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Project Summary

The Fate of Trace Metals in a Rotary Kiln Incinerator with a Single-Stage Ionizing Wet Scrubber

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A 3-week series of pilot-scale incineration tests was performed at the U.S. Environmental Protection Agency's (EPA) Incineration Research Facility (IRF) in Jefferson, AR, to evaluate the fate of trace metals fed to a rotary kiln incinerator equipped with a single-stage ionizing wet scrubber for control of particulates and acid gas. Test variables were kiln temperature, ranging from 816° to 927°C (1500° to 1700°F); afterburner temperature, ranging from 982° to 1205°C (1800° to 2200°F); and feed chlorine content, ranging from 0% to 8%.

The test results indicated that cadmium and bismuth were relatively volatile, with an average of less than 40% discharged with the kiln ash. Arsenic, barium, chromium, copper, lead, magnesium, and strontium were relatively nonvolatile, with an average of greater than 80% discharged with the kiln ash. Observed relative metal volatilities generally agreed with the volatilities predicted based on vapor pressure/temperature relationships, with the exception of arsenic, which was much less volatile than predicted. Cadmium, bismuth, and lead were more volatile at higher kiln temperature; the discharge distributions of the remaining metals were not significantly affected by kiln temperature.

Enrichment of metals in the fine-particulate fraction was observed at the afterburner exit, with an average of roughly 50% of the flue-gas particulate metal in the less-than-10-μm size range. The distributions of the more-volatile metals were shifted to fine particulate more so than those of the less-volatile metals. Both increased kiln temperature and the addition of chlorine to the synthetic waste feed caused a shift of metals to fine particulate. Apparent scrubber collection efficiencies for the metals averaged 22% to 71%, and were generally higher for the less-volatile metals. The overall average metal collection efficiency was 43%. It should be noted that industrial applications of ionizing wet scrubbers are typically in multiple stages and, as such, would be expected to collect metals more efficiently than the single-stage scrubber at the IRF.

This Project Summary was developed by EPA's Risk Reduction Engineering Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The hazardous waste incinerator performance standards, promulgated by EPA in January 1981 under the Resource Conservation and Recovery Act, established particulate and HCl emission limits and mandated 99.99% destruction and removal efficiency for principal organic hazardous constituents (POHCs). Subsequent risk assessments have suggested that hazardous trace-metal emissions may pose the largest component of the total risk to human health and the environment from otherwise properly operated incinerators. The data base on trace-metal emissions from incinerators is sparse, however; data on the effects of waste composition and incinerator operation on these emissions are particularly lacking.

In the response to these data needs and with support from the Office of Solid Waste, an extensive series of tests was conducted at EPA's IRF to investigate the fate of trace metals fed to a rotary kiln incinerator equipped with a single-stage, ionizing wet scrubber. This program was a continuation of a previous IRF test program, conducted in 1988, that employed a venturi scrubber/packed-column scrubber as the primary air pollution control system.

The primary objective of these test programs was to investigate the fate of five hazardous and four nonhazardous trace metals fed to a rotary kiln incinerator in a synthetic solid-waste matrix. Of interest was the distribution of the metals as a function of incinerator operating temperatures and feed chlorine content. The hazardous trace metals investigated were arsenic, barium, cadmium, chromium, and lead. The nonhazardous metals were bismuth, copper, magnesium, and strontium.

Test Program

The test program consisted of nine parametric tests in which the waste feed contained the nine metals identified above. All tests were conducted in the pilot-scale rotary kiln incinerator system at the IRF (Figure 1).

Synthetic Waste Mixture

The synthetic waste contained a mixture of organic liquids added to a clay absorbent material. Trace metals were incorporated by spiking an aqueous mixture of the metals of interest onto the clay/organic-liquid material. The waste was fed to the rotary kiln via a twin-auger screw feeder at a nominal rate of 63 kg/hr (140 lb/hr).

The organic-liquid base consisted of toluene, with varying amounts of tetrachloroethylene and chlorobenzene added to provide a range of chlorine contents. Synthetic waste chlorine was varied from 0% to nominally 8%. The analyzed organic fractions for the three waste-feed mixtures are given in Table 1. Table 2 summarizes the average metal concentrations in the combined waste feed over the nine tests.

Test Conditions

The test variables were kiln temperature, afterburner temperature, and the chlorine content of the synthetic waste feed. Seven specific combinations of these variables were selected at test points. Target and average achieved values for these three variables are summarized in Table 3. For all tests, excess air was nominally 11.5% oxygen in the kiln and 8% oxygen in the afterburner exit flue gas. Estimated solids residence time within the kiln was 1 hr.

Test Results

Average Trace-Metal Discharge Distributions

Figure 2 shows the amounts of metal found in each discharge stream, as a fraction of the total in the three discharge streams: kiln ash, scrubber-exit flue gas, and scrubber liquor. In Figure 2, the bar for each metal represents the range in the fraction accounted for by each discharge stream over all nine tests, with the average fraction from all tests noted by the midrange tick mark. Metal discharge distribution data in Figure 2 are plotted versus the volatility temperature of each metal, which is the temperature at which the effective vapor pressure of the metal is 10^{-6} atm. The effective vapor pressure is the sum of the equilibrium vapor pressures of all species containing the metal. It reflects the quantity of metal that would vaporize under a given set of conditions. A vapor pressure of 10^{-6} atm is selected because it represents a measurable amount of vaporization. The lower the volatility temperature, the more volatile the metal is expected to be.

Figure 2 indicates a correlation between observed volatility and volatility temperature for all the metals tested, except arsenic. With the exception of arsenic, average normalized kiln-ash fractions generally increased with increasing volatility temperature. Cadmium and bismuth were relatively volatile and were less prevalent in the kiln ash than were the more-refractory metals. Kiln-ash fractions accounted for the majority of arsenic, lead, barium, copper, strontium, magnesium, and chromium.

Based on volatility temperature, arsenic is expected to be the most volatile element. The data, however, show arsenic to be apparently refractory, remaining largely with the kiln ash. The volatility temperature for arsenic is based on the vapor pressure of As_2O_3. The fact that arsenic is significantly less volatile than expected (were As_2O_3 the predominant arsenic species) suggests that either some other, less-volatile arsenic compound (perhaps an arsenate) was preferred or that some other chemical interaction, such as strong adsorption to the clay, occurred.

Effects of Incinerator Operating Conditions on Metal Distributions

Increased kiln temperature caused a noticeable increase in the volatility of cadmium, bismuth, and lead. Figure 3 shows that as the kiln temperature increased there was a significant decrease in the kiln-ash fraction of these metals, with corresponding increases in the scrubber-exit flue-gas and scrubber-liquor fractions. Although the volatility of lead increased with higher kiln temperature, lead still remained relatively refractory and was found primarily in the kiln ash. Kiln temperature within the tested range had no significant effect on the discharge distributions of any of the remaining metals.

Afterburner temperatures within the tested range did not clearly affect the distributions of any of the metals among the scrubber-exit flue-gas and scrubber-liquor discharge streams. Data on the effect of feed chlorine content are inconclusive pending investigation of an apparent relationship between feed chlorine and the efficiency of the analytical procedure for metals in kiln ash.

Apparent Scrubber Collection Efficiencies

The apparent scrubber collection efficiency for flue-gas metals was determined for each test. The apparent efficiency represents the ratio of the normalized metal fraction measured in the scrubber liquor to the sum of the normalized metal fractions measured in the scrubber liquor and scrubber-exit flue gas. Figure 4 summarizes the efficiency data. The bar for each metal represents the range of scrubber efficiencies over the nine tests, with the overall average for the nine tests noted by the midrange tick mark. Average metal collection efficiencies ranged from 22% to 71%; the overall average for all metals was 43%. It should be noted that industrial applications of ionizing wet scrubbers are typically in multiple stages and, as such, would be expected to collect metals more efficiently than the single-stage scrubber at the IRF. Figure 4 shows that there were significant variations in the efficiencies for each metal. Average efficiencies, however, were generally higher for the less-volatile metals.

Within the limits of data variability, none of the test variables affected scrubber collection efficiencies for arsenic, barium, strontium, magnesium, and chromium. Efficiencies for cadmium, bismuth, lead and copper increased with increased kiln temperature and waste feed chlorine content. Increased efficiency might be expected with increased feed chlorine content if the presence of chlorine leads to the formation of more-soluble metal chlorides. It is unclear, however, why increased kiln temperature would directly lead to increased collection efficiency. Apparent scrubber collection efficiencies for metals did not vary with afterburner exit temperature.

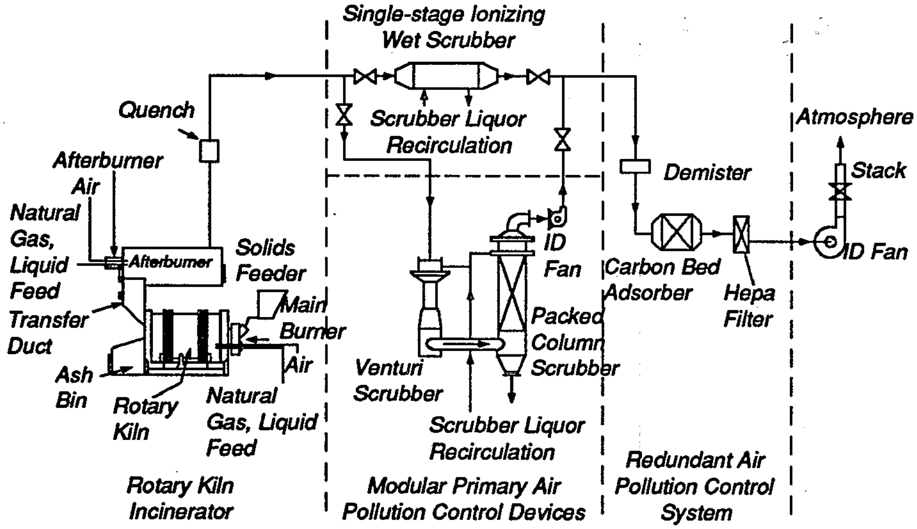

Figure 1. *Schematic of the IRF rotary kiln incineration system.*

Metal Distributions in Flue-Gas Particulate by Particle Size

The particulate samples from the afterburner-exit flue-gas sampling train were size-fractionated, and trace-metal distributions as a function of particle size were determined. Figure 5 shows the metal distributions in the particle-size range of less than 10 µm, averaged over all nine tests. The average of the nine total particulate samples is also shown. The data show a relationship between the relative volatility of each metal (as indicated by its volatility temperature noted on the horizontal axis) and its propensity for redistribution to finer particulate. This is indicated by the higher fractions of the metals with lower volatility temperatures in the less-than-10-µm particle-size fractions.

This behavior is consistent with expectation. Most metal vaporized at some point in the incinerator will ultimately condense when the flue gas cools. Condensation occurs via fume formation or condensation onto available flue-gas particulate. Fume formation results in very fine particulate. Condensation onto available particulate results in concentrating the metal in fine particulate, because condensation is a per-unit of surface area event and the surface-area-to-mass ratio is increased in fine particulate. Both mechanisms tend to concentrate volatilized metal in fine particulate. Interestingly, arsenic behaves as a volatile metal with respect to enrichment in fine particulate.

The effects of kiln temperature, afterburner temperature, and waste feed chlorine content are shown in Figure 6. The size distributions of the metals most nearly reflect the overall sample particle-size distribution for Test 2 (lowest kiln temperature), Test 5 (highest afterburner temperature), and Test 1 (no chlorine in the waste feed); very little redistribution among the particulate was observed. For these three tests, an average of about 20% to 25% of each metal and the total particulate sample were in the less-than-10-µm particulate.

With increased kiln temperature, the size distributions of all metals except chromium shifted to about 60% less than 10 µm. Increased afterburner temperature caused a shift in the overall sample to coarser particulate, most likely because of fine particles melting or softening and coalescing into larger particles. A corresponding shift in metal-specific distributions to coarse particulate was observed.

The addition of chlorinated compounds to the synthetic waste feed mainly affected cadmium, lead, copper, and chromium distributions. With chlorine content increased from 0% to 4%, the fraction of cadmium, lead, and copper accounted for by the less-than-10-µm particulate increased from about 20% to roughly 55%. No further redistributions of these metals were observed with increased chlorine from 4% to 8%. For chromium, increasing chlorine content from 0% to 4% to 8% caused a corresponding shift of 2% to 20% to 50% in particulate of less than 10 µm.

Conclusions

Test conclusions include the following:

• Cadmium and bismuth were relatively volatile, with an average of less than 40% of the discharged metal accounted for by the kiln ash. Arsenic, barium, chromium, copper, lead, magnesium, and strontium were relatively nonvolatile, with an average of greater than 80% of the discharged metal accounted for by the kiln ash

• Observed metal volatilities generally agreed with the order predicted by metal volatility temperatures, with the notable exception of arsenic. Arsenic has the lowest volatility temperature of metals tested but was observed to be one of the least-volatile of the metals. This suggests that As_2O_3 was not the predominant arsenic species in the incinerator or that the arsenic was adsorbed by the clay/ash matrix.

• Kiln temperature affected the relative volatility of cadmium, bismuth, and lead. The fractions of these metals discharged in the kiln ash decreased with increasing kiln temperature.

• Afterburner exit temperature did not clearly affect metal partitioning among the scrubber-exit flue-gas and scrubber-liquor discharge streams.

• Enrichment of metals in the fine-particulate fraction of the afterburner-exit particulate was observed; an average of roughly 50% of the flue-gas particulate metal was in the less-than-10-µm size range compared with an average of about 30% for the total particulate sample. The distributions of the more-volatile metals were shifted to fine particulate more so than those for the less-volatile metals. Arsenic behaved as a volatile metal with respect to its distributions among the afterburner-exit flue-gas particle-size ranges.

• Each test variable affected the distributions of at least some of the metals among the flue-gas particulate particle-size ranges. Size distributions of the metals most nearly reflected the overall sample particle-size distribution for Test 2 (lowest kiln temperature), Test 5 (highest afterburner temperature), and Test 1 (no chlorine in the waste feed); very little redistribution among the particulate was observed. For these three tests, about 20% to 25% of each metal and the total particulate sample were found in the less-than-10-µm particulate

• Increasing kiln temperature from 816° to 927°C (1500° to 1700°F) caused the average particle-size distributions to shift from roughly 20% less than 10 µm to an average of 60% less than 10 µm for all test metals except chromium. For cadmium, copper, and lead, an increase in waste feed chlorine content from 0% to 4% caused their distributions to shift from roughly 20% less than 10 µm to 55% less than 10 µm. No further effects with feed chlorine increased to 8% were observed for these metals. For chromium, increasing chlorine content from 0% to 4% to 8% caused a corresponding shift of 2% to 20% to 50% in particulate less than 10 µm.

Table 1. POHC Concentrations in Clay/Organic-Liquid Feed

Test	Weight % in mixture			
	Toluene	Tetrachloroethylene	Chlorobenzene	Chlorine Content*
1	23.1	0	0	0
2 through 8 (average)	17.8	3.1	3.0	3.6
9	11.6	6.0	5.6	6.9

*Calculated based on measured tetrachloroethylene and chlorobenzene concentrations.

Table 2. Average Integrated Feed Metal Concentrations

Metal	Concentration, mg/kg	Metal	Concentration, mg/kg
Arsenic	48	Copper	380
Barium	390	Lead	45
Bismuth	330	Magnesium	18,800
Cadmium	10	Strontium	410
Chromium	40		

Table 3. Target and Average Achieved Test Conditions

Test	Date	Feed Mixture Cl Content, %		Kiln Exit Temperature, °C(°F)		Afterburner Exit Temperature, °C(°F)	
		Target	Actual	Target	Average	Target	Average
1	8/17/89	0	0	871 (1600)	900 (1652)	1093 (2000)	1088 (1990)
2	8/2/89	4	3.5	815 (1500)	819 (1507)	1093 (2000)	1095 (2002)
3	8/4/89	4	3.5	927 (1700)	929 (1704)	1093 (2000)	1092 (1998)
4	8/1/89	4	3.5	871 (1600)	877 (1610)	1093 (2000)	1096 (2006)
5	8/16/89	4	3.7	871 (1600)	885 (1625)	1204 (2200)	1163 (2125)
6	8/15/89	4	3.6	871 (1600)	887 (1629)	982 (1800)	1017 (1863)
7*	8/9/89	4	3.5	871 (1600)	881 (1618)	1093 (2000)	1103 (2018)
8*	8/11/89	4	3.8	871 (1600)	879 (1615)	1093 (2000)	1098 (2008)
9	7/28/89	8	6.9	871 (1600)	881 (1617)	1093 (2000)	1087 (1988)

*Test points 7 and 8 are replicates of test point 4; together the three tests provided the components of an IRF trial burn.

- The 9-test averages of apparent scrubber collection efficiencies for each of the metals ranged from 22% to 71%; they were generally higher for the less-volatile metals. The overall average collection efficiency for all metals was 43%. Note, however, that the IRF ionizing wet scrubber is a single-stage unit; industrial applications of ionizing wet scrubbers are typically in multiple stages and, as such, would be expected to collect metals more efficiently.
- Apparent scrubber collection efficiencies for cadmium, bismuth, lead, and copper increased with increased kiln temperature and waste feed chlorine content. Afterburner temperature had no discernible effect on apparent scrubber collection efficiencies for any of the metals.

The full report was submitted in fulfillment of Contract 68-C9-0038 by Acurex Corporation under the sponsorship of the U.S. Environmental Protection Agency.

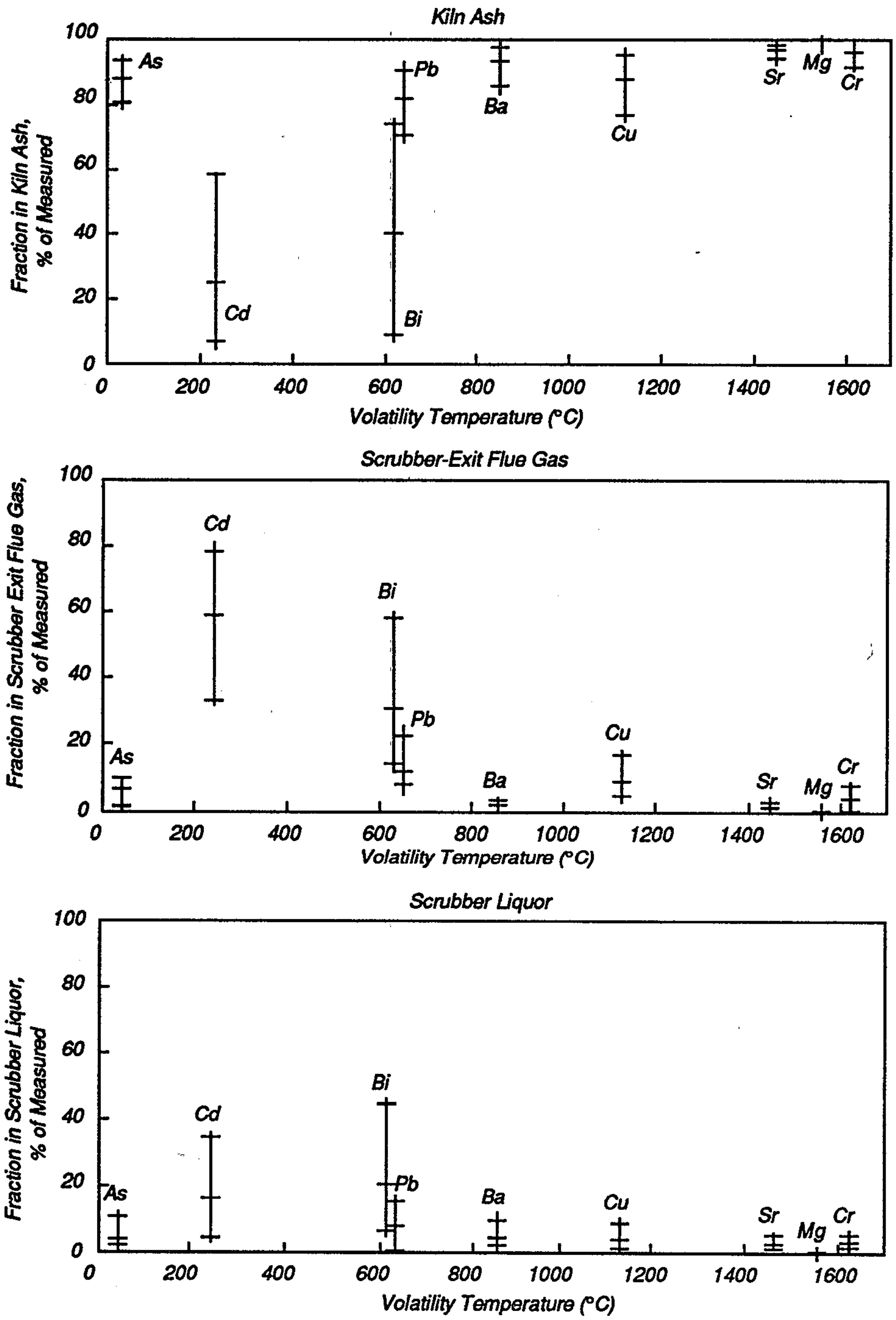

Figure 2. *Normalized distributions of metals in the discharge streams.*

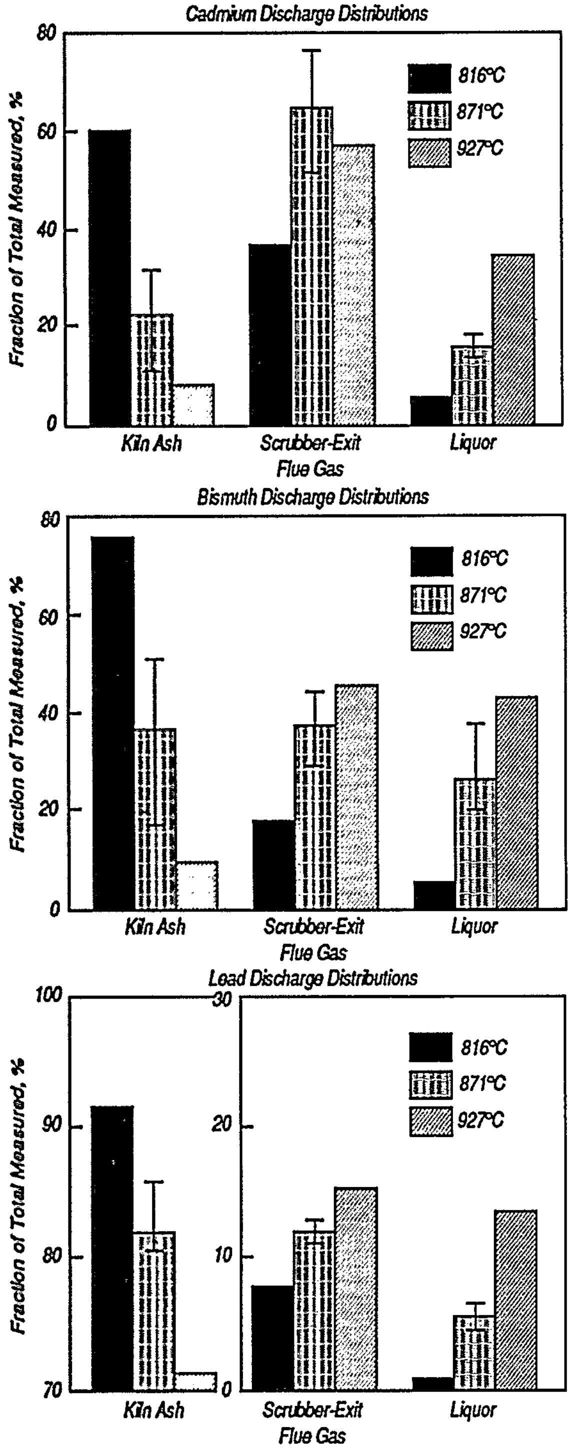

Figure 3 Effects of kiln temperature on the discharge distributions of cadmium, bismuth, and lead.

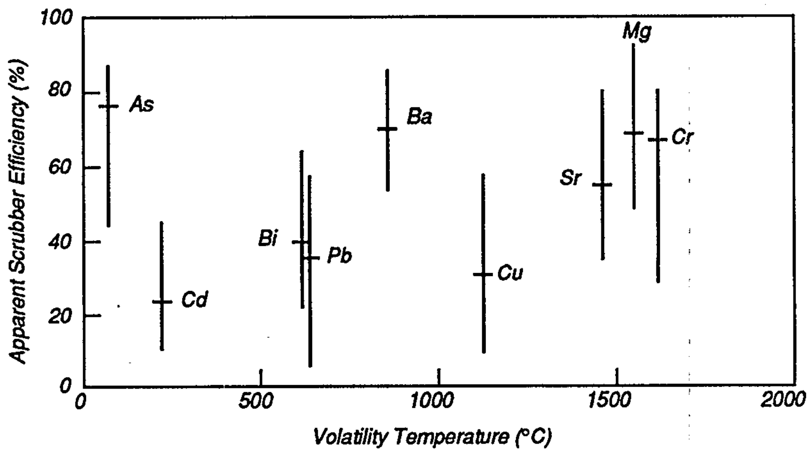

Figure 4 Apparent scrubber collection efficiencies for metals.

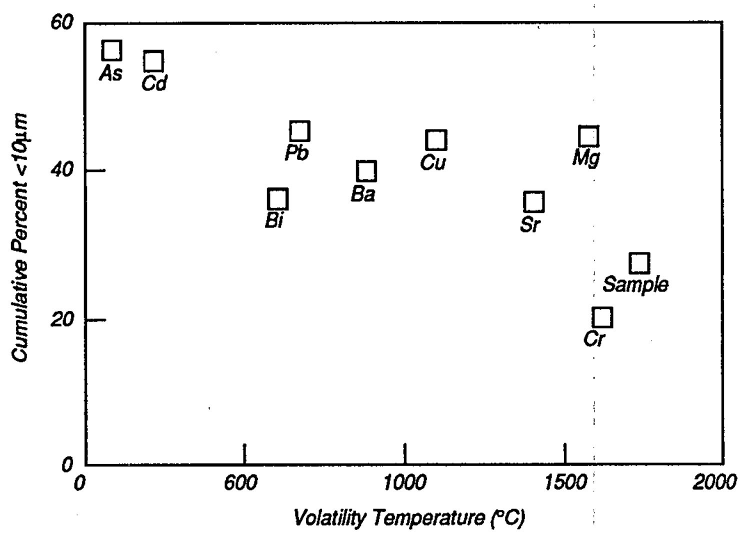

Figure 5. Average distribution of metals of less than 10µm in afterburner-exit flue-gas particle-size fractions.

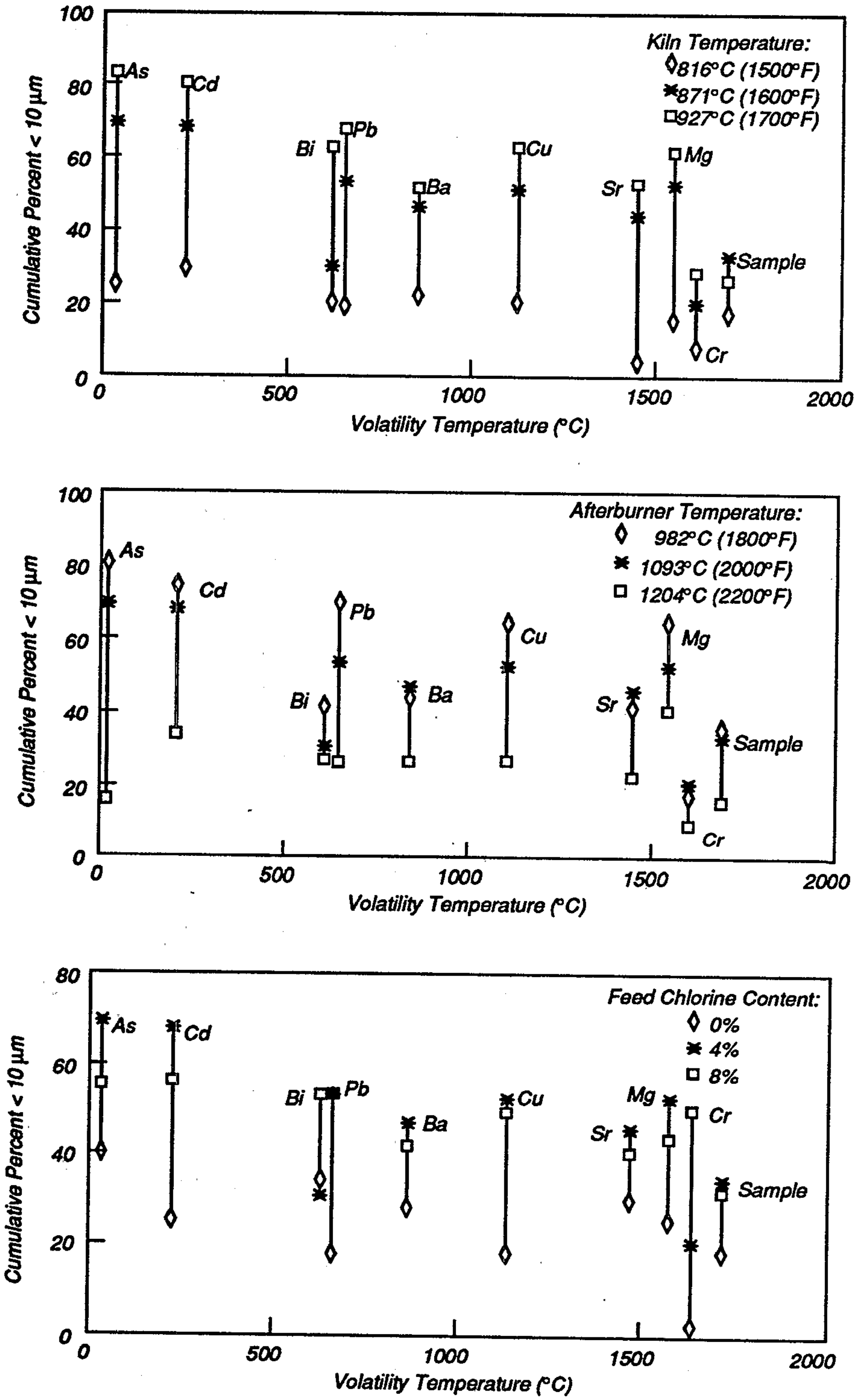

Figure 6. *Effects of kiln temperature, afterburner temperature, and waste feed chlorine content on the particle-size distribution of metals in the afterburner exit flue gas.*

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The complete report consists of two volumes entitled "The Fate of Trace Metals in a Rotary Kiln Incinerator with a Single-Stage Ionizing Wet Scrubber."
"Volume I: Technical Results," (Order No. PB91-223 388; Cost: $23.00, subject to change).
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