

The inconsistent behavior observed for lead may be because the volatility temperature of lead is within the range of kiln temperatures tested or may be related to increased lead volatility in the presence of chlorine. The volatilities of some metals may be altered through reactions in the incineration system. For example, chlorine can react with some metals to form new compounds that volatilize more readily. Many metal chlorides are more volatile, as indicated by a lower volatility temperature than their corresponding oxide or elemental forms. For example, equilibrium calculations for a mixture containing 5-percent chlorine result in PbCl_2 as the principal vapor phase species. The corresponding volatility temperature of -15°C (5°F) is considerably less than the volatility temperature of 627°C (1160°F) for lead under oxidizing conditions. Test data presented in the next section suggests that lead became more volatile with increasing kiln temperature and with increasing chlorine. Although the tests were performed under the same nominal conditions, minor differences between the two programs may have combined with the sensitivity to both of these test variables to cause the wide variation in lead discharge distributions.

EFFECTS OF INCINERATOR OPERATING CONDITIONS ON METAL DISTRIBUTIONS

Test results from the single-stage ionizing wet scrubber test series show that increasing the kiln temperature from 816°C to 927°C (1500°F to 1700°F) caused a noticeable increase in the volatility of cadmium, bismuth, and lead. Figure 4 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 nonvolatile and was found primarily in the kiln ash for this test series. Changes in kiln temperature had no significant effect on the discharge distributions of any of the remaining metals. Data from the venturi/packed-column test series showed that kiln temperature had less pronounced effects on metal volatility.

Changes in afterburner temperature did not significantly affect the distributions of any of the metals among the scrubber exit flue gas and scrubber liquor discharge streams for either test series.

Variations in feed chlorine content did not affect metal discharge distributions within the limits of data variability established by replicate test conditions during the single-stage ionizing wet scrubber test series. However, as shown in Figure 5, increased feed chlorine content did cause increased volatility of copper and lead during the venturi/packed-column scrubber test series. As noted, the calculated lead volatility temperature is reduced significantly for cases that consider the presence of chlorine. The calculated volatility temperature for copper also decreases significantly when chlorine is considered (from 1116°C to 127°C (1975°F to 260°F)). However, because neither metal was as volatile as would be expected if its volatility temperature were that of the metal chloride, it is suspected that only part of the lead and copper reacted with the chlorine to form the more volatile metal chloride species. The absence of a similar clear relationship between chlorine and the volatility of these metals during the single-stage ionizing wet scrubber test series also suggests that only partial reactions occurred.

METAL FLUE GAS PARTICLE SIZE DISTRIBUTIONS

Metals find their way into flue gas particulate via two pathways. In one pathway, the metal remains in a condensed phase through the entire incinerator system and is carried out of the system with entrained ash in the combustion gas. In the second pathway, the metal vaporizes at some point in the incinerator, then recondenses when the flue gas cools. Both vaporization and condensation can occur locally under proper conditions.

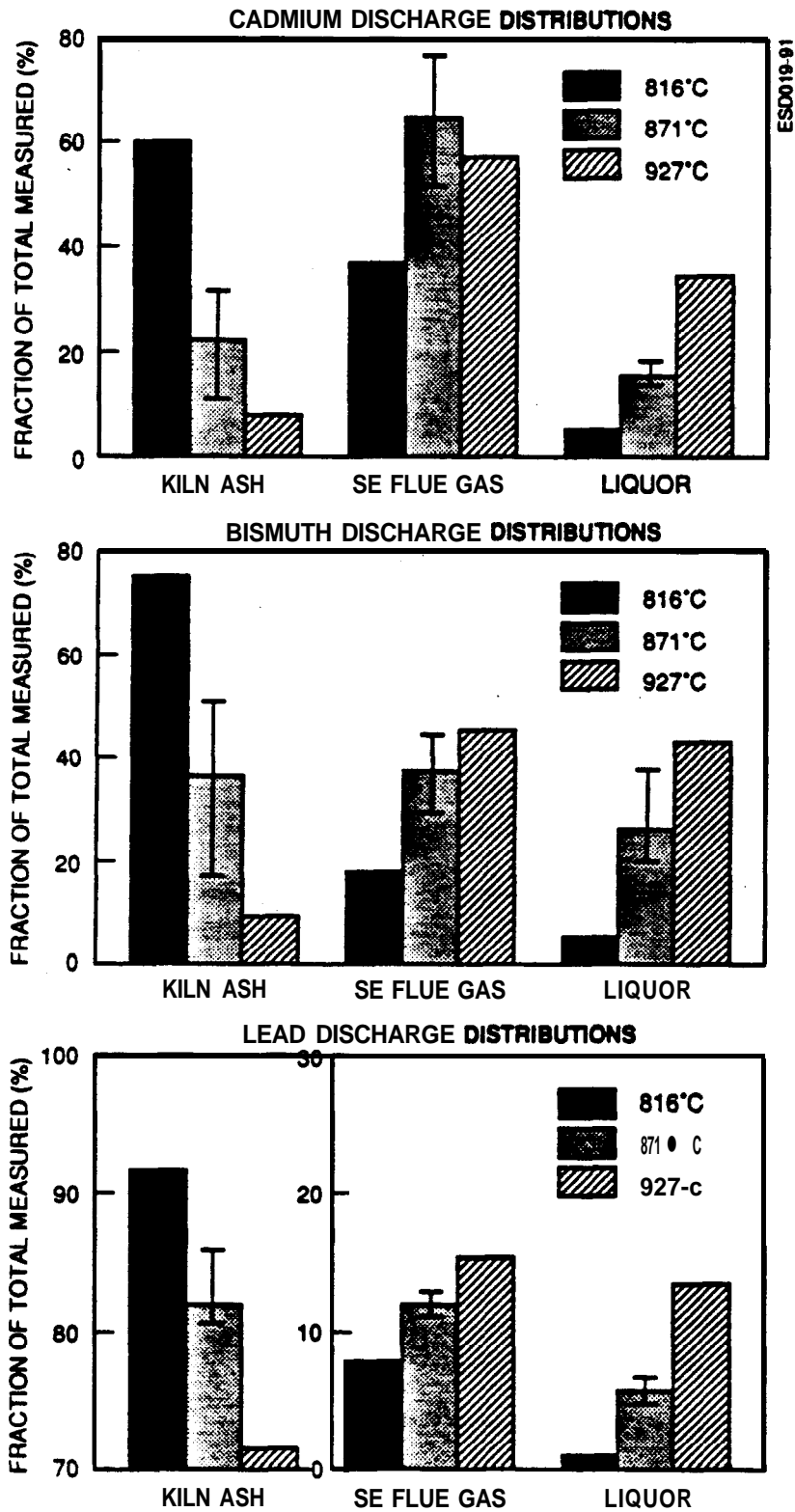


Figure 4. Effects of kiln temperature on the discharge distributions of cadmium, bismuth, and lead in the single-stage ionizing wet scrubber tests.

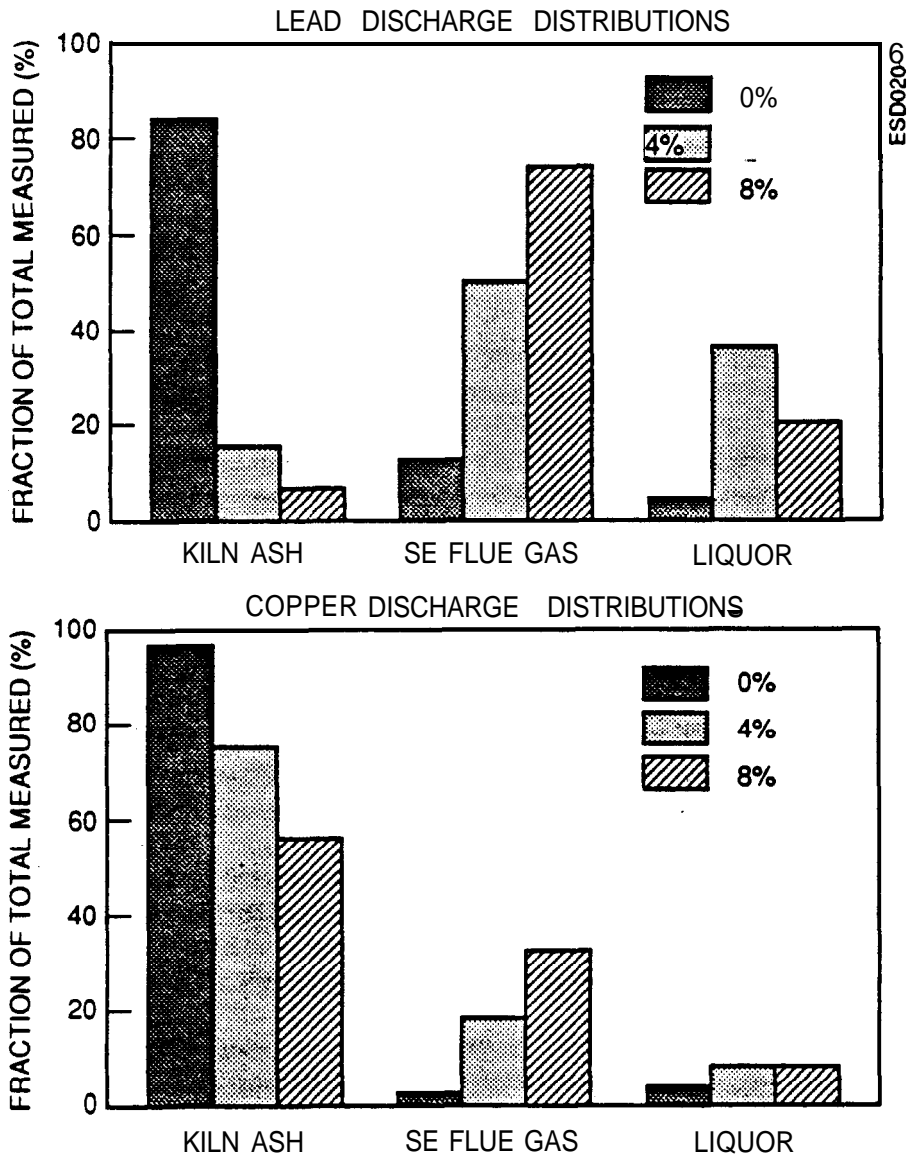


Figure 5. Effects of feed chlorine content on the discharge distributions of copper and lead in the venturi/packed-column scrubber tests.

Vaporized metals can condense homogeneously into condensation nuclei that grow into a very fine fume, or they can condense heterogeneously onto existing flue gas particulate. In both mechanisms the tendency is to enrich (be found at higher per mass concentration) in fine particulate. In the former mechanism, fume particles are very **fine** (1 μm or less). In the latter mechanism, the surface-to-mass ratio is higher for fine particles than for coarse particles. Because condensation onto an available surface is a per surface area event, this also leads to enrichment in fine particulate.

Via the above mechanisms, the distribution of a given metal among **flue** gas particle size ranges is strongly influenced by the extent to which the metal vaporizes in the incineration system. Refractory metals that do not vaporize significantly tend to be relatively evenly distributed in the flue gas particulate size ranges on a per mass (mg/kg particulate) basis. Volatile metals tend to enrich in the fine particulate fractions, with enrichment tendency increasing with increasing volatility.

Figure 6 shows the fractions of the particulate metal found in the less than 10 μm size range during the single-stage ionizing wet scrubber test series. The effects of increased kiln exit temperature are shown. The fractions of the total particulate sample in this size range are also shown. Values for the three replicate test conditions were averaged and plotted as a single point. Metal particulate distributions are plotted against the volatility temperatures to facilitate comparison of relative metal behavior.

With the exception of chromium, the average metal distributions in the flue gas particle size range less than 10 μm shifted from roughly 20 percent to an average of 60 percent as the kiln temperature was increased from 816° to 927°C (1500° to 1700°F). In addition, the redistribution of metals to this size range generally correlated with the relative **volatilities** of the metals, with the volatile metals most affected. Interestingly, arsenic in the flue gas behaved as the most volatile metal with respect to particle size redistribution; more than 80 percent of the arsenic particulate was found in the less than 10 μm size fraction at a kiln exit temperature of 927°C (1700°F). Although most of the arsenic remained in the **kiln** ash, the fraction that exited with the **flue** gas became **significantly** enriched in the **fine** particulate fractions during tests at higher temperatures. Observed enrichment of the test metals in the less than 10 μm particulate suggests that some metal vaporization occurred in the system, even though many of these metals were predominantly nonvolatile as indicated by their tendency to remain predominantly in the kiln ash.

Although a relatively small fraction of the metal fed may escape the kiln, a propensity to concentrate in the **finer** particulate fractions may increase the risk posed by these emissions. These data are significant given the greater challenge to air pollution control devices posed by smaller particulate, the ability of **smaller** particles to penetrate the deep lung, and the toxicity of many metals. However, the data also suggest that metal enrichment in the **fine** particulate fractions can be controlled operationally by limiting incinerator temperature.

The effects of the waste feed chlorine content on total particulate and metal-specific size distributions are shown in Figure 7. When feed chlorine was increased from 0 to 4 percent, the fraction of total particulate in the less than 10 μm fraction increased from 20 to approximately 35 percent. This is expected if the presence of chlorine in the feed serves to increase the volatility of some feed inorganic constituents. When reviewing the data, the effects of chlorine were taken to be most significant when the metal distributions were shifted more than the distributions of the

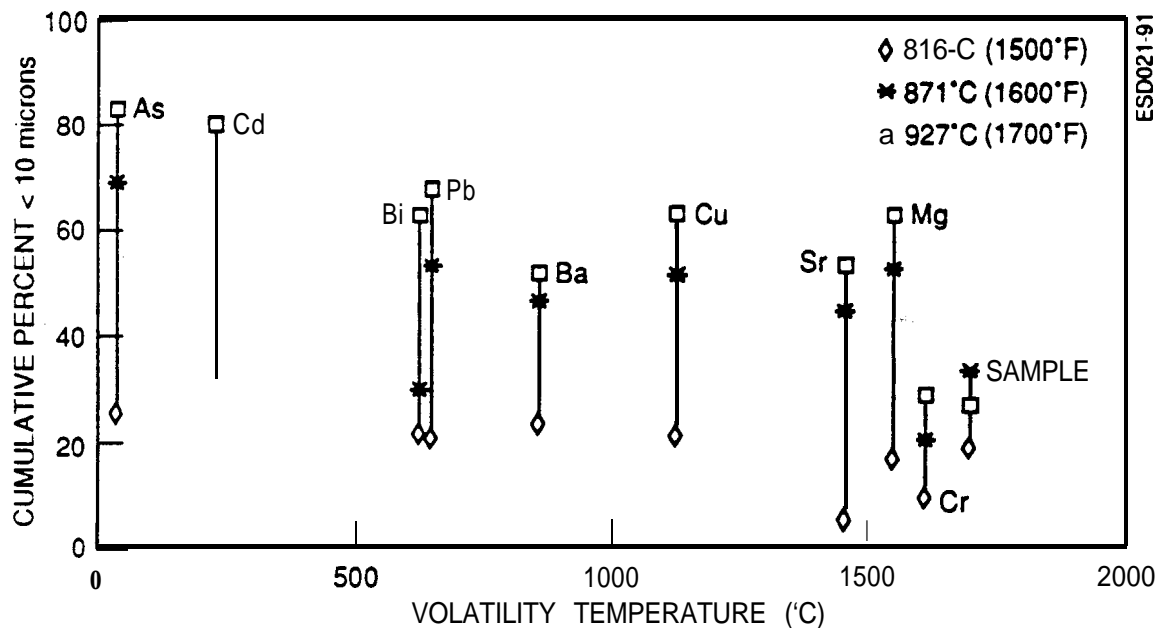


Figure 6. Effect of kiln temperature on the distribution of metals in the afterburner exit flue gas particulate size fractions in the single-stage ionizing wet scrubber tests.

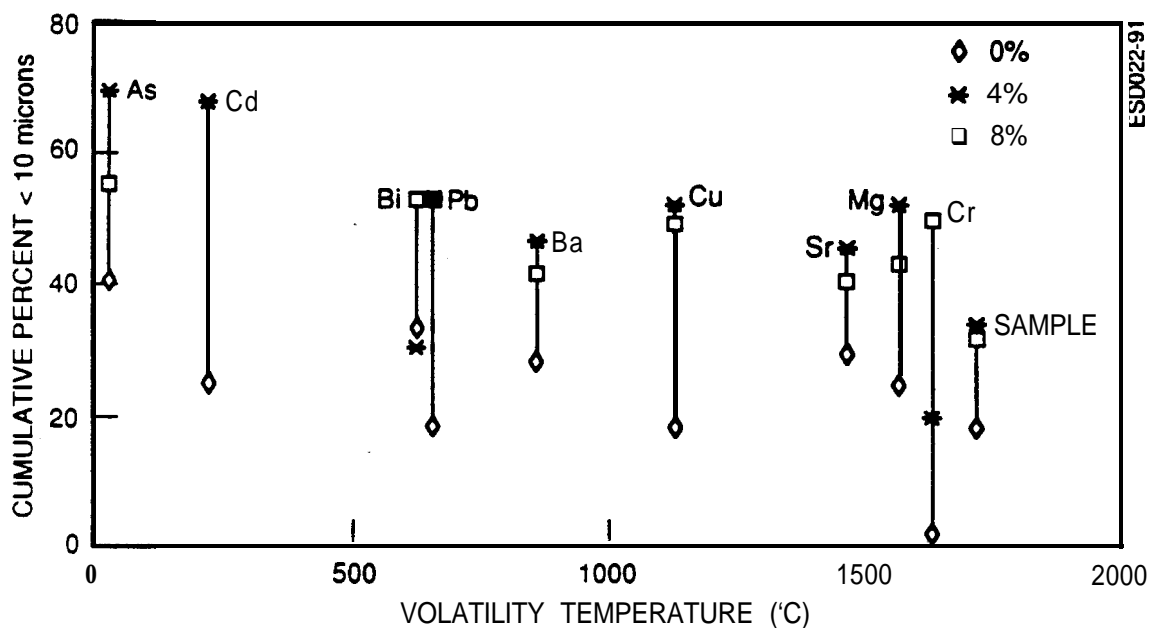


Figure 7. Effect of feed chlorine content on the distribution of metals in the afterburner exit flue gas particulate size fractions in the single-stage ionizing wet scrubber tests.

total particulate sample. Thus, flue gas particulate size distributions for barium and strontium and, to a lesser extent, arsenic, bismuth, and magnesium, were considered not to be significantly affected by waste feed chlorine concentrations. For these metals, the magnitude of the shift to the finer particulate fractions was about the same as the shift for the total particulate sample, primarily reflecting the shift in the particulate sample size distribution.

Chlorine had a more pronounced effect on the particulate size distributions of cadmium, chromium, copper, and lead. For cadmium, copper, and lead, the shift to **finer** particulate occurred with the initial feed chlorine content increase from 0 to 4 percent. The distribution of these metals in particulate of less than 10 μm increased from approximately 20 to approximately 55 percent. No additional redistribution occurred with the further feed chlorine content increase to 8 percent. Chromium distribution in particulate of less than 10 μm increased with both feed chlorine content increases, from 2 to 20 to 50 percent with chlorine increased from 0 to 4 to 8 percent. The impact on copper and lead particulate distributions is expected based on their reduced volatility temperatures in the presence of chlorine. Cadmium and chromium **redistributions** to **finer** particulate with increased chlorine are not similarly predicted by reduced volatility temperatures.

APPARENT SCRUBBER COLLECTION EFFICIENCIES

The apparent scrubber efficiency for collecting flue gas metals was determined for each test. The apparent scrubber 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. Figures 8 and 9 summarize the collection efficiencies for the venturi/packed-column scrubber and single-stage ionizing wet scrubber test series, respectively. The bar for each metal represents the range of scrubber efficiencies over the respective test series, with the average noted by the midrange tick mark.

For the venturi/packed-column scrubber test series, average metal-specific collection efficiencies ranged from 31 to 88 percent; the overall average for **all** metals was 57 percent. For **the single-stage ionizing** wet scrubber test series, average metal-specific collection efficiencies ranged from 22 to 71 percent; the overall average for **all** metals was 43 percent. Figures 8 and 9 show that the collection efficiencies for each metal varied significantly during each test series. However, average efficiencies were generally **higher** for the less volatile metals.

CONCLUSIONS

The following conclusions are based on the results of the two completed trace metals test programs in the pilot-scale incinerator at the IRF:

- In the rotary kiln incinerator, cadmium and bismuth were relatively volatile. Over all tests, the average fractions of these metals recovered in the **kiln** ash was less than 40 percent.
- In the rotary kiln incinerator, arsenic, barium, chromium, copper, magnesium, and strontium were relatively nonvolatile. Over all tests, the average fractions of these metals recovered in the kiln ash was greater than 75 percent.

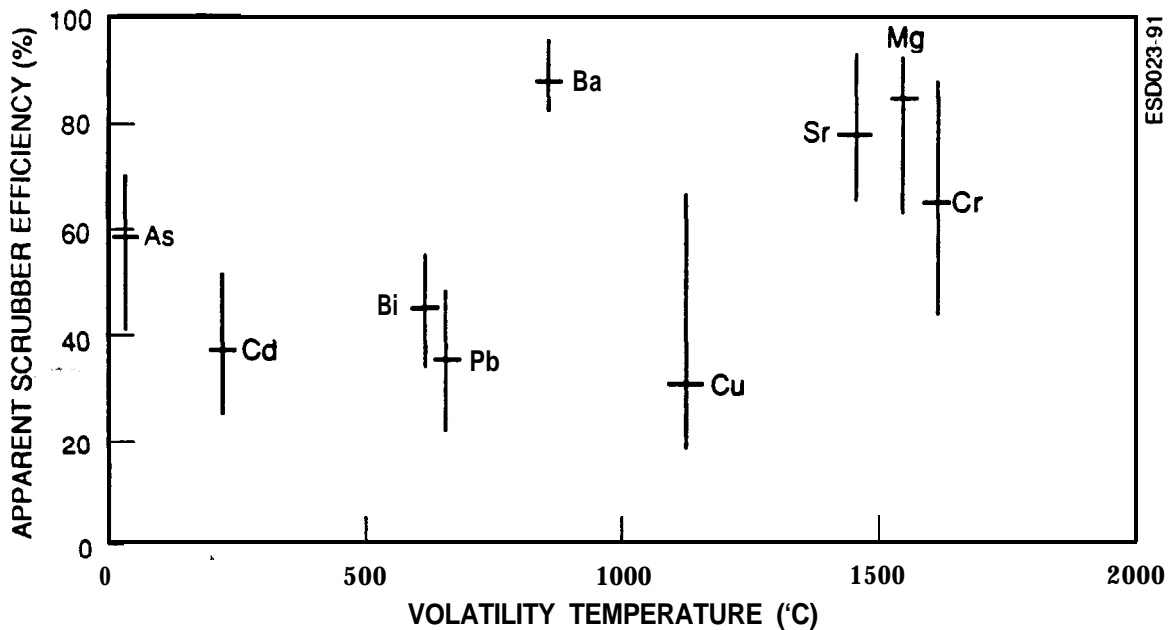


Figure 8. Apparent collection efficiencies for metals achieved by the venturi/packed-column scrubber.

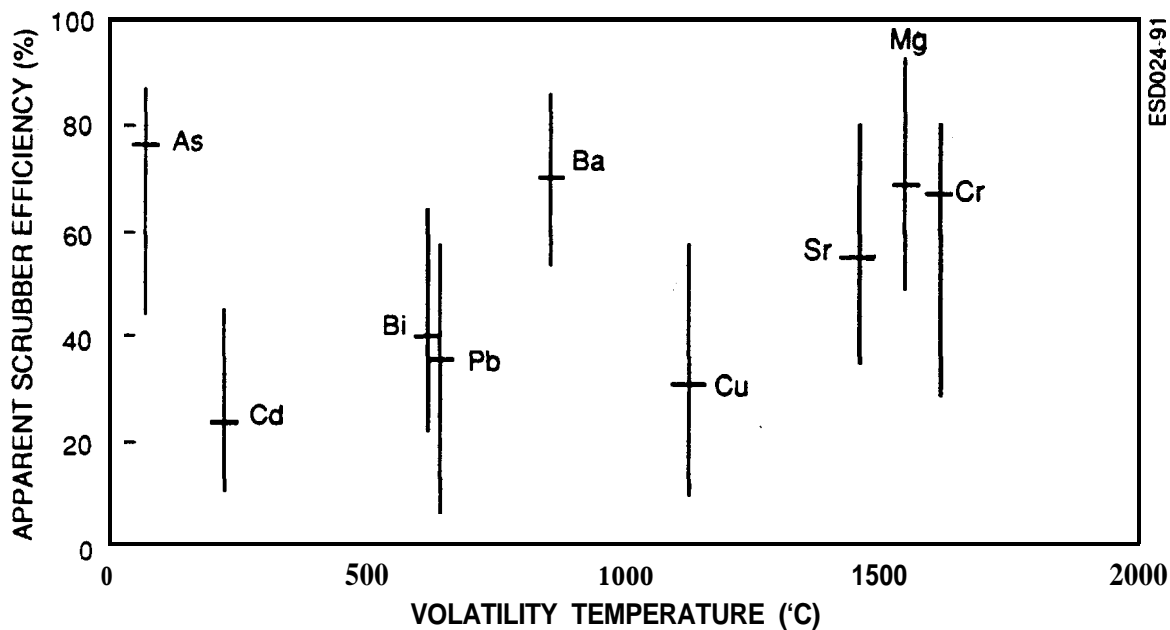


Figure 9. Apparent collection efficiencies for metals achieved by the single-stage ionizing wet scrubber.

- Lead behavior in the rotary kiln differed between the two test series. For the venturi/packed-column test series, the average fraction of lead discharged to the kiln ash was 20 percent. For the ionizing wet scrubber test series, the average fraction of lead discharged to the kiln ash was 82 percent. This inconsistent behavior may be related to the strong relationship between lead volatility temperature and chlorine or to the sensitivity of lead volatility to temperature over the range tested.
 - Relative metal volatilities in the kiln generally agreed with expectations based on metal volatility temperatures, with the exception of arsenic, which was much less volatile than expected. It is possible that arsenic forms a thermally stable compound in the incineration environment or becomes physically bound in the solid matrix.
 - Results from the ionizing wet scrubber test series showed that increased kiln temperature caused increased volatility of bismuth, cadmium, and lead. 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. Discharge distributions of the remaining metals were insensitive to changes in kiln temperature.
 - Afterburner temperature did not affect metal distribution to the scrubber exit flue gas and scrubber liquor discharge streams.
 - Increased feed chlorine content caused increased volatility of copper and lead during the venturi/packed-column test series. 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. Discharge distributions of the remaining metals did not vary conclusively with changes in feed chlorine content. **Also**, variations in feed chlorine content did not conclusively affect any metal discharge distributions during the single-stage ionizing wet scrubber test series.
 - Both kiln temperature and feed chlorine content affected the distributions of at least some of the metals among the flue gas particulate in the less than 10 μm size range. Size distributions of the metals most nearly reflected the overall entrained particulate size distribution for the tests with the lowest kiln temperature and no chlorine in the waste feed; very little redistribution among the particulate was observed. For these two tests, approximately 20 to 25 percent of each metal and of the total particulate sample were in the less than 10 μm particulate.
 - Increasing the kiln temperature to 927°C (1700°F) caused the average size distribution to shift to approximately 60 percent less than 10 μm for all test metals except chromium. The test data suggest that increased kiln temperature over this range caused the flue gas particulate metal distributions to shift to the finer particulate size fractions. Additionally, the redistribution of metals to this size range generally correlated with the relative volatilities of the metals, with the volatile metals most affected. Interestingly, arsenic in the flue gas behaved as the most volatile metal, becoming most enriched in the less than 10 μm particulate size range. Test data show that even metals that are classified as relatively nonvolatile based on their behavior in the kiln undergo some vaporization and recondensation, with resulting concentration in the finer particulate size range.
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- The addition of chlorinated compounds to the waste feed primarily affected cadmium, chromium, copper, and lead distributions in the flue gas particulate less than 10 μm . For cadmium, copper, and lead, the increase in waste feed chlorine content from 0 to 4 percent caused the distributions to shift from roughly 20 percent to approximately 55 percent less than 10 μm . No further effects with feed chlorine increased to 8 percent were observed for these metals. For chromium, increased chlorine content from 0 to 4 to 8 percent caused **redistributions** of 2 to 20 to 50 percent in the particulate less than 10 μm .
 - Average metal collection efficiencies for the venturi/packed-column scrubber ranged from 31 to 88 percent; the overall average for all metals was 57 percent. For the single-stage ionizing wet scrubber, average metal collection efficiencies ranged from 22 to 71 percent; the overall average for all metals was 43 percent. In **general**, collection efficiencies were higher for the less volatile metals.
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 - Average metal collection efficiencies for the venturi/packed-column scrubber ranged from 31 to 88 percent; the overall average for all metals was 57 percent. For the single-stage ionizing wet scrubber, average metal collection efficiencies ranged from 22 to 71 percent; the overall average for all metals was 43 percent. In general, collection efficiencies were higher for the less volatile metals.
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