95% of the data points when the data are normally distributed.

A primary objective of this paper is to examine test data to obtain a better understanding of the variability of emissions data, and to begin to look for evidence to distinguish between the waste stream variability and that resulting from operational procedures and the combustion and emissions technology itself.

ANALYSIS OF STACK TEST DATA

Emissions data from three quite different combustion and emission control technologies are examined: (a) mass-burn refractory-wall combustion with dry lime injection and fabric filter (DI/FF.) (Eastmont, 1988), (b) mass-burn water-wall combustion with spray-dry reactor and fabric filter (SD/FF) (Ogden, 1994 & 1995), and (c) refuse-derived (prepared refuse) fuel combustion with spray-dry reactor and electrostatic precipitators (SD/ESP) as well as fabric filters (Zakaria, 1984). Since acid gas controls are operated so as to maintain the desired emission levels of SO_2 and HCl, these data are not analyzed here. Rather, the focus is on emissions of total solid particulate (TSP) or particulate matter (PM), and the CAA regulated heavy metals, specifically cadmium, lead and mercury, which may be collected as part of, or along with, the particulate. Emissions of dioxins plus furans (D+F) or a toxic equivalent amount of 2,3,7,8 tetrachlorinated dibenzo-p-dioxin (TEQ TCDD) are also included to show that these emissions follow similar trends. The EPA uses a factor of 60 to divide into total D+F to obtain the TEQ absent site or project specific information.

Stack test data obtained from periodic tests performed at various facilities over a period of four or five years are analyzed chronologically, then as statistical distributions. The emission factors and the percentage of each metal in the particulate are plotted against PM concentrations to determine the extent that the metals emissions tend to be constant in quantity, independent of PM, or to vary with the emitted PM (constant in relative concentrations, reflecting the efficiency of the air pollution control device.

Historic range of stack emissions of a single facility

Historic trends in PM and heavy metals emissions from the WTE facility having dry lime injection and a fabric filter are shown chronologically in Figure 1. The data are from all the compliance test runs performed over a roughly four-year period. Three replicate tests are usually averaged. Toxic equivalent dioxin (Massachusetts weighting scheme) emissions in nanograms per dry standard cubic meter (ng/dscm) are also shown. Emissions measured during the first compliance tests were in some cases lower and in other cases higher than those measured in the following years.

- Mercury emissions from this facility had emission factors ranging from as high as 10,000 pounds per million tons of MSW (lb/MT), to as low as 15 lb/MT, a 600-fold range. The general reduction in mercury was attributed to recycling of mercury-containing batteries from the waste stream, reducing the flue gas temperature entering the air pollution control (APC) filter, and increasing the carbon content of the fly ash by reducing combustion efficiency. The fact that dry carbon cell battery manufacturers have greatly reduced the mercury content cannot be ignored.
- Lead emissions in the last test period were about the same as those in the first test, that is, 100 lb/MT; but they varied from as low as 30 lb/MT to as high as 1,000 lb/MT, a 33-fold range, and a factor of three times below, and 10 times higher than those measured during the first compliance test.
- Cadmium shows variations from 3 lb/MT 100 lb/MT, a 33-fold range. Chromium ranged from 20 lb/MT to 2,400 lb/MT, a 120-fold range. Toxic equivalent (TEQ) dioxins ranged from 0.01 ng/dscm to as high as 2 ng/dscm, a 200-fold range, leveling off at 0.45 ng/dscm.

Figure 2 shows the historical test data from 1991 to 1994 from WTE facilities having water-wall furnaces and SD/FF.

- Mercury emissions have fallen, while TEQ have increased. Lead shows a downward trend, while cadmium shows an upward trend during the period.
- PM shows a high single three-run test at 0.03 gr/dscf, after which emissions were greatly reduced.

The metals data from Figure 1 are plotted as a uniform distribution in Figure 3 by spacing the points, sorted in ascending order, at an equal distance apart. Since these data fall fairly closely along straight lines on logarithmic coordinates, the data set can be said to exhibit the characteristic of a log uniform distribution. It is notable that lead and cadmium appear to follow similar tracks.

Range of emissions of WTE with scrubber/baghouses

Controlled stack emissions from the 45 compliance tests at 19 WTE facilities listed in the EPA document AP-42, or published elsewhere, are shown as a uniform distribution in Figure 4 (EPA, 1993).

- Lead emissions ranged from below 8 to 600 lb/MT, a 75-fold range which is remarkably similar to the range seen in Figure 1, even including the outlying points mentioned above.
- The cadmium distribution is similar. The data at the lower range of cadmium emissions are unknown or below the detection limit. If necessary, such data can be treated by special procedures, such as by plotting measured values and extrapolating the apparently straight

line into the unknown region, picking out the data points indicated, and using them to calculate the mean and standard deviation (Rigo, 1992).

- Emission factors for mercury range from 75 to 4,500 lb/MT of MSW, a 60-fold range. Note that AP-42 emission factor data, expressed as lb/MT, has been converted from micrograms per dry standard cubic meter (mg/dscm) by dividing by 8.06, based on the EPA assumption that the heating value of the waste is 4,500 Btu per pound and using the procedure in 40 CFR 60, Subpart A, Reference Method 19.

Estimation of 50, 90, 95 and 99% probabilities

In order to estimate the environmental impact of new facilities or upgraded existing facilities, we need to obtain reasonably reliable estimates of annual average emissions. How much confidence can we have in the median of the data (the central point below which 50% of the data lies), the average of all test data, or other estimates? When faced with periodic compliance testing of the facility, we need to obtain estimates of the highest emission rates which are likely to be measured during these future tests. What are the emissions rates which will probably not be exceeded in 90% of the tests? 95% or 99% of tests? To answer these questions, we can examine historical data employing appropriate statistical procedures.

Most environmental data are lognormally distributed (Ott, 1990); that is, it closely follows straight lines when plotted on lognormal probability paper which can be extrapolated. Figure 4 shows the data set of Figure 1 plotted on log-probability paper, providing a means of extrapolating the data to obtain the 95% and 99% probability of occurrence. In this form the geometric mean is the 50% point.

Data Outliers

The data points which curve up at the upper ends of the lines can be problematic. For example, if the distribution line changes slope, such as seen for lead, extrapolating the lines to 95 and 99% results in very high numbers. There may be outlying (unusual) data, or two or more populations may be present, and further investigation is necessary. Techniques are given in Rigo (1992) for identifying and dealing with this problem.

Confidence limits

The arithmetic mean, or simple average of the data collected periodically over a period of time, such as a year or several years, may be a good estimate of the actual average emissions to the environment if there is not too much variation in the data. The more samples available, the better the estimate.

Strictly speaking, when applying normal statistics to lognormal data, all analysis should be performed on the logarithms of the data, then converted back. The USEPA document SW-846 states that if the variance (the square of the standard deviation) of the data set approaches the mean, the data are probably not normally distributed, and should be transformed before the mean, standard deviation and confidence limits are calculated. Since most environmental data are found to be lognormally distributed, the appropriate way to transform the data is to take the logarithms and then transform the calculated results back to original units. The mean value obtained by using log transforms is the geometric mean (GM).

To compensate for small numbers of samples, SW-846 recommends the use of the Student "t" procedure and the calculation of the 90 percent Upper Confidence Limit (UCL_{90}), the limit below which the average of a set of data will probably fall in 90 cases out of 100 (EPA, 1982) or for air pollution data instead of TCLP results, 95 out of 100 times using the 95 percent statistical confidence level (40 CFR 60, Appendix A, Method 19).

Table 2 shows the data and calculations for cadmium from Figure 1. The UCL_{90} can be calculated, in accordance with SW-846, using the arithmetic mean and the standard deviation, s.

$UCL = x + t_{0.20} (s/n^{0.5})$

Normal Distribution

x = Mean = 263

s = Std. Dev. = 256

n = Number of samples = 24

$t_{0.20}$ = Student t for n-1 samples = 1.71

Then: UCL_{90} = 263 + 1.71*246/4.9

= 349 lb/MT

Normal versus lognormal data distributions

Assuming the data are normally distributed, for 23 samples, there is a 90% confidence that the highest average emission factor would be less than 37.8 lb/MT.

The average of the logarithms of the data is transformed back to obtain the geometric mean (GM) of 17.16, which (as it must be for lognormally distributed data) is close to the median of the data set, 18 above and below which 50% of the samples fall.

Table 2. STATISTICAL ANALYSIS OF CADMIUM DATA

Test Number	CADMIUM - lb/million Tons Data	Sorted	ln
1	10.44	3.105	1.13
2	3.132	3.132	1.14
3	3.105	5.337	1.67
4	5.337	5.625	1.73
5	49.32	6.75	1.91
6	18	7.182	1.97
7	104.4	8.1	2.09
8	11.34	9.27	2.23
9	11.34	10.44	2.35
10	9.27	11.34	2.43
11	8.1	11.34	2.43
12	5.625	18	2.89
13	7.182	26.1	3.26
14	6.75	27	3.30
15	61.65	31.05	3.44
16	32.04	31.5	3.45
17	39.06	32.04	3.47
18	103.5	34.02	3.53
19	31.05	39.06	3.67
20	31.5	49.32	3.90
21	34.02	61.65	4.12
22	26.1	103.5	4.64
23	27	104.4	4.65
MEAN:	27.79	27.79	2.84
STD. DEV:	28.11	28.11	1.01
MEAN+STD.DEV:	56	56	3.85
MEAN + 2 SD:	84	84	4.86
MEAN + 3 SD:	112	112	5.87
Maximum:	104	104	4.65

Arith. Mean, x:	27.79
Geom. Mean, GM:	17.16
Std. Deviation, s:	28.11
Logarithmic S.D., LSD:	1.01
Spread Factor, S= exp(LSD):	2.75
Median, M:	22.05
Cv = s/x	1.01
Cv (large pop):	1.33
x/xg = x/M =	1.67
82% limit = GM/S	47
97.5% limit, GM *((S)^2):	129
99.9% limit, GM *((S)^3):	355
(64% limit)/(Mean)	1.70
(95% limit)/(Mean)	4.65
(99% limit)/(Mean)	12.78

Spread Factor

The calculation of the 95%, 99% and 99.9% limits of a set of lognormally-distributed data is presented in Table 1 by two methods, for comparison. The average (Mean) of the data is 27.79, and the standard deviation, s, is 28.11. The median, or central value of the data series, is 18. For a normal distribution, 82% of the data are less than the mean, x, plus one standard deviation, s, or (x + s); 97.5% are less than (x + 2*s); and 99.9% of the data are less than (x + 3*s).

Using the logarithms of the data, the geometric mean, GM (the antilog of the arithmetic mean of the logarithms), is calculated to be 17.16. The standard deviation of the logarithms, LSD, 1.01, is used to calculate the spread factor, S, which is the exponential of the LSD, or 2.75. For the lognormal distribution, 82% of the data are less than the GM*(S), 97.5% are less than GM*(S)^2, and 99.9% of the data are less than GM*(S)^3.

The comparison the two methods of estimating these limits is given below:

Percent less than	Arithmetic Estimate	Logarithmic Estimate
50%	28	17
82%	56	47
97.5%	84	129
99.9%	112	355

The arithmetic estimate using three standard deviations (99.9%) is 112; close to the actual maximum of the 23 readings, 104. The logarithmic estimate of 97.5%, by comparison, is 129. It is apparent that ignoring the lognormal characteristic of the data overestimates the mean and 82% limits, and under-estimates the 97.5% and 99.9% limits. Note that the 97.5% limit is 3.0 times the arithmetic mean, and 3.8 times the median, and 4.6 times the arithmetic average. The logarithmic estimate is 7.5 times the GM. These relationships are shown in Figure 6. The lesson here is that in 40 readings, 97.5% or 39 readings will be less than 4.6 times the easily calculated arithmetic mean. Log-probability paper can be used to calculate other limits, as noted above in reference to Figure 4.

Predicting future performance and compliance

The above calculations reveal widely different estimates can be made depending upon the method used. The Upper Tolerance Limit has been used as a method for estimating future emissions in 90, 95 or 99% of periodic tests as the plant operates, and as a basis for setting permit limits for future or upgraded facilities since it uses available data to establish the value below which a given percentage of future tests is likely to be found. Unlike the t-distribution, it recognizes that both the mean and standard deviation are data derived rather than just the variability being estimated from the data. The "K" factors shown in Table 3 are used instead of "t" values for this purpose.

Table 3. One-sided statistical tolerance limit factor (k)* for a normal distribution.

	Proportion		
n = number of Samples	90%	95%	99%
4	4.16	5.14	7.04
8	2.58	3.19	4.35
12	2.21	2.74	3.75
16	2.03	2.52	3.40

*The K factor is such that the probability is 0.95 that at least the specified proportion P of the distribution will be less than X +K*s, where X and s are the estimate of the mean and standard deviation computed from a sample size of n.

Due to the many factors influencing emissions and the risk that numerical emissions limits which are part of a permit could be exceeded, it may be necessary to perform careful statistical studies on the data obtained from periodic tests, investigating issues such as the time period during which the emission sample was collected (sampling time) and dealing with data reported as "less than the detection limit." These issues are treated by Rigo (1992) who provides applicable statistical tables and procedures, including methods for determining the limit which is likely to bound the largest individual test run in a future test series, the next test average, averages for a specified number of future tests, and a specified percentage of all future runs or test averages.

COMPARING DIFFERENT FACILITY TECHNOLOGIES

Figure 7 shows the range of emissions, in pounds per million tons of MSW, from annual tests of each of refractory mass-burn combustors having dry-injection lime injection and fabric filters (DI/FF) (Eastmont, 1988). As PM decreased seven times, from 0.007 to 0.001 gr/dscf, lead declined 25-fold, whereas mercury and cadmium declined about 3-fold. Chromium did not show a significant decline.

Figure 8 shows the range of emission factors for a water-wall mass-burn facility with spray dry absorbers and fabric filters (SDA/FF). A similar drop in mercury and lead is seen, and the cadmium trend is indeterminate, in spite of a 4:1 reduction in PM emissions.

Figure 9, for another water-wall facility with SD/FF, shows no trends for arsenic, lead and mercury (Ogden, 1994). Only one cadmium reading was above the detection level.

Figure 10 shows the variation in emission factors over four years of testing at a processed refuse-fuel (PRF) burning facility with SDA/ESP on Units #1 and #2, and SDA/FF on Unit #3 (Zakaria, 1994). No clear change in the lead emission factors is noted, but mercury shows a clear decline with PM. Arsenic data varied widely. The new Unit #3, having a fabric filter, showed emission factors about ten times lower than those of Units #1 and #2.

Figure 11 shows the emission factors reported for 45 individual tests of WTE facilities with acid gas controls (EPA, 1993). These vary by factors of 10:1 to 100:1, while PM ranged 100-fold. Most of the mercury data showed no trend with PM, but lead clearly increased and cadmium apparently decreased with PM.

Metals as a percent of particulate matter

Particulate matter (PM) has been suggested as a surrogate for metals emissions, i.e., if PM emissions are limited, then the metals are also limited. If metals are proportional to PM, then the concept of control efficiency, related to PM, can be applied to metals. If metals go down faster than PM, then equal control efficiency would be a conservative assumption. If the metals emissions are independent of PM, waste composition, furnace temperature, and APC temperature may be the main factors which control them or the metals may be associated with either the

fine or coarse particulates so that disproportionate changes occur depending on the surface area ratio of different particulate emissions.

It is important to determine whether any specific APC technology is significantly more effective than another, based on actual metals emission factors. Considering the wide range of PM and metals emissions reported at a single facility, it would appear that the nature of the waste, seasonality, APC operating temperatures, and the detailed operating procedures used at any time may be over-riding factors which can obscure differences between dry-injection and SDAs and differences between ESPs and baghouses. Differences in efficiency are difficult to pin down since they can only be discerned from simultaneous input/output data which is extremely costly and sometimes impossible to obtain.

Figure 12 shows metals as a percent of particulate emissions plotted against measured PM emissions, for the facility with dry lime injection and baghouse. This graph is for the first three years of operation when PM data were collected. PM measurements ranged from 0.001 to 0.0067 gr/dscf. Mercury and cadmium are seen to be almost a constant percentage of particulate; lead appears to exhibit a lower percentage at low PM levels. Chromium shows an opposite trend, indicating a constant emissions factor, independent of PM.

Figure 13 shows metals as a percent of PM at the facility with a SDA/FF. Mercury concentrations clearly increase as the PM levels are reduced; no clear trend is seen for lead and cadmium. Extrapolating the mercury line to 0.001 gr/dscf shows that as PM decreased by 100 times, the metal percentages increased by 100 times. Mercury thus appears to be constant in quantity throughout this wide range of PM emissions, and perhaps the same applies to lead and cadmium as is seen in Figure 9.

Figure 14, a water-wall facility with SDA/FF, show rising concentrations of mercury, arsenic and lead as PM is reduced.

Figure 15 shows metals as a percent of PM for the processed refuse-fuel (PRF)-burning facility having a SDA/ESP. Here lead and cadmium also shows a clear increase with reduced PM indicating higher concentrations in the fine particulate. Mercury shows a triangular spread with two separate and conflicting trend lines. Unit #3 shows much lower concentrations in the fine particulate than those from the ESPs, and mercury and lead show up-trends.

The percentage of metals in the emissions from the broad group of facilities with acid gas controls seen in Figure 16 does not show a clear trend versus PM for lead and cadmium, but a clear upward trend for mercury is indicated. The wide data scatter obscures the general trends which can be seen in the data from individual facilities.

If metals are approximately a constant percent of PM, then PM may be considered to be an effective surrogate for metals. If the metals increase as a percent as the PM is less, it may be that the metals emissions are relatively constant, independent of PM. In fact, mercury did not change with PM in most cases. Lead went down with the DI and SDA with fabric filter and air pollution control systems, but not with the ESP pointing toward these metals concentrating in the fines. Cadmium did not change with PM for individual plants which is inconsistent with the findings for lead, another metal that volatalizes under MWC conditions.

The emissions of lead, cadmium and chromium may also be influenced by the flame temperature in the furnace as well as the temperature at which the APC operates. The metals emissions should also reflect what is in the waste although correlations between MSW composition and emissions has not been established by field data.

Comparing mercury emissions from various facilities

Figure 16 shows the mercury emissions from twelve different facilities employing activated carbon injection in conjunction with previously existing emission controls (Licata, 1994). The highest emission rate for these facilities was roughly twice the average, and the lowest about half the average, characteristic of lognormal distributions. The average emissions ranged from about 2 to about 50 mg/dscm, a 25-fold range. This range indicates variations in the effort, and success in the effort, to control mercury, but also the amount of mercury in the waste, which in itself has been declining rapidly with time. Not to be overlooked is the finding that when activated carbon is used to control mercury or the PM, carbon content is increased. Dioxins are also removed.

Distinguishing between random variability and other variables and uncertainties.

Burmaster and Hull (1995) have investigated the use of lognormal probability plots as a way to distinguish and visualize variability and uncertainty in a lognormal random variable. The term variability is used to represent knowledge of heterogeneity in a well characterized population, usually not reducible through further measurement or study, and uncertainty to represent ignorance about a poorly characterized phenomenon or model, sometimes reducible through further investigation. Such procedures may be applicable to distinguish different sources of variability such as waste composition from those due to system technological design and variations in operating procedures. Applying these techniques to the data analyzed in this paper would help shed light on this question.

CONCLUSIONS

- Emissions of dioxins, PM, arsenic, lead, cadmium, chromium and mercury measured periodically at four individual MSW combustion facilities having DI or SDA with fabric filters or ESPs over the course of several years are lognormally distributed. Emissions from about twenty WTE facilities listed in the EPA database having acid gas scrubbers and fabric filters exhibit variations similar to those seen at the individual facilities measured over time.
- PM emissions decreased by factors of ten to 100 over four to five years of operation. The source of the variability is unknown.
- Emissions factors for lead, cadmium, and mercury showed varying degrees of decline with reduced PM emissions at three of the four facilities studied, but no change for the facility with SD/FF. The emission factors for the AP-42 listed facilities were scattered, but showed the same general tendencies.
- The mercury, lead and cadmium as a percent of PM increased as PM declines in all facilities analyzed, including the EPA database of facilities with DI or SDA and fabric filters.
- Emission factors of arsenic, lead, cadmium and mercury emissions were relatively constant throughout a 10 to 100-fold range of PM at the specific facilities investigated indicating that they are largely independent of PM. The 10 to 100-fold variations in metals emission factors indicate that there are substantial differences in waste composition, combustion and emission control technology or some other factor influencing emissions.
- The data indicate that PM is a reasonable surrogate for the metals because the metals emission factors either remain constant or decline in pounds per ton of MSW burned at PM.
- In spite of a 20-fold reduction in PM emissions, mercury is not a percent of PM. This indicates that furnace temperatures, APC operating temperatures or some other factor may be more important.
- Although not demonstrated in this paper, total dioxins and furans and toxic equivalent dioxin emissions exhibited variations similar to those of PM and the metals, and did not exceed the EPA limits.
- Graphical procedures and statistical calculations can be used to estimate the Upper Confidence Level for the mean or average emissions over the course of a year, and the Upper Tolerance Limit to predict the maximum emission rate which might be measured 90, 95 or 99% of the tests which are carried out in the future.
- Differences in the performance of the emission control system over time and between different types of APC devices are noted, but

deciding if the variation is due to the waste itself or some other as yet unidentified factors has not yet been done.

- The selection of the "best performing facilities" or even representative facilities, is complicated and confounded by variability.

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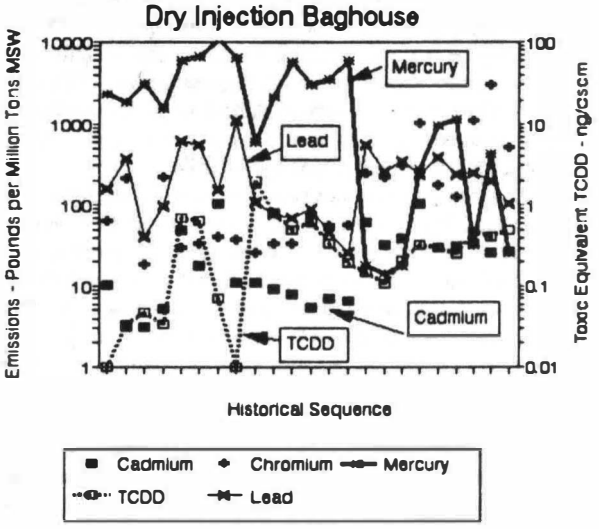

FIG. 1 HISTORICAL SEQUENCE OF EMISSION FACTORS FOR METALS (LB/MILLION TONS), PM (GR/DSCF), AND TOXIC EQUIVALENT TCDD (NG/DSCM) AT FACILITY WITH DRY LIME INJECTION AND FABRIC FILTERS. (EASTMONT)

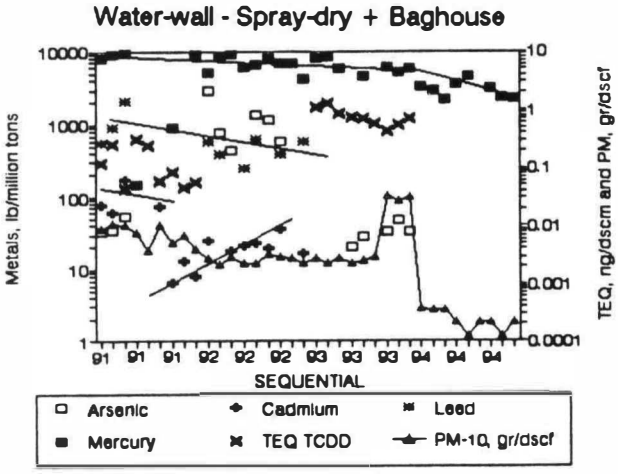

FIG. 2 EMISSION FACTORS FROM FOUR YEARS OF STACK TESTS FOR METALS (MG/DSCM), PM (GR/DSCF), AND TOXIC EQUIVALENT DIOXINS (NG/DSCM) AT WTE FACILITY WITH WATERWALL FURNACES, SPRAY-DRY SCRUBBERS AND FABRIC FILTERS.(OGDEN 1995)

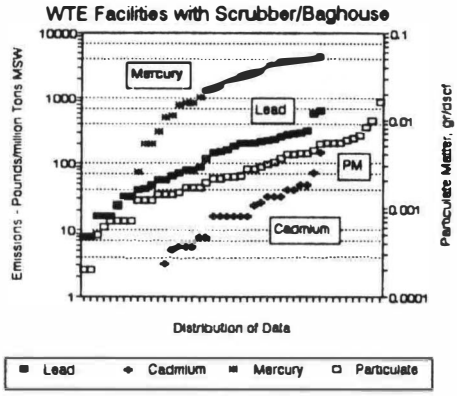

FIG. 3 DISTRIBUTION OF EMISSION FACTOR DATA FOR METERS (MG/DSCM), PM (GR/DSCF), AND DIOXINS (NG/DSCM) FROM 23 STACK TESTS AT WTE FACILITIES DRY INJECTION AND FABRIC FILTER. (EASTMONT)

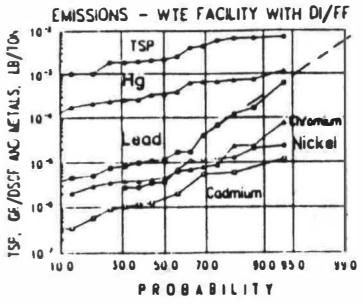

FIG. 4 LOG-PROBABILITY DISTRIBUTION PLOT OF STACK EMISSIONS OF METALS (LB/TON) AND PM (GR/DSCF) FROM REFRACTORY FURNACE WTE FACILITY WITH LIME INJECTION AND FABRIC FILTER. EASTMONT)

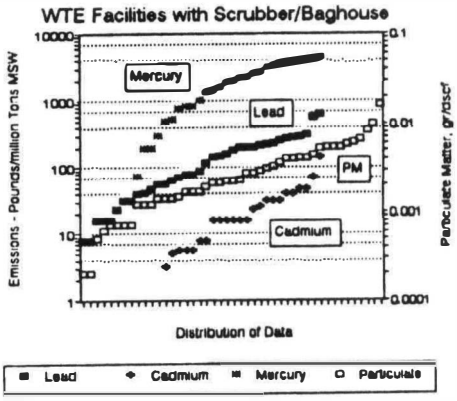

FIG. 5 DISTRIBUTION OF EMISSION FACTOR DATA FROM TESTS OF 40 WTE FACILITIES WITH DRY SCRUBBERS INCLUDED IN EPA DATA BASE. (EASTMONT)

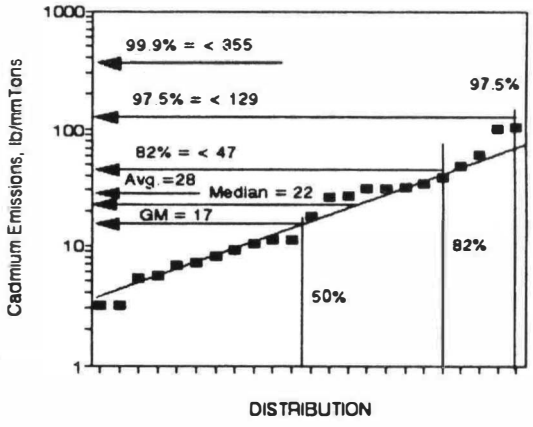

FIG. 6. LOG DISTRIBUTION OF FOUR YEARS OF CADMIUM EMISSIONS FACTORS FROM SINGLE FACILITY, SHOWING AVERAGE, MEDIAN, GEOMETRIC MEAN AND 82%, 97.5% AND 99.9% PROBABILITIES.

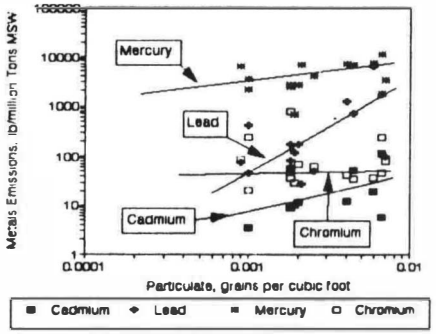

FIG. 7 EMISSION FACTORS VERSUS PARTICULATE (GR/DSCF) MEASURED OVER A PERIOD OF FOUR YEARS AT REFRACTORY WTE FACILITY WITH LIME INJECTION AND FABRIC FILTER.

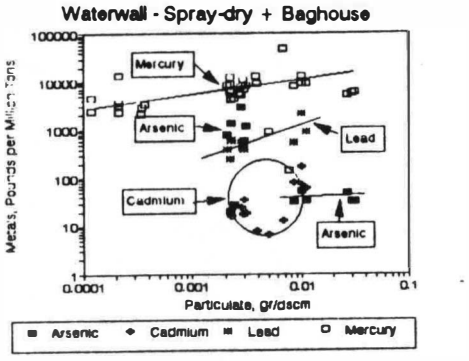

FIG. 8 STACK METALS EMISSION FACTORS VERSUS PARTICULATE (GR/DSCF) MEASURED OVER FOUR YEAR PERIOD AT WATERWALL WTE FACILITY [L] WITH SPRAY-DRY SCRUBBER AND FABRIC FILTER. (OGDEN)

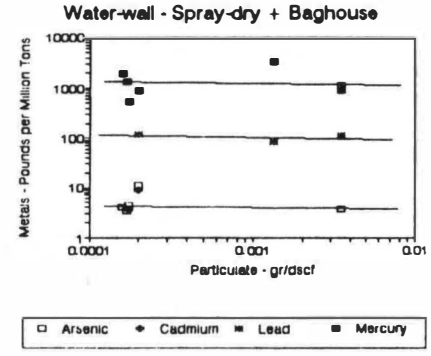

FIG. 9 STACK METALS EMISSION FACTORS VERSUS PARTICULATE (GR/DSCF) MEASURED OVER FIVE YEAR PERIOD AT WATERWALL WTE FACILITY [K] WITH SPRAY-DRY SCRUBBER AND FABRIC FILTER. EACH POINT IS THE AVERAGE OF THREE TESTS. (OGDEN, 1994)

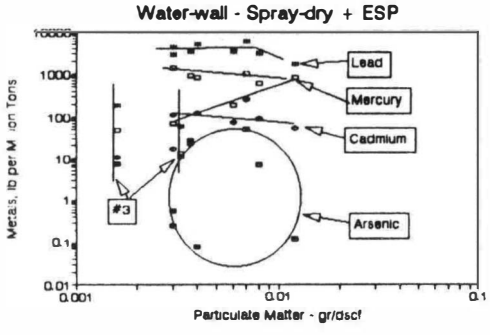

FIG. 10 STACK METALS EMISSION FACTORS VERSUS PARTICULATE (GR/DSCF) MEASURED OVER A FIVE YEAR PERIOD AT WATERWALL WTE FACILITY [SEM] BURNING PROCESSED REFUSE FUEL (PRF) WITH SPRAY-DRY LIME SCRUBBERS. UNITS #1 AND #2 HAVE ESPS; UNIT #3 HAS FABRIC FILTER. (ZAKARIA)

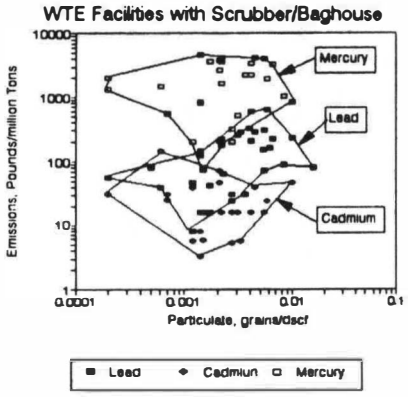

FIG. 11 STACK METALS EMISSION FACTORS FROM 45 STACK TESTS AT WTE FACILITIES WITH ACID GAS CONTROLS AND FABRIC FILTERS, PLOTTED VERSUS PARTICULATE (GR/DSCF). (EPA, 1993)

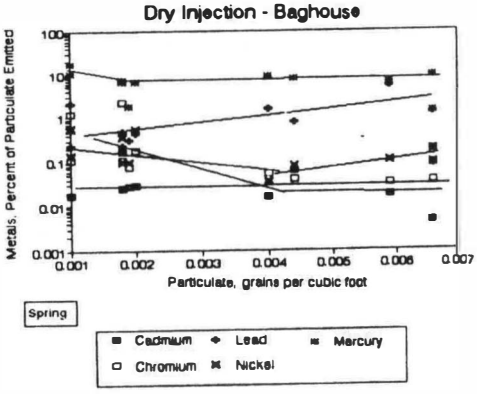

FIG. 12 PERCENT OF METALS IN PM EMISSIONS OF REFRACTORY WTE FACILITY WITH LIME INJECTION AND BAGHOUSE. (EASTMONT)

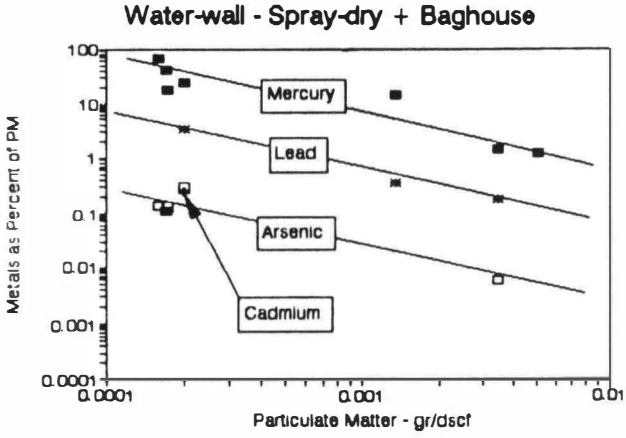

FIG. 13 PERCENT OF METALS IN PM EMISSIONS OF WATERWALL WTE FACILITY [L] WITH SPRAY-DRY LIME SCRUBBER AND BAGHOUSE. (OGDEN, 1995)

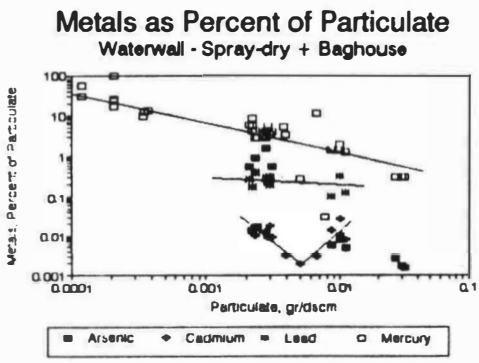

FIG. 14 PERCENT OF METALS IN PM EMISSIONS OF WATERWALL WTE FACILITY [K] WITH SPRAY-DRY LIME SCRUBBER (OGDEN, 1995)

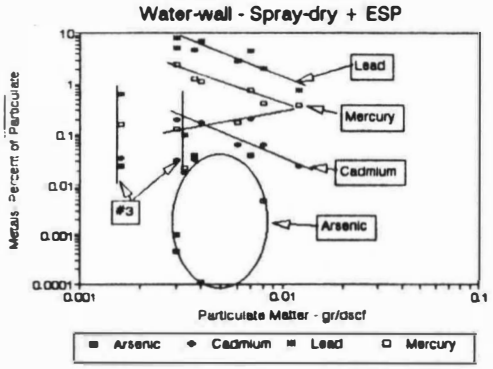

FIG. 15 PERCENT OF METALS IN PM EMISSIONS OF WATERWALL PRF-BURNING WTE FACILITY WITH SPRAY-DRY LIME SCRUBBERS, TWO

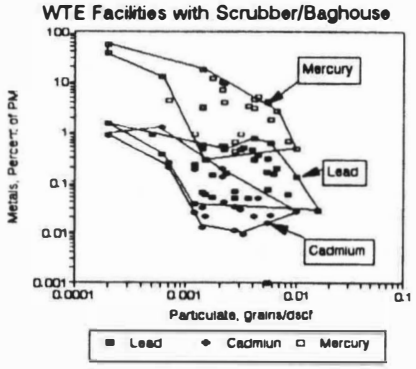

FIG. 16 PERCENT OF METALS IN PM EMISSIONS OF ABOUT 20 WTE FACILITIES WITH LIME SCRUBBER/BAGHOUSE ACID GAS CONTROLS. (EPA, 1993)

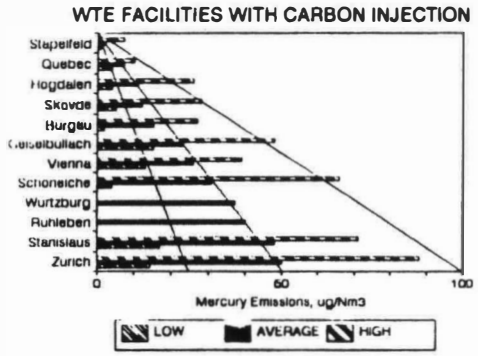

FIG. 17 MERCURY EMISSIONS OF WTE FACILITIES WITH CARBON INJECTION, SHOWING THE WIDE RANGE OF DATA. (LICATA)