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by

DONALD CLARK HICKMAN

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## ABSTRACT

The California Air Resources Board (CARB) has reported relatively high concentrations of cadmium and lead in recent tests of Bio-Medical Waste Incinerators (BMWIs) in California. Cadmium in the 100's of  $\mu\text{g}/\text{m}^3$  and lead in the 1,000's of  $\mu\text{g}/\text{m}^3$  have been observed in the stack gas of incinerators before application of controls. Both metals appear to have been enriched in the fly ash.

Sources of cadmium and lead in BMWIs were investigated. Based on a review of the literature, compounds of cadmium and lead are used as heat and light stabilizers, and as pigments in various plastics, particularly in polyvinyl chlorides (PVC). The high HCl content of stack gases indicates a significant fraction of the waste stream contains chlorinated plastics. In samples analyzed from a hospital waste stream lead was found in several plastic items, as well as in paper packaging material. A source of cadmium was not positively identified, however, it appeared to be present in the casing of an alkaline battery. Both metals may also be present in inks, metallic items (needles, scalpels, etc), paper products, and paints. However, there was no evidence from which it could be concluded that such items contributed to the observed levels of cadmium and lead. If sources of cadmium and lead can be identified, hospital administrators may be able to reduce or eliminate metal emissions by pressuring industry to change the composition of the source materials or by limiting their introduction into the incinerator waste stream.

The equilibrium solution for cadmium and lead metal distribution was investigated under several assumed stack gas compositions using the STANJAN thermodynamic equilibrium solver. From the results of these analyses it appears that cadmium sulfide and lead chloride are favored over

other chemical forms of these metals in reducing environments, and that cadmium chloride and lead sulfate are favored under oxidizing conditions (over the range of conditions: 1 atmosphere, temperature range 400 - 1100 K, stoichiometric ratio range 0.25 - 1.13). These results are consistent with the observed partitioning of metal concentrations between the bottom ash and fly ash in the reducing environment associated with the primary chamber of controlled air incinerators.

## 1. INTRODUCTION

Results of recent tests of Bio-Medical Waste Incinerators (BMWIs) conducted by the California Air Resources Board (CARB) have raised concern within the air pollution community. In tests of seven BMWIs conducted over the period August, 1986, to April, 1988, CARB found high levels of polychlorinated dibenzo-*p*-dioxins (PCDD), polychlorinated dibenzofurans (PCDF), and the toxic metals cadmium (Cd) and lead (Pb) (Jenkins, 1987a, 1987b, 1988a, 1988b; McCormack 1988a, 1988b, 1988c). Concentrations of PCDD and PCDF in the fly ash of BMWI are generally much greater than those observed in tests of hazardous waste incinerators (HWI) and in the same range or somewhat lower than those observed in tests of older municipal waste incinerators (MWI) (Hagenmaier, 1987; Beychok, 1987). In fact, BMWI are the only known, consistent source of PCDDs and PCDFs in California. Cadmium and lead concentrations in fly ash from BMWI are greater than those seen in MWI, but less than the highest concentrations measured from HWI (Greenburg, 1978; Oppelt, 1987).

The State of California requires infectious bio-medical waste (BMW) be sterilized by incineration, autoclaving, or some other method. Approximately 70% of hospitals in the US incinerate their infectious waste (Lee et al., 1988) and this fraction is probably typical of practice in California. Most hospitals and bio-medical facilities are located in or near large concentrations of people and because of their proximity, emissions from BMWI pose an immediate and perhaps serious threat to public health. Therefore, BMWI emissions are of particular concern to the hospital industry, regulatory agencies and the public-at-large. However, neither the federal government nor the State of California

regulates the use, operation or emissions of BMWIs; local air pollution control districts have jurisdiction over BMWIs.

Regulation of BMWIs should be based on the potential public health risk posed by the relatively high emission levels of PCDD, PCDF, cadmium, and lead. Public health concerns will likely force the adoption of federal and/or state regulations governing BMWIs. Currently BMWIs are not permitted differently than other conventional combustion sources. However, it would be a mistake for the incineration option to be eliminated. Incineration is capable of reducing waste volume by up to 90% (Morrison, 1987) and it is an effective means of dealing with infectious wastes. Rising landfill disposal costs and declining availability of landfill space make incineration economically important. Waste volume reduction can reduce operation costs considerably for many hospitals. If the bio-medical industry can reduce or eliminate PCDD, PCDF, cadmium, and lead emissions by limiting the introduction of materials containing cadmium and lead into the waste stream and optimizing incinerator performance, the impacts of future regulation should be minimized.

There is some evidence linking the presence of metals found in fly ash to the catalytic formation of PCDD and PCDF on fly ash under post-flame conditions (Hagenmaier et al., 1987). Whether cadmium or lead in BMWIs can facilitate PCDD and PCDF formation on fly ash has yet to be demonstrated. If elemental cadmium and lead and their chlorides function as catalysts in this process, limiting cadmium and lead concentrations in the waste stream may reduce PCDD and PCDF emissions. Investigations of the formation of PCDD and PCDF and the possible catalytic effects of cadmium and lead are beyond the scope of this thesis. The possible link between high cadmium and lead levels and PCDD and PCDF levels is mentioned only to highlight the importance of reduction of cadmium and lead in the waste stream.

## OBJECTIVES

This project was motivated by the need to reduce the high levels of PCDD, PCDF, cadmium, and lead found in California BMWIs. The National Science Foundation Workshop on Incineration of Municipal, Hazardous, and Bio-Medical Wastes recommended the following in April, 1988:

Fundamental research should be pursued on metal-compound formations (such as oxides or halides) in incineration to allow useful input separations, additions of reactants for metals uptake, and reductions of metals contents in fly ash and bottom ash to acceptable levels or else permit stabilization of ash outputs for useful commercial applications.

The objectives of this project, derived in part from the NSF recommendations, were to: 1) Identify sources of cadmium and lead in BMWI; 2) Determine, by means of thermodynamic equilibrium models, BMWI operating conditions that enhance cadmium and lead concentration on fly ash; and 3) Based on the findings from objectives 1) and 2), develop a control strategy for the reduction of cadmium and lead emissions from BMWIs. Specific sub-objectives with respect to the identification of sources of cadmium and lead in BMWI included:

1. Conducting an extensive literature review on cadmium and lead sources. Of significant interest are plastics, which constitute a major fraction of bio-medical waste streams.
2. Subjecting bulk samples of items suspected of containing metals to elemental analysis.

## **SCOPE**

The scope of this project is by nature very broad. A complete determination of cadmium and lead sources in BMWI is not known to have been attempted. Such a study would require analysis of a large volume of heterogeneous waste, including, but not limited to, cafeteria, general housekeeping, administrative, and infectious (bio-medical) wastes. Such a study was beyond the resources of this project. This thesis was limited to a literature review and analysis of samples from a hospital waste stream, and was intended to lay the groundwork for future investigations in this area of research. Thermodynamic equilibrium analyses were also conducted to determine incinerator operating conditions which promote deposition of cadmium and lead on fly ash. The work is presented in two distinct divisions: a literature review and preliminary identification of sources of cadmium and lead in waste streams (Chapter 3) and a thermodynamic equilibrium analysis (Chapter 4).

## **2. BACKGROUND**

A definition of bio-medical waste (BMW) is presented in this section and is followed by a discussion of Federal and State regulations pertaining to BMWI. Results of the CARB tests are then presented and are followed by a comparison of cadmium, lead, PCDD, and PCDF emissions from BMWI, MWI and HWI. The section is concluded with a discussion of potential public health risks of each toxin.

### **BIO-MEDICAL WASTES**

Bio-Medical Waste (BMW) is defined and its characteristics are discussed in this section.

#### **Definition of Bio-Medical Waste**

Bio-medical waste refers to potentially infectious waste generated by the health care industry. Hospitals, primary and emergency care clinics, medical, research, and environmental safety laboratories are all sources of BMW. Bio-medical waste is characteristically heterogeneous and consists of three fractions: 1) Infectious waste, 2) chemical waste, and 3) radioactive waste. Chemical wastes are regulated under the Resource Conservation and Recovery Act (RCRA) and are generally not incinerated in BMWI. Radioactive wastes are regulated by the Nuclear Regulatory Commission (NRC) and are not purposely introduced into the BMWI waste stream, though they may be present at low levels in tissues. Incineration of infectious waste is the focus of this research project.

## Infectious Waste

Infectious waste is classified "red bag" waste by most facilities in the US. "Red bag" refers to the red plastic disposal bags that are used to designate infectious waste items. Infectious waste can consist of 1) human and animal anatomical wastes, 2) disposable equipment, instruments, utensils and like items from a patient who is known or suspected to have a communicable disease, 3) laboratory wastes such as pathological specimens, body fluids, excreta and disposable fomites, and 4) emergency and operating room specimens and disposable fomites. Infectious waste may also contain toxic components such as waste pharmaceuticals and cytotoxic agents which are exempt from RCRA (Lee et al., 1988).

In Canada, infectious wastes are separated into four classifications, with distinct bag colors for each (see Table 2-1). This bag color code system is used to a lesser degree in the US, but not at any of the hospitals tested by CARB.

Table 2-1  
Canadian Hospital Waste Classification System <sup>1</sup>

Classification	Description	Bag Color Code
Type A, Class 1	Human anatomical	Red
Type A, Class 2	Animal anatomical, infected	Orange
Type A, Class 3	A- non-anatomical, infected	Yellow
	B- laboratory wastes	Yellow
	C- waste from DNA work	Yellow
Type B, Class 1	Non-infected animal anatomical	Blue

<sup>1</sup> Lee et al. (1988)

Ease of use and economic pressures have resulted in a widespread dependence on disposable instruments by the health care industry. Marrack (1988) found in two hospitals in Houston, Texas, that disposable gowns and drapes formed the major fraction of red bag waste. Polyvinyl chloride (PVC) accounted for 9.4% of the total weight of the waste, and total plastics accounted for 14.2%. Sharps-tainers® are disposed of in red bag waste, and typically contain hypodermic needles, razors and disposable scalpels.

### **Bio-Medical Waste Stream**

Few facilities burn only infectious waste in their BMWI. Incineration reduces waste volume by up to 90% (Morrison, 1987) which can represent considerable savings in transportation and landfill disposal costs for the waste. Additionally, waste heat can be used to generate steam for laundry, heating, kitchen and autoclaving. Infectious waste accounts for approximately 15% of the total waste stream in facilities that incinerate both infectious and general waste (Doyle et al., 1985). The fraction varies depending on individual facility waste management policies and current operating conditions. For example, a major surgical operation will result in a larger percentage of infectious waste. Although infectious waste will typically hold a flame, waste volume is not great enough for significant heat recovery. Therefore, the presence of a BMWI encourages burning other wastes. Hospitals tend to burn their general waste in BMWI, as costs savings can be significant. General waste is similar to domestic waste. It includes, but is not limited to, administrative, cafeteria, and housekeeping wastes. Diapers, newspapers, styrofoam and paper are examples of general waste. For the purposes of this thesis, combined waste (general and infectious) are defined as bio-medical waste (BMW).

The combined bio-medical waste typically contains 20% plastics, but levels as high as 30% have been observed (Doyle et al., 1985). In comparison, municipal solid waste usually contains 3 to 7% plastics. High levels of chlorinated plastics can lead to generation of toxic air pollutants (including PCDD and PCDF) and may be responsible for the high levels of cadmium and lead observed in BMWI fly ash. A typical cross-section of combined waste is listed in Table 2-2.

Table 2-2  
Typical Cross-Section of Bio-Medical Waste <sup>1</sup>

Artificial linens	Paper
Flowers	Waste food
Cans	Diapers
Plastic cups	Syringes
Scalpels	Tweezers
Rubber gloves	Pathological objects
Blood test tubes	Petri dishes
Test tubes from misc. service	Dropper bottles
Medicine bottles	Drop infusion equipment
Transfusion equipment	Suction catheters
Bladder catheters	Urinal catheters
Colostomi bags	Hypodermic needles
IV tubing	Packaging material

<sup>1</sup> Morrison (1987)

## REGULATION OF BIO-MEDICAL INCINERATORS

Until recently, most public and regulatory attention has been focused on MWI and HWI. Municipal waste incinerators tend to be large volume incinerators that are visible to the public. Hazardous waste incinerators destroy dangerous chemicals and public concern has been directed toward disposal practices. Smaller scale BMWIs have not yet received much attention by the public or media because the data that indicate high emission levels of PCDD,

PCDF and toxic metals have become available only recently . The CARB tests account for the majority of these data. Public attention was focused on BMW in August, 1988, when AIDS infected needles washed onto beaches in New Jersey. Hospital waste disposal practices even became an issue of the 1988 election campaign. However, attention was not directed at incinerator practices.

Currently, there are no regulations specifically governing BMWI on either the Federal or State (California) levels. The EPA requires BMWI (along with other incinerators) to conform to New Source Performance Standards (NSPS) for "conventional" priority pollutants (Lee et al., 1988). The State of California requires all BMWI to be permitted. Additionally, California requires all BMW to be sterilized by incineration, autoclaving, ethylene oxide (EtO) , or some other method. Air quality is regulated by individual Air Quality Management Districts. Regulations can and do vary to some extent from district to district (Brunner and Brown, 1988). For example, the Sacramento County Air Pollution Control District regulates opacity and particulate matter emissions of BMWI.

### **CALIFORNIA AIR RESOURCES BOARD BIO-MEDICAL WASTE INCINERATOR TEST RESULTS**

A goal of the CARB hospital incinerator test program is the generation of a set of operational guidelines for BMWI. During the period August, 1986, to April, 1988, the California Air Resources Board tested seven Bio-Medical Waste Incinerator facilities in California (Jenkins, 1987a, 1987b, 1988a, 1988b; McCormack, 1988a, 1988b, 1988c). The tests included six hospital waste incinerators and one environmental safety laboratory incinerator. Relatively high levels of the toxic metals cadmium and lead were found in the fly ash of all seven incinerators (211-1790  $\mu\text{g/g}$  Cd and 2640-24200  $\mu\text{g/g}$  Pb). Levels of polychlorinated dibenzo-*p*-dioxins (PCDD) and polychlorinated dibenzofurans

(PCDF) in the seven incinerators were found to be generally greater than what is found in HWI and municipal waste incinerators (MWI) of modern design, though less than emissions from older MWIs.

As mentioned above, CARB conducted seven tests of BMWIs over the last two years. The test locations and dates are shown in Table 2-3. Elevated concentrations of cadmium, lead, PCDD, and PCDF were also observed in a test of the Royal Jubilee Hospital Incinerator (Morrison, 1987).

Observed average cadmium and lead concentrations upstream of air pollution control devices (if applied) of the eight sampled BMWIs are listed in Table 2-4. Concentration of both metals in the stack gas (grains/dry standard cubic foot) and on the fly ash ( $\mu\text{g}$  metal/g fly ash) are presented along with average concentrations of cadmium and lead per waste load ( $\mu\text{g}$  metal/g waste). Concentrations of cadmium and lead in the waste stream were estimated from the average mass emission rate of each metal and the average waste feed rate of the incinerator. Average tetra-, penta-, hexa-, hepta- and total PCDD concentrations before application of controls (if applied) are presented in Table 2-5. Concentrations of PCDD in terms of California Toxicity Equivalency Factors are also given (in parentheses). Average tetra-, penta-, hexa-, hepta- and total PCDF concentrations before application of controls (if applied) are presented, along with values in terms of Toxicity Equivalency Factors, in Table 2-6. Data for PCDD and PCDF emissions from Kaiser-Permanente were not available at the time this thesis was prepared. Morrison (1987) did not make it clear if values for Royal Jubilee were corrected to 12% CO<sub>2</sub>.

Table 2-3  
Location and Description of Bio-Medical Waste Incinerators

Facility	Location	Test Date	Incinerator Feed Rate (lb/hr)	Control Device/Heat Recovery	Type of Incinerator <sup>1</sup>
St. Agnes Medical Center	Fresno, California	12-14 Aug 1986	783	No/Yes	CA
Cedars Sinai Medical Center	Los Angeles, California	29-31 Oct 1986	980	Fabric Filter/Yes	CA
Sutter General Hospital	Sacramento, California	29-31 Jul 1987	474	No/Yes	CA
Stanford University Env. Safety Facility	Stanford, California	30,31 Jun; 1,2 Jul 1987	675	Scrubber/No	CA
Saint Bernadines Hospital	San Bernadino, California	30 Nov; 1-4 Dec 1987	<100	No/No	CA
LA County - USC Medical Center	Los Angeles, California	7-11 Mar 1988	<100	No/No	CA
Kaiser Permanente Hospital	San Diego, California	25-28 Apr 1988	600	No/Yes	CA
Royal Jubilee Hospital	Victoria, B.C.	Report Date April 1983	1930	No/?	CA

<sup>1</sup> Controlled Air

Table 2-4  
Average Cadmium and Lead Concentrations  
in Stack Gas of Bio-Medical Waste Incinerators

Facility	Cadmium		Lead	
	gr/dscf <sup>1</sup> (x10 <sup>-6</sup> )	µg/g (Cd/ly ash)	gr/dscf <sup>1</sup> (x10 <sup>-6</sup> )	µg/g (Pb/ly ash)
		µg/g <sup>2</sup> (Cd/Waste)		µg/g <sup>2</sup> (Pb/Waste)
St. Agnes	55	666	749	8990
Cedars Sinai <sup>3</sup>	92	1790	896	18100
Sutter General	16.9	504	225	6480
Stanford <sup>3</sup>	25.4	738	843	24200
St. Bernadines	8.2	211	103	2640
LA County	116	279	1460	21800
Kaiser-Permanente	77	850	1150	12600
Royal Jubilee	38.6	NA	662	NA

<sup>1</sup> grains/dry standard cubic foot

<sup>2</sup> Estimated average concentration of metal in waste stream

<sup>3</sup> Before application of air pollution control devices

<sup>4</sup> Not Available

Table 2-5  
Average Polychlorinated Dibenzo-p-Dioxin (PCDD)  
Concentrations from Bio-Medical Waste Incinerators in ng/dscm<sup>1</sup>

Facility	Tetra-CDD	Penta-CDD	Hexa-CDD	Hepta-CDD	Total PCDD <sup>2</sup>
	(2,3,7,8)	(1,2,3,7,8)	(1,2,3,4,7,8) (1,2,3,6,7,8) (1,2,3,7,8,9)	(1,2,3,4,6,7,8)	
<i>Toxicity Equivalency Factor</i>	(1.00)	(1.00)	(0.03)	(0.03)	(0.03)
St. Agnes	1.37 (1.37)	8.94 (8.94)	56.0 (1.68)	273.00 (8.19)	339.31 (19.46)
Cedars Sinai <sup>3</sup>	0.58 (0.58)	2.60 (2.60)	14.7 (0.44)	73.30 (2.20)	91.28 (5.82)
Sutter General	0.36 (0.36)	7.41 (7.41)	92.3 (2.77)	249.00 (7.48)	349.07 (18.02)
Stanford <sup>3</sup>	0.11 (0.11)	0.68 (0.68)	5.00 (0.15)	25.70 (0.77)	31.49 (1.71)
St. Bernadines	<0.04 (<0.04)	0.31 (0.31)	2.10 (0.06)	16.54 (0.50)	18.95 (0.87)
LA County	3.15 (3.15)	12.64 (12.64)	87.82 (2.63)	440.90 (13.23)	544.51 (31.65)
Kaiser-Permanente	Not Available				
Royal Jubilee	26.98 (26.98)	46.18 (46.18)	42.93 (1.29)	25.73 (0.77)	141.82 (75.22)

<sup>1</sup> Corrected to 12% CO<sub>2</sub> and in terms of Toxic Equivalence Levels (when shown in parentheses)

<sup>2</sup> Total for isomers for which Toxicity Equivalency Factors are available

<sup>3</sup> Before application of air pollution control devices

Table 2-6  
Average Polychlorinated Dibenzofuran (PCDF)  
Concentrations from Bio-Medical Waste Incinerators in ng/dscm<sup>1</sup>

Facility	Tetra-CDF	Penta-CDF	Hexa-CDF	Hepta-CDF	Total PCDF <sup>2</sup>
	(2,3,7,8)	(1,2,3,7,8) (2,3,4,7,8)	(1,2,3,4,7,8) (1,2,3,6,7,8) (1,2,3,7,8,9) (2,3,4,6,7,8)	(1,2,3,4,6,7,8) (1,2,3,4,7,8,9)	
<i>Toxicity Equivalency Factor</i>	(1.00)	(1.00)	(0.03)	(0.03)	
St. Agnes	5.38 (5.38)	52.89 (52.89)	162.70 (4.88)	290.30 (8.71)	511.37 (71.86)
Cedars Sinai <sup>3</sup>	3.45 (3.45)	30.14 (30.14)	95.70 (2.87)	199.30 (5.98)	328.62 (42.44)
Sutter General	12.28 (12.28)	136.20 (136.20)	468.30 (14.05)	622.70 (18.68)	1239.51 (181.21)
Stanford <sup>3</sup>	1.23 (1.23)	8.00 (8.00)	30.30 (0.91)	106.30 (3.19)	145.86 (13.33)
St. Bernadines	0.50 (0.50)	7.65 (7.65)	19.75 (0.59)	40.91 (1.23)	68.81 (9.97)
LA County	19.13 (19.13)	92.93 (92.93)	482.27 (14.47)	865.30 (25.96)	1459.63 (152.49)
Kaiser-Permanente	Not Available				
Royal Jubilee	ND <sup>4</sup> ND	10.18 (10.18)	13.78 (0.41)	16.73 (0.50)	40.69 (11.09)

<sup>1</sup> Corrected to 12% CO<sub>2</sub> and in terms of Toxic Equivalence Level (when shown in parentheses)

<sup>2</sup> Total for isomers for which Toxicity Equivalency Factors are available

<sup>3</sup> Before application of air pollution control devices

<sup>4</sup> Not Detected

## COMPARISON OF INCINERATOR EMISSIONS

Municipal waste incinerator (MWI) and hazardous waste incinerator (HWI) emissions have been tested and monitored for a number of years. A comparison of emissions from BMWI with those of MWI and HWI is presented in this section.

Both MWI and HWI are required by Federal and, in many cases State, regulations to operate at or below some maximum pollutant emission levels. Use of add-on pollution control devices for the removal of fly ash are required. Electrostatic precipitators (ESP) and fabric baghouses form the majority of air pollution control devices.

Concentrations of cadmium and lead on BMWI fly ash fall somewhere between those of MWI and HWI (see Table 2-7). Values for MWI and HWI are assumed to be before application of control devices, though the authors do not make this clear. Municipal waste incinerator emissions of both metals tend to be less than BMWI levels, while those of HWI tend to be greater. Greenburg (1978) cites suspended particle concentrations of cadmium and lead, which were higher than fly ash concentrations. They did not define "suspended particle", however, so fly ash concentrations are reported here.

Concentrations of PCDD and PCDF in BMWI stack gas fall between those of HWI and older MWI, with MWI values being greatest (see Table 2-8). Here again, the values for MWI and HWI are assumed to be prior to application of control devices, though the authors do not make this clear. Huffman (1987) reports levels as low or lower than HWI in modern MWIs (Marion County and Montreal). Emission levels of PCDD and PCDF from BMWI are significantly greater than or comparable to those of HWI and modern MWI, even though the

volumetric flowrate is lower. Application of control devices on MWI and HWI reduces emission levels, while BMWI are often not controlled.

Table 2-7  
Average Cadmium and Lead Concentrations  
from Bio-Medical Waste Incinerators, Municipal  
Waste Incinerators and Hazardous Waste Incinerators

Facility	Concentration, $\mu\text{g/g}$ on fly ash	
	Cadmium	Lead
BMWI <sup>1</sup>		
St. Agnes	666	8990
Cedars Sinai	1790	18100
Sutter General	504	6480
Stanford	738	24200
St. Bernadines	211	2640
LA County	279	21800
Kaiser-Permanente	850	12600
MWI <sup>2</sup>		
A	42	4000
B	185	--
HWI <sup>3</sup>		
A	890	85500
B	140	3100
C	1120	25600
D	4000	98000

<sup>1</sup> Refer to Table 2-4

<sup>2</sup> Greenburg et al. (1978)

<sup>3</sup> Oppelt (1987)

Table 2-8  
Average Polychlorinated Dibenzo-*p*-Dioxin (PCDD)  
and Polychlorinated Dibenzofuran (PCDF) Concentra-  
tions from Bio-Medical Waste Incinerators, Municipal  
Waste Incinerators and Hazardous Waste Incinerators

Facility	Concentration, ng/m <sup>3</sup> on fly ash	
	PCDD	PCDF
BMW <sup>1</sup>		
St. Agnes	339	511
Cedars Sinai	91	328
Sutter General	349	1240
Stanford	31	145
St. Bernadines	31	68.8
LA County	545	1460
Kaiser-Permanente	Not Available	
Royal Jubilee	142	40.7
MWI		
A <sup>2</sup>	4400	9400
B <sup>2</sup>	3550	3490
C <sup>2</sup>	2800	10560
D <sup>2</sup>	2040	2480
Marion County, OR <sup>3</sup>	1.5	0.6
Neustadt, FRG <sup>3</sup>	80	95
Albany, NY <sup>3</sup>	300	88
Montreal, Q <sup>3</sup>	0.01	0.02
HWI <sup>4</sup>		
A	16	56
B	ND <sup>5</sup>	7.3
C	ND <sup>5</sup>	3.0
D	1.1	ND

<sup>1</sup> Refer to Table 2-5 and Table 2-6

<sup>2</sup> Beychock (1987)

<sup>3</sup> Huffman (1987)

<sup>4</sup> Oppelt (1987)

<sup>5</sup> Not Detected

## HEALTH RISKS

The health risks of cadmium, lead, PCDD, and PCDF are presented in this section.

### Cadmium

Cadmium and cadmium compounds are cumulative poisons and have been shown to exhibit acute and chronic toxicity in humans. Of interest to this project are the chronic and carcinogenic effects of cadmium. Emission levels from BMWI are not great enough to produce acute cadmium exposure.

*Patty's Industrial Hygiene and Toxicology* (Clayton and Clayton, 1981) reports several toxic effects of cadmium from chronic exposure. Proteinuria has been observed in workers exposed to CdO fumes for an average of 20 years. Other evidence of renal dysfunction have also been reported. Pulmonary emphysema has been observed in workers exposed to CdO dusts, while CdS dusts appear to be inert. A moderate degree of anemia has also been observed in workers exposed to CdO dust and fumes for 5-30 years. A significant correlation between high Cd and low hemoglobin levels has been demonstrated. Severe back and extremity pain has been reported by battery workers in France and symptoms of a severe chronic cadmium poisoning in Japan were similar. The disease is known as "Itai-itai" (ouch-ouch) disease.

Cadmium has been shown to be carcinogenic to rats, mice, and other laboratory animals. The California Department of Health Services (CDHS) lists the unit risk factor for cadmium as  $12 \times 10^{-3} (\mu\text{g}/\text{m}^3)^{-1}$  and cites sufficient animal and limited human evidence as the weight of evidence for classification as a human carcinogen. There are no federal or State of California ambient air

quality standards for cadmium. However, CARB lists cadmium as an identified toxic air pollutant and is in the process of developing appropriate standards.

### **Lead**

Lead and lead compounds are cumulative poisons in the human body and the chronic toxic effects of lead are of interest to this project. Lead can enter the body through the gastrointestinal and respiratory tracts. Between 25 and 50% of inhaled lead will be absorbed depending on size, shape and density of the particulate matter (Engel et al., 1971). Lead retention is relatively poor, and chronic exposure is normally necessary for clinical symptoms to appear.

Clinical lead poisoning is known as plumbism (Engel et al., 1971). Plumbism is characterized by abdominal cramps, headaches, loss of appetite, fatigue, anemia, motor-nerve paralysis, and encephalopathy (confined to children). *Patty's Industrial Hygiene and Toxicology* (Clayton and Clayton, 1981) reports motor-nerve damage, encephalopathy, anemia, and kidney damage (nephritis and renal failure) as effects of chronic lead exposure. There is also some evidence linking lead to cancer. The ambient air quality standard for lead is  $1.5 \mu\text{g}/\text{m}^3$  on a 30-day average. The California Department of Health Services (CDHS) does not publish a unit risk factor for lead or cite any evidence that it is a human carcinogen.

### **Polychlorinated Dibenzo-*p*-Dioxins (PCDD) and Polychlorinated Dibenzofurans (PCDF)**

Both of these classes of chlorinated organic compounds are acute and chronic toxins. Chlorinated dioxins, particularly the 2,3,7,8 isomer, are considered by many to be among the most toxic chemicals known to man. Both

PCDD and PCDF are known animal carcinogens and are suspected human carcinogens. The California Department of Health Services cites PCDD and PCDF as carcinogens, but has not yet established unit risk factors for the toxins.

### 3. SOURCES OF CADMIUM AND LEAD

Potential sources of cadmium and lead in bio-medical waste streams are discussed in this section. Several likely sources of these metals in municipal waste streams are reported in the literature. These sources are discussed in the section titled Literature Review. Identification of cadmium and lead in bio-medical waste streams was attempted by elemental analyses of bio-medical waste samples. Particle Induced X-ray Emission (PIXE) and X-Ray Fluorescence (XRF) were conducted in an attempt to identify wastes containing cadmium and lead. The elemental analyses are discussed in the section titled Preliminary Identification of Cadmium and Lead in Bio-Medical Waste Streams.

#### LITERATURE REVIEW

A review of available literature has shown that no work has been accomplished regarding sources of cadmium and lead in bio-medical waste stream (BMWS). A request for a literature search was submitted to the Hazardous Materials Technical Center (HMTTC) (Hazardous Materials Technical Center, 1988). Enviroline, Pollution Abstracts, CASearch, NTIS, and Water Resources were searched by HMTTC for sources of cadmium in BMWI. CASearch, Melvyl and Medline searches (for cadmium and lead) were also conducted on UC Davis facilities. No studies of metal sources in BMWI were identified. Marrack (1988) determined contents of typical "red bag" (infectious) waste in a Texas hospital, and Doyle et al. (1985), Lee et al. (1988), and Brunner and Brown (1988) list cross sections of typical BMW. No study includes a list of sources of cadmium or lead. The work conducted as part of this thesis is one of the first determinations of cadmium and lead sources in BMWS.

Important sources of cadmium and lead in municipal waste streams were reported in the literature. Bio-medical waste streams, combined general and infectious waste, are similar in composition to municipal waste streams. Significant work towards determining sources of cadmium and lead in municipal wastes are reviewed here, and these findings are important to BMWI.

### **Sources of Cadmium and Lead**

Major uses of cadmium and lead and sources of these metals in municipal waste streams are presented in this section.

**Cadmium** Cadmium has five principal uses: 1) protective plating on steel, 2) a constituent in various alloys, 3) a constituent in pigments, 4) in the manufacture of nickel-cadmium batteries, and 5) in plastic stabilizers (Hutchinson and Meema, 1987; US EPA, 1981). Of these, the last three (pigments, stabilizers and batteries) are potential sources of cadmium in BMWS.

Cadmium is used as a pigment in water-based paints, plastics, rubber and inks (US EPA, 1981). Cadmium pigments are non-bleeding and alkali-resistant, and are found in shades ranging from yellow to deep maroon. Cadmium pigments tend to be mixed with pigments of other metals such as zinc, mercury, barium and selenium, and exhibit good light, heat and moisture stability. Yellow, orange and red plastic items are potential sources of cadmium in BMWS.

Nickel-cadmium batteries are rechargeable cells that find extensive use in alarm systems, pacemakers, portable tools and calculators (US EPA, 1981; Hutchinson and Meema, 1987). It is possible, though unlikely, that nickel-cadmium batteries may find their way into BMWI.

Salts of long-chain organic acids and cadmium form a variety of heat and UV-light stabilizers for plastics. Many plastics contain stabilizers, but polyvinyl chloride (PVC) and related resins account for the majority of their use (Greek, 1988). Stearic, lauric and other carboxylic acid salts of cadmium (and typically associated with barium) protect PVC from thermo and photo (UV) degradation (Farnsworth, 1980). Both thermo and photo stabilizers scavenge HCl released by dehydrohalogenation. Cadmium/barium stabilizers account for 25% of PVC stabilizers used in the US. Lead (to be discussed later) and tin stabilizers account for the majority of the rest (Farnsworth, 1980). Calcium/zinc stabilizers are used to a small extent, primarily in PVC where toxicity is a factor (food packaging, and perhaps the medical industry).

Cadmium stabilizers are used in almost every plastic except for food packaging (US EPA, 1981). Cadmium stabilizers are found in packaging of calendered goods, flooring, garden hose, film and heavy-gauge plastics from automobiles (Sarvetnick, 1969; Greek, 1988). Their status in medical equipment was not found in the literature. Inquiries were made of several manufacturers of plastic medical products (Stewart, 1988; Winfield Corp., 1988) but yielded denials of cadmium and lead use by the medical industry. However, cadmium-based stabilizers remain as primary suspects as sources of cadmium in BMWS.

**Lead** The largest single use of lead is in the manufacture of storage batteries. The second largest use is as tetraethyl and tetramethyl lead (gasoline additives). Other uses include alloys, ammunition, sheet, pipe, foil, radiation shielding and paint pigments (Clayton and Clayton, 1981). Lead is also used in plastic pigments and stabilizers.

Lead storage batteries are the type found in automobile and heavy equipment. These batteries should not find their way into BMWI. Paint pigments are a likely source of lead in BMWS, and are discussed in detail in the discussion of municipal waste streams.

Salts of long-chain organic salts (such as stearic, maleic, phthalic and others) and lead form a large number of PVC stabilizers (Wypich, 1986). The vast majority of lead stabilizers are found in electrical cable insulation, foams and rigid extruded products (Sarvetnick, 1969; Greek, 1988), with electrical cables being the primary application. Lead stabilizers are not found in food containers (Sarvetnick, 1969). Lead stabilizers may be present in rigid plastics such as Sharps-tainers® and bedpans. Most lead in bio-medical plastics is likely in the form of pigments.

#### **Sources of Cadmium and Lead in Municipal Waste Streams**

Sources of cadmium and lead in the combustible fraction of MWS were identified by Haynes et al. (1978), Law et al. (1978), and by Lorber (1985). Important sources of cadmium and lead in MWS are reviewed in this section. These sources may be wholly or partially responsible for cadmium and lead levels found in BMWS.

Municipal waste is similar in composition to bio-medical waste (combined general and infectious waste). An important difference, however, is the percentage of plastics in each waste stream. Municipal wastes contain between 3 and 7% plastics, while BMW contains around 20%, with reported values as high as 30% (Doyle et al., 1985). Plastics, particularly PVC, are suspected as the major source of cadmium and lead in BMW, and a higher percentage of plastics in BMWS could account for higher emission levels of cadmium and lead from BMWI relative to MWI.

Haynes et al. (1978) report that cadmium in the combustible fraction (waste was separated into light and heavy combustibles and non-combustibles) of municipal waste can be attributed to inks, pigments and plastics, with plastics being the primary source. Light combustibles account for almost one-half of cadmium in the total combustible fraction (see Table 3-1). Light combustibles are likely to reflect composition of a BMWS. Haynes et al. (1978) claim that complete separation of plastics would leave only a negligible percentage of cadmium remaining in the combustible fraction.

Table 3-1  
Cadmium and Lead in the Combustible Fraction  
(in ppm)<sup>1</sup>

Metal	Total Combustible	Light Combustible	Range
Cd	9	4	<2 - 23
Pb	330	270	90 - 1600

<sup>1</sup> Haynes et al. (1978)

Lead is found primarily as pigments in paper, paper products and plastics. Pigment colors range from yellow through orange to green, and are typically associated with lead chromate ( $\text{PbCrO}_4$ ). Lead in MWS was not linked to a single major source as was cadmium (plastics). The metal was concentrated in light combustibles however (see Table 3.1), and Haynes et al. (1978) state that  $\text{PbCrO}_4$  is the primary form of lead in municipal waste. Reduction in the use of lead chromate would reduce lead inputs to MWI, and presumably to BMWI.

Lorber (1985) reports cadmium and lead partitioning between sieve fractions (0-8 mm and 8-40 mm), leather/rubber, paper, plastics and putrescibles in refuse derived fuel (RDF). Thirty-seven percent of the cadmium was found in the small sieve fraction (0-8 mm), 28% in the large sieve fraction (8-40 mm) and 27% in plastics. Lead was primarily found in the small sieve fraction (>70%). Sieve fractions roughly correspond to Haynes' light combustible fraction.

### **Discussion of Literature Review**

Of the five principal uses of cadmium, pigments, batteries, and plastic stabilizers are potential sources of the metal in BMWS. Paper and plastic products with colors ranging from yellow to maroon may contain cadmium. Reusable nickel-cadmium batteries are probably not consistent components of BMWS. Polyvinyl chloride and related resins can contain cadmium-based thermo and photo stabilizers. Stabilizers found in PVC and other plastics are primary suspects as sources of cadmium in BMWS.

Lead-based pigments found in paper and plastic products are primary suspect sources of lead in BMWS. Colors can range from yellow and orange to green. Lead appears to concentrate in the light combustible fraction of municipal waste.

### **PRELIMINARY IDENTIFICATION OF CADMIUM AND LEAD IN BIO-MEDICAL WASTE STREAMS**

Elemental analysis of bio-medical waste samples by Particle Induced X-Ray Emission (PIXE) and X-Ray Fluorescence (XRF) were conducted in an attempt to identify wastes containing cadmium and lead. Results of these analyses are presented in this section.

### **Particle Induced X-ray Emission (PIXE)**

Samples of a typical BMWS were collected at the University of California, Davis, Medical Center in Sacramento, CA. Likely sources of cadmium and lead were chosen. Sample collection was based on pigments (yellow to red) and/or composition (PVC or rigid plastic). Bio-medical waste and a few other samples were analyzed by PIXE. In addition to PIXE, most samples were analyzed by X-Ray Fluorescence (to be discussed later).

Particle Induced X-ray Emission analysis were conducted at the Crocker Nuclear Laboratory, UC Davis. The nature of the samples prevented collection of quantitative data (the samples were too thick). However, qualitative information was collected on elements with an atomic number greater than 10 (neon). Particle Induced X-ray Emission analyses were conducted in June 1988, July 1988, and September 1988. Cadmium was not specifically tuned for except in the September, 1988, PIXE analysis. Earlier analyses should have detected cadmium if it was present, however, as the detection limit was on the order of 2 ppm (by mass). Sample identification and results from the June analysis are presented in Tables 3-2 and 3-3 respectively. Sample identification and results from the July analysis are presented in Tables 3-4 and 3-5 respectively. The September analysis results are given in Table 3-6; samples were from the July analysis.

Table 3-2  
 Sample Identification Key for Table 3-3  
 PIXE, June, 1988

Sample Number	Identification
1	Large Red Infectious Waste Bag
2	Small Red Infectious Waste Bag
3	Large "Redwood" Brown Bag
4	Beige Garbage Bag
5	Yellow Linen Bag
6	Autoclave Bag
7	Autoclave Bag, Letter "A"
8	Travenol Vinyl Glove
9	Black Copy From Photocopy Machine
10	Small, Clear "Poly" Bag
11	Latex Gloves
12	Package from Latex Gloves
13	Transparent PVC Slide Holder
14	Newsprint

Table 3-3  
 Presence of Metal Species Determined  
 by Elemental Analysis, PIXE, June, 1988

Sample No.	Cd	Pb	Ba	Fe	Zn	Ca
1	no	no	no	yes	no	no
2	no	no	no	yes	no	yes
3	no	no	no	yes	no	yes
4	no	no	no	yes	no	yes
5	no	yes	no	no	no	no
6	no	no	no	no	no	no
7	no	yes	no	no	no	no
8	no	no	no	no	no	no
9	no	no	no	yes	no	no
10	no	no	no	yes	no	no
11	no	no	no	no	yes	yes
12	no	no	no	no	no	no
13	no	yes	no	no	yes	yes
14	no	no	no	no	no	no

Table 3-4  
 Sample Identification Key for Table 3-5  
 PIXE, July, 1988

Sample Number	Identification
1	Ash from Heat Exchanger Tube (Kaiser-Permanente Hospital)
2	Ash from entrance of Heat Exchanger Tube
3	Yellow Bedpan
4	Red Sharps-tainer®
5	Syringe Cover
6	Yellow Bedpan
7	Red Sharps-tainer®
8	Red Sharps-tainer®
9	Red Sharps-tainer®

Table 3-5  
 Presence of Metal Species Determined  
 by Elemental Analysis, PIXE, July, 1988

Sample No.	Cd	Pb	Ba	Fe	Zn	Ca
1	no	yes	no	yes	yes	yes
2	no	yes	no	yes	yes	yes
3	no	yes	no	no	no	no
4	no	no	no	yes	yes	no
5	no	no	no	no	yes	no
6	no	yes	no	yes	yes	yes
7	no	no	no	yes	yes	yes
8	no	yes	no	yes	yes	yes
9	no	no	no	yes	yes	yes

Table 3-6  
Presence of Metal Species Determined  
by Elemental Analysis, PIXE, September, 1988

Sample No.	Cd	Pb	Ba	Fe	Zn	Ca
1	no	yes	no	yes	yes	yes
2	yes	yes	no	yes	yes	yes
3	no	yes	no	no	yes	no
4	no	yes	no	yes	yes	yes

Cadmium was detected in Sample 2 (re-analysis of ash from entrance to heat exchanger tube, tuned for detection of cadmium) in the September, 1988 analysis. Cadmium was expected to be present in both ash samples (because it was present in the fly ash), though this was not confirmed by PIXE. Cadmium was not detected when PIXE was not specifically tuned for the metal. Thus the absence of detectable levels in the plastic items does not mean that cadmium was not present in low concentrations. It is important to note that cadmium and barium are reported to be almost always associated in plastic stabilizers, and that barium was not detected in any sample.

Lead was observed in several samples. Yellow linen bags, yellow bedpans, the yellow top of a urine container, and the transparent PVC slide holder all contained lead. Color of an item is not necessarily a determinant of the presence of lead or cadmium as lead was detected in the PVC slide holder. As expected, lead was detected in both ash samples. PIXE detected lead in several samples of the Sharps-tainer<sup>®</sup>, but not in all of them.

Zinc and calcium were observed in many of the hospital waste samples. Stabilizers based on these metals are known to replace cadmium and lead as plastic stabilizers in food handling products. Zinc and calcium are also

extensively used in pigments for plastic and paper products. Because zinc and calcium do not pose human toxicity concerns, their use as stabilizers and pigments by the medical industry should be expected. Confirmation of their use was not found in the literature, though Stewart (1988) claimed that zinc and calcium replace other metals as stabilizers in bio-medical plastics.

### **X-Ray Fluorescence (XRF)**

As with PIXE, qualitative information on the presence of cadmium and lead, along with other metals, was obtained by XRF. Many new items along with several samples from the PIXE analysis were tested. A list of samples used in the XRF analysis is presented in Table 3-7. Results of the XRF analysis are presented in Table 3-8.

Table 3-7  
Sample Identification Key for Table 3-8  
XRF, October, 1988

Sample Number	Identification
1	Yellow Bedpan
2	Red Infectious Waste Bag
3	Yellow Linen Bag
4	Red Sharps-tainer®
5	Yellow Top from Urine Container
6	Ash from Entrance to Heat Exchanger
7	Alkaline Battery
8	Hypodermic Needle
9	IV Tubing (PVC)

Cadmium and zinc were detected in the casing of an alkaline battery (see Table 3-8). The battery came from a disposable pen light of the type used by physicians for patient examinations. Cadmium is present in all zinc ores in a concentration of approximately 0.2 to 0.4 % (by mass), and should be present in most refined zinc. Cadmium was also observed in the heat exchanger ash, but not in any other sample, including the hypodermic needle and IV tubing.

Table 3-8  
Presence of Metal Species Determined  
by Elemental Analysis,  
XRF, October, 1988

Sample Number	Cadmium	Lead
1	no	yes
2	no	yes
3	no	yes
4	no	no
5	no	yes
6	yes	yes
7	yes	no
8	no	no
9	no	no

Lead was detected in the yellow bedpan, red infectious waste bag, yellow linen bag, yellow cap from a urine container and in the heat exchanger ash. Lead was not detected in the hypodermic needle, IV tubing, alkaline battery casing or red Sharps-tainer®.

## Discussion of Elemental Analysis Results

Cadmium was identified by XRF in a battery from a disposable examination penlight. Cadmium was not detected in any plastic or paper sample by PIXE or XRF. The metal was detected in ash from the entrance to the heat exchanger tube, but not in the ash from the inside of the heat exchanger tube. Cadmium was expected to be found in both samples (cadmium was emitted in the stack gas of the Kaiser-Permanente BMWI). Therefore, PIXE was probably not an appropriate analytical method for determining the presence of cadmium in BMWS. Results of PIXE and XRF analyses for cadmium were inconclusive in the sense that detection limits were on the order or greater than levels expected from average waste concentrations.

Lead was identified by PIXE and XRF in a variety of plastic samples. Colors of these samples ranged from yellow (bedpan) to deep maroon (Sharps-tainer®). Lead was also detected in a transparent (colorless) PVC slide holder (by PIXE), but not by XRF in the IV tubing. Therefore color alone is not a necessary condition for the presence of lead in a plastic item. Particle Induced X-ray Emission (PIXE) and XRF appeared to function as acceptable analytical methods for determining the presence of lead in BMWS.

The combination of evidence from the literature review, CARB test data, manufacturer interviews, and X-ray analyses *suggests* that cadmium and lead are probably not present in the majority of plastic items that are used to contact fluids that might also come into contact with patients. It is interesting to note that concentrations of cadmium and lead on the fly ash in BMWI and MWI appear to be roughly proportional to the percentage of plastic in the waste feed. Thus the sources of cadmium and lead in plastics are *probably* associated with the general wastes that are mixed with the infectious wastes. It is particularly ironic that the few sources of lead identified by X-ray analysis were associated with

the items used to contain infectious waste. Changes in product composition could rectify that problem.

#### **4. THERMODYNAMIC EQUILIBRIUM ANALYSIS**

Reactions of cadmium and lead at cooler temperatures (<1000 °C) and under varying oxidation/reduction environments away from the immediate flame regime were investigated with the STANJAN thermodynamic equilibrium solver (Reynolds, 1986). The means by which these metals leave BMWI is dependent on their form and chemical speciation. The distribution of metals between various incinerator effluent streams is referred to as "partitioning".

Condensation and coagulation, chemical reaction, or no change of state are possible responses of cadmium and lead to cooler temperatures and varying chemical environments. Cadmium and lead remain vaporized, are deposited in the bottom ash, or concentrate in the fly ash depending on their response to changing environments. An understanding of combustion conditions which enhance fly ash concentration of cadmium and lead may allow operators to reduce emissions by controlling incinerator combustion environments. The analyses which follow were conducted to gain insight on likely forms of cadmium and lead in incinerator environments.

#### **METAL PARTITIONING**

Metals leave BMWI in bottom ash, in spent scrubber water, in collected particulate matter from air pollution control devices (APCD), concentrated on fly ash, or as vapor in the stack gas. Non-volatile metals and metal compounds tend to concentrate in the bottom ash. Volatile metals and metal compounds vaporize and either condense on and enrich fly ash as the gas cools, or escape as vapor (see Figure 4-1).

Physical constants of cadmium and cadmium compounds are given in Table 4-1. Atomic cadmium and  $\text{CdCl}_2$  are volatile below 1000 °C. Physical

constants of lead and lead compounds are given in Table 3-2. Lead has a low boiling point (327.5 °C) and  $PbCl_2$  is volatile below 1000 °C.

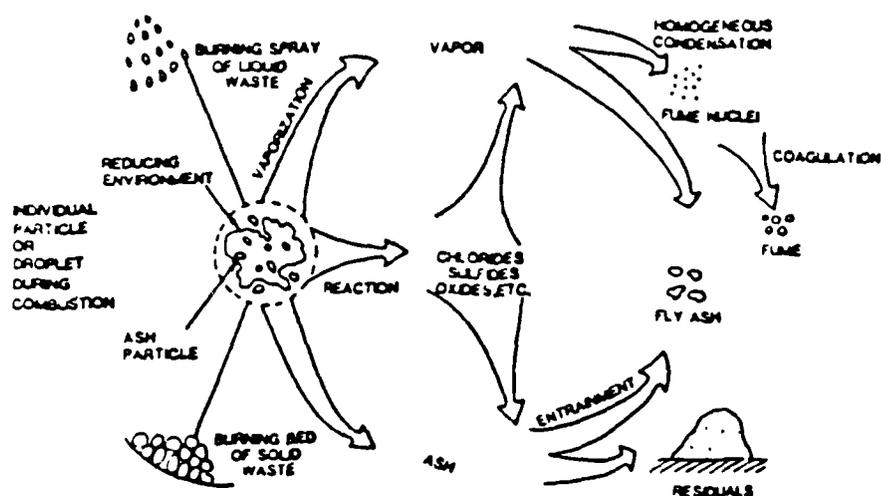


Figure 4-1  
Behaviour of Metals in Combustion Devices  
Adapted from Lee (1988)

Two chemical environments are likely in an incinerator. Reducing environments are present when the stoichiometric ratio (SR) is less than 100% of the required oxygen. Stoichiometric ratios of greater than 100% result in oxidizing environments. Chemical reactions between cadmium and lead and other elements and chemical species are highly dependent on chemical environment and time-temperature history. Oxides may appear in oxidizing environments and sulfides in reducing environments. High concentrations of chlorine in incinerator gas should result in cadmium and lead chlorides in both environments, though they may not be the dominant species.

Table 4-1  
Physical Constants for Cadmium  
and Cadmium Compounds

Compound	Molecular Mass	Melting Point (°C)	Boiling Point (°C)
Cd	112.41	320.9	765
CdCO <sub>3</sub>	172.41	<500 <sup>1</sup>	
CdCl <sub>2</sub>	182.32	568	960
CdO	128.40	>1500	1559 <sup>2</sup>
CdS	144.46	>1000	

1 Decomposes  
2 Sublimates

Cadmium and CdCl<sub>2</sub> are both highly volatile. Cadmium carbonate is unstable above 500 °C. Cadmium oxide and CdS are relatively non-volatile at normal incinerator operating temperatures (see Table 4-1). Under oxidizing conditions, CdO would be expected to be the dominant form and possibly would reside in the bottom ash. However, in controlled air incinerators conditions in the primary chamber are reducing so that Cd or CdCl<sub>2</sub> would be the dominant form and would be expected to volatilize, ultimately condensing on the fly ash.

Lead and PbCl<sub>2</sub> are both volatile. The melting and boiling points of PbCl<sub>2</sub> are similar to those of CdCl<sub>2</sub>. Lead carbonate decomposes at 315 °C. Lead oxide, PbSO<sub>4</sub> and PbS are much less volatile than lead chloride (see Table 4-2). Under oxidizing conditions PbO or PbSO<sub>4</sub> would be expected to

dominate and possibly remain in the bottom ash. Lead or  $\text{PbCl}_2$  would be expected to volatilize and ultimately condense on the fly ash.

Table 4-2  
Physical Constants for Lead  
and Lead Compounds

Compound	Molecular Mass	Melting Point (°C)	Boiling Point (°C)
Pb	207.19	327.5	1740
$\text{PbCO}_3$	267.20	315 <sup>1</sup>	
$\text{PbCl}_2$	278.10	501	950
PbO	223.19	886	
$\text{PbSO}_4$	303.25	1170	
PbS	239.25	1114	

<sup>1</sup> Decomposes

## METHODS

The STANJAN thermodynamic equilibrium solver is described in this section. Additionally, parameters used in the model analysis are outlined.

### STANJAN Thermodynamic Equilibrium Solver

STANJAN is a thermodynamic equilibrium solver developed at Stanford University by W. C. Reynolds (1986). STANJAN is based on the element-potential method for equilibrium analysis and its calculations are based on physical constants, enthalpy and entropy data for each individual species. Yang et al. (1987) investigated equilibrium distributions of a variety of

hydrocarbon-air mixtures containing heteroatoms such as sulfur, chlorine and nitrogen. Lee (1988) investigated partitioning of mercury, lead and chromium in HWI using a thermodynamic equilibrium analysis.

Entropy and enthalpy data were obtained from *Thermodynamic Data for Mineral Technology* (Pankratz et al., 1984). A companion program, JANFILE, was used to prepare species data for use in STANJAN. STANJAN is an interactive program designed for use on desktop and mainframe computers. STANJAN and JANFILE were run on an IBM PC model XT.

### **Cases Examined**

Analysis of metal partitioning was based on assumptions of local equilibrium, ideal gas and liquid behaviour, and complete mixing of all species (Lee, 1988; Yang et al., 1984). The analysis was a "worse case scenario", with very high levels of chlorine (as might be found in the combustion of PVC) and with either relatively high concentrations of sulfur or no sulfur (for cadmium only). Reaction conditions were modeled for environments away from the flame where gas and entrained elements cool and may be subject to a variety of stoichiometric oxygen ratios. In controlled air incinerators of the type tested by CARB, conditions are sub-stoichiometric in the primary chamber, with excess air present (on average) in the secondary chamber. Cadmium and lead were introduced at approximate mole fractions of  $10^{-8}$  and  $10^{-7}$  respectively. These concentrations are consistent with those observed in the stack gas of BMWI based upon mass concentration values from the CARB tests. A variety of stoichiometric ratios were analyzed, representing both reducing (carbon and hydrogen rich) and oxidizing (oxygen rich) environments. Pressure was held constant at 1 atmosphere, and temperature ranged from 400 K to 1100 K (127 °C to 827 °C). Equilibrium concentrations for up to 20 separate chemical

species could be calculated simultaneously by STANJAN in the PC version used. Preliminary analyses were conducted to determine which species needed to be included in the final calculations.

**Table 4-3**  
**Oxidizing Environment Species**  
**for STANJAN Thermodynamic**  
**Equilibrium Analysis**

O <sub>2</sub>	H <sub>2</sub> O
N <sub>2</sub>	Cl <sub>2</sub>
HCl	CO
C(solid)	CO <sub>2</sub>
SO <sub>2</sub>	H <sub>2</sub> SO <sub>4</sub>
H <sub>2</sub> S	

The final model reactor species compositions differed slightly for reducing and oxidizing environments. Oxidizing and reducing reactor species are reported in Tables 4-3 and 4-4, respectively. Hydrogen sulfide and C(solid) were simply carried over for convenience.

**Table 4-4**  
**Reducing Environment Species**  
**for STANJAN Thermodynamic**  
**Equilibrium Analysis**

O <sub>2</sub>	H <sub>2</sub> O
N <sub>2</sub>	Cl <sub>2</sub>
HCl	CO
C(solid)	CC <sub>2</sub>
H <sub>2</sub> S	H <sub>2</sub> SO <sub>4</sub>
CCl <sub>4</sub>	CCl <sub>2</sub> H <sub>2</sub>

Several chemical species of cadmium and lead were considered in the STANJAN analyses in an attempt to better understand species dominance and partitioning in the incinerator environment. Cadmium and lead are both volatile and were included as distinct chemical species. Solid, liquid, and vapor phases of both metals were analyzed. Cadmium and lead chlorides were

Table 4-5  
Cadmium Species for STANJAN  
Thermodynamic Equilibrium Analysis

Cd gas	Cd(L) liquid
Cd(S) solid	CdO gas
CdO(S) solid	CdCO <sub>3</sub> (S) solid
CdCl <sub>2</sub> (L) liquid	CdCl <sub>2</sub> (S) solid
CdS gas	CdS(S) solid
CdCl <sub>2</sub>	

Table 4-6  
Lead Species for STANJAN  
Thermodynamic Equilibrium Analysis

Pb gas	PbO(S) solid
Pb(S) solid	PbO gas
PbCO <sub>3</sub> (S) solid	PbCl <sub>2</sub> (L) liquid
PbSO <sub>4</sub> (S) solid	PbCl <sub>2</sub> (S) solid
PbCl <sub>2</sub>	PbS(S) solid

included because their relative volatility and high chlorine levels in incinerator flue gases. Oxides and carbonates of both metals were also considered. Sulfur-species (sulfates and sulfides) were considered as a means of sequestering cadmium and lead in insoluble and non-volatile forms. Cadmium sulfide, PbS and PbSO<sub>4</sub> all have boiling points greater than 1000 °C.

Cadmium and lead species used in final analysis for both environments are reported in Tables 4-5 and 4-6, respectively.

Carbon (C), hydrogen (H), and chlorine (Cl) concentrations were determined as simple ratios (C:H:Cl) representing a fuel consisting of hydrocarbons and chlorinated hydrocarbons of varying composition. Carbon:hydrogen:chlorine ratios are reported along with corresponding chlorinated hydrocarbons in Table 4-7. Notice that one ratio, 1:4:0 (CH<sub>4</sub>), does not include chlorine.

Table 4-7  
Carbon : Hydrogen : Chlorine ratios  
used in STANJAN Thermodynamic  
Equilibrium Analysis

Corresponding Chlorinated hydrocarbon	Ratio (C:H:Cl)
CH <sub>4</sub>	1:4:0
CH <sub>3</sub> Cl	1:3:1
CH <sub>2</sub> Cl <sub>2</sub>	1:2:2
CHCl <sub>3</sub>	1:1:3
C <sub>2</sub> H <sub>3</sub> Cl	1:1.5:0.5
C <sub>2</sub> H <sub>2</sub> Cl <sub>2</sub>	1:1:1
C <sub>2</sub> HCl <sub>3</sub>	1:0.5:1.5

Oxygen concentrations were based on the stoichiometric requirement for complete combustion of the simple chlorinated hydrocarbons to CO<sub>2</sub>, H<sub>2</sub>O and HCl. Oxygen and nitrogen sources from the waste were assumed to be negligible. Stoichiometric oxygen requirements for each C:H:Cl ratio are given in Table 4-8. Nitrogen concentration was assumed to be the standard ratio between nitrogen (N<sub>2</sub>) and oxygen (O<sub>2</sub>) in the atmosphere, or 3.74 to 1. Sulfur was introduced at an approximate mole fraction of 10<sup>-3</sup>. Reducing

environments (carbon and hydrogen rich) were created by allowing less than stoichiometric amounts (<100%) of oxygen in the reaction condition. Greater than stoichiometric amounts (>100%) produced oxidizing environments (oxygen rich).

Table 4-8  
Stoichiometric Oxygen Requirements for  
Combustion of Simple Chlorinated Hydrocarbons

Chlorinated Hydrocarbon	Oxygen required	SR (%)
CH <sub>4</sub>	4	100
CH <sub>3</sub> Cl	3	100
CH <sub>2</sub> Cl <sub>2</sub>	2	100
CHCl <sub>3</sub>	2	100
C <sub>2</sub> H <sub>3</sub> Cl	5	100
C <sub>2</sub> H <sub>2</sub> Cl <sub>2</sub>	4	100
C <sub>2</sub> HCl <sub>3</sub>	4	100

## RESULTS

Results of STANJAN thermodynamic equilibrium analysis of cadmium and lead are presented in this section. Analyses were completed on both metals under all carbon:hydrogen:chlorine ratios (see Table 4-7) in both reducing (carbon and hydrogen rich) and oxidizing (oxygen rich) environments. Additionally, both metals were analyzed for no sulfur conditions and these results are discussed under a separate section. Results represent metal compound speciation under a particular stoichiometric oxygen ratio and over the temperature range 400 to 1100 K, and do not necessarily represent

concentration of cadmium and/or lead compounds on fly ash, bottom ash, or in vapor forms.

### **Cadmium**

Graphs of the results of the equilibrium analyses for cadmium compounds are presented in Figures 4-2 through 4-15. All species with a mole fraction greater than  $10^{-20}$  are shown. The reader is reminded that cadmium was input at  $10^{-8}$  moles relative to 1 to 4 moles of carbon and hydrogen (see Table 4-7), explains why the maximum concentration of cadmium is so low (on the order of  $10^{-8}$ ).

STANJAN failed for several reaction conditions. All solid and liquid species (both metallic and organic) concentrations went to zero at the same temperature, and were replaced by appropriate gaseous species. This behaviour is believed to be an artifact of the solution algorithm. Data generated before the numerical failure condition are believed to be valid, however, and allow determination of dominant species and trends.

Complete entropy and enthalpy data for cadmium species in the temperature range 400-1100 K were not reported by Pankratz et al. (1984). However, JANFILE extrapolated values for cadmium compounds based on based on available data. Temperature ranges where thermochemical data were extrapolated for cadmium compounds are listed in Table 4-9. Entropy and enthalpy data for all lead species considered in the temperature range 400-1100 K were available.

Table 4-9  
Temperature Range for Extrapolation  
of Thermochemical Data by JANFILE

Species	Temperature (K)
Cd (S)	above 400
Cd (L)	below 600
Cd	above 1000
CdCl <sub>2</sub> (S)	above 800
CdCl <sub>2</sub> (L)	below 700
CdCO <sub>3</sub> (S)	above 700
CdS	above 800

**Reducing Environment** For all C:H:Cl ratios CdS was the dominant cadmium species (see Figures 4-2 through 4-7). The concentration of CdCl<sub>2</sub>, both liquid and solid phases, tended to be 2 to 4 orders of magnitude less than CdS. Solid CdCl<sub>2</sub> dominated liquid CdCl<sub>2</sub> for all temperatures and C:H:Cl. Cadmium sulfide vapor became important at higher temperatures, as did cadmium vapor, though to a lesser extent, except for the case C:H:Cl ratio 1:1.5:0.5 (see Figure 4-8) where Cd vapor dominated CdS vapor. Cadmium oxide and CdCO<sub>3</sub> were not present in significant quantities in the reducing environment.

Results of C:H:Cl ratio 1:4:0 (no chlorine) were similar to those noted above (see Figure 4-8). Cadmium sulfide dominated all but the highest temperatures (up to 1000 K), where Cd vapor dominated.

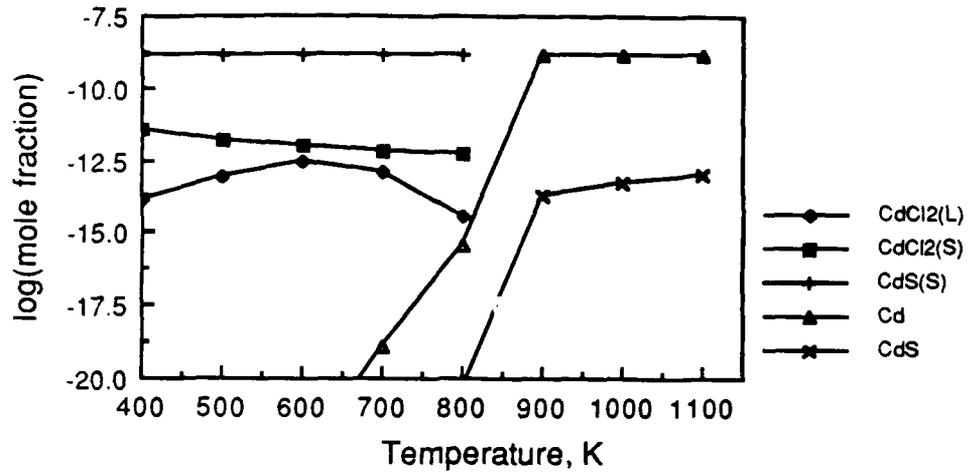


Figure 4-2

Equilibrium Product Distributions of  
Cadmium Compounds for C:H:Cl ratio 1:3:1  
Stoichiometric Ratio = 83%

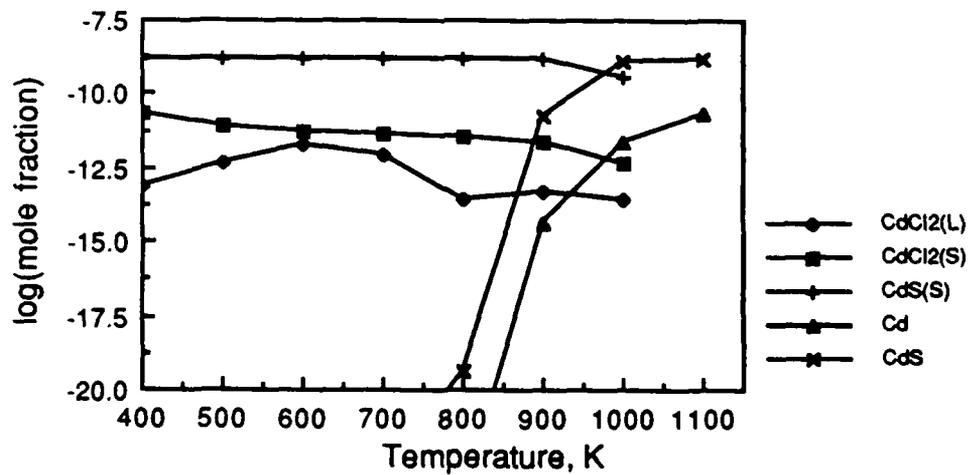


Figure 4-3

Equilibrium Product Distributions of  
Cadmium Compounds for C:H:Cl ratio 1:2:2,  
Stoichiometric Ratio = 88%

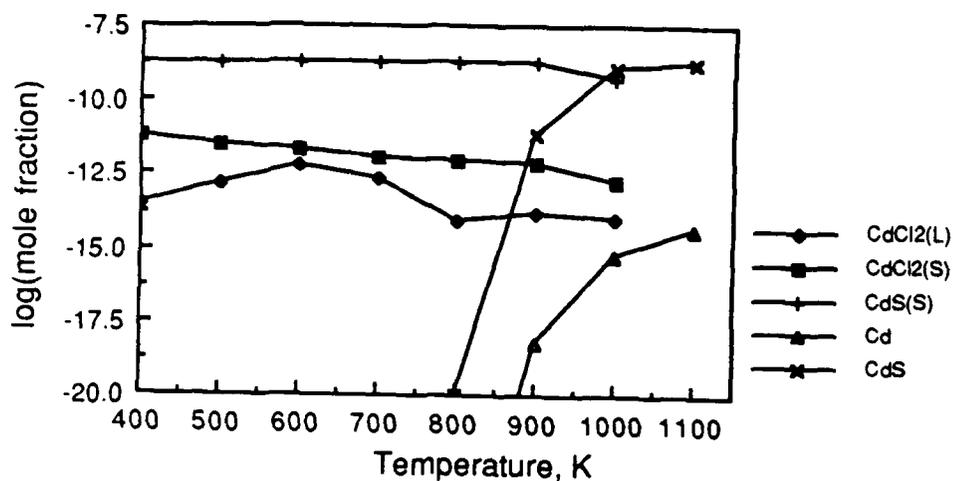


Figure 4-4

Equilibrium Product Distributions of  
Cadmium Compounds for C:H:Cl ratio 1:1:3,  
Stoichiometric Ratio = 75%

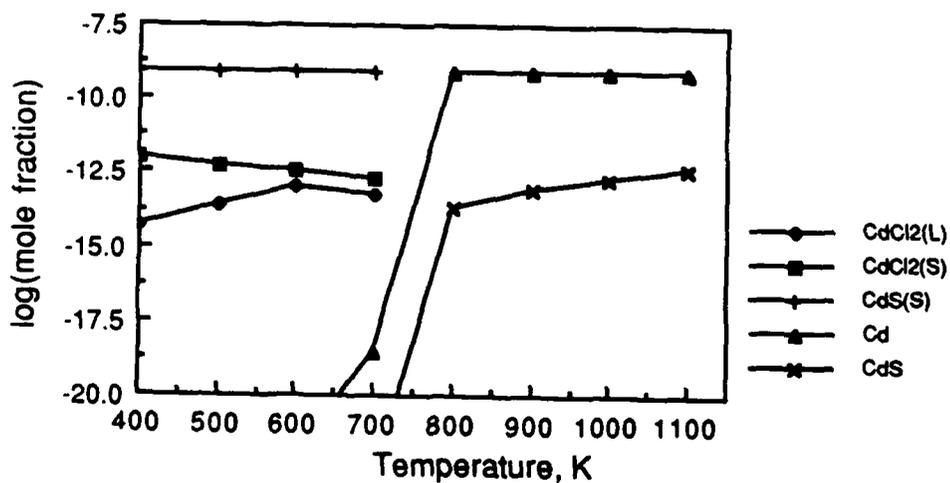


Figure 4-5

Equilibrium Product Distributions of  
Cadmium Compounds for C:H:Cl ratio 1:1.5:0.5,  
Stoichiometric Ratio = 75%

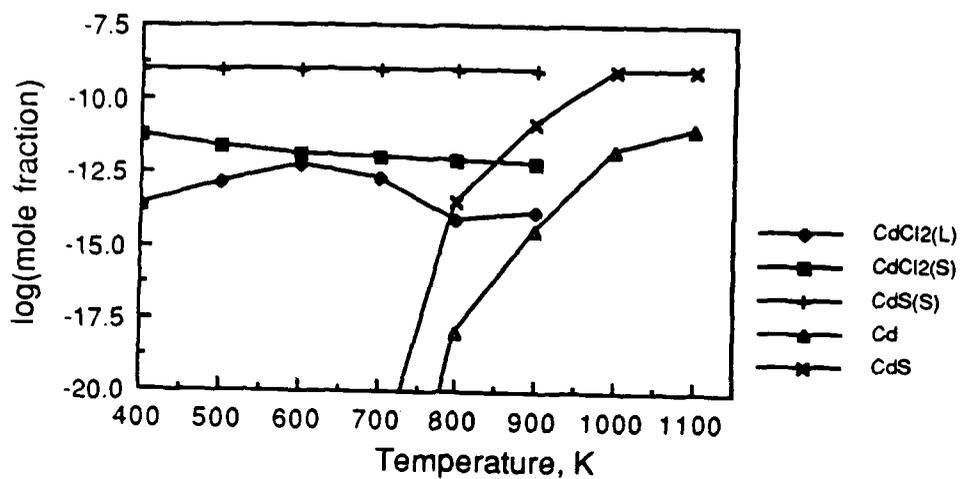


Figure 4-6

Equilibrium Product Distributions of  
Cadmium Compounds for C:H:Cl ratio 1:1:1,  
Stoichiometric Ratio = 94%

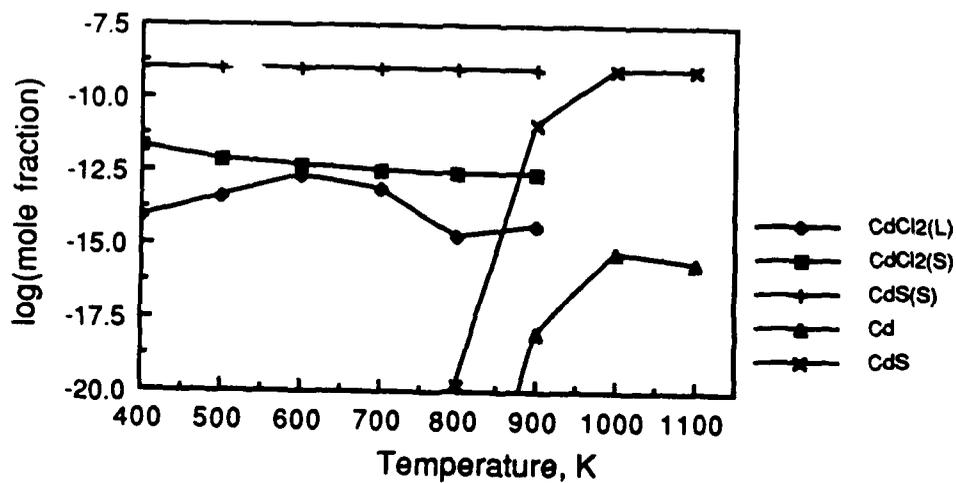


Figure 4-7

Equilibrium Product Distributions of  
Cadmium Compounds for C:H:Cl ratio 1:0.5:1.5,  
Stoichiometric Ratio = 88%

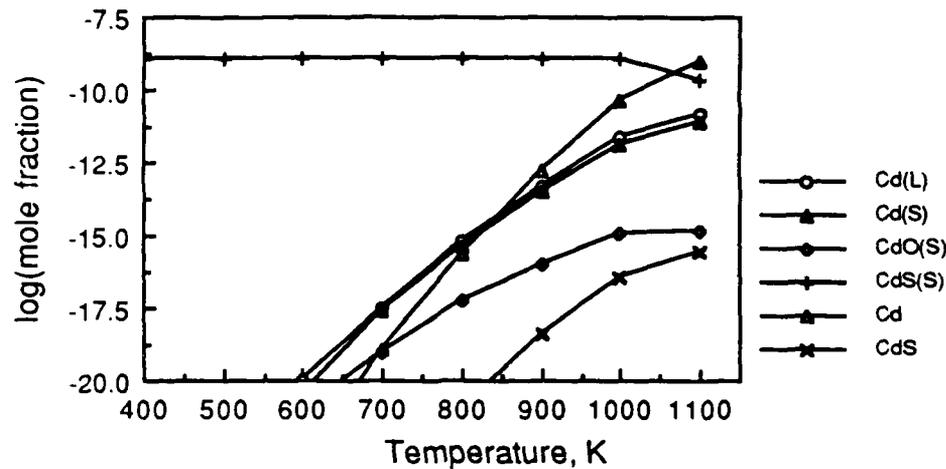


Figure 4-8

Equilibrium Product Distributions of  
Cadmium Compounds for C:H:Cl ratio 1:4:0,  
Stoichiometric Ratio = 92%

**Oxidizing Environment** Solid  $\text{CdCl}_2$  was the dominant species for all C:H:Cl ratios except 1:4:0 (see Figures 4-9 through 4-14). Liquid  $\text{CdCl}_2$  was the next most important species and its concentration was 1 to 2 orders of magnitude less than solid  $\text{CdCl}_2$ . Cadmium oxide became significant at higher temperatures. Cadmium vapor may have been dominant above 1100 K (see Figures 4-11 and 4-14). Cadmium carbonate was present at lower concentrations above 500 K, as was  $\text{CdS}$  vapor at higher temperatures.

Results of C:H:Cl = 1:4:0 (no chlorine) were not similar to those of the other ratios (see Figure 4-15). Cadmium carbonate was predominate at lower temperatures (< 600 K). Cadmium oxide dominated mid-range temperatures (600 to 900 K) and Cd vapor was dominant at higher temperatures (> 900 K).

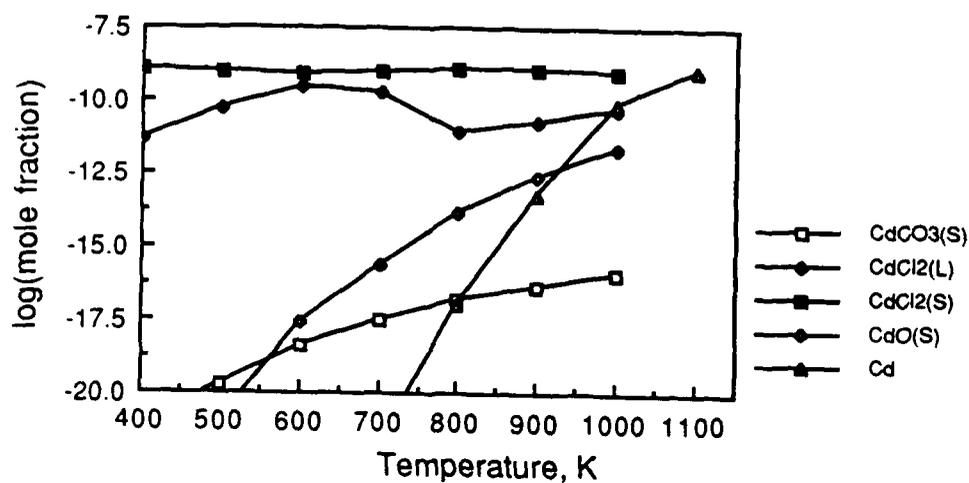


Figure 4-9

Equilibrium Product Distributions of  
Cadmium Compounds for C:H:Cl ratio 1:3:1,  
Stoichiometric Ratio = 108%

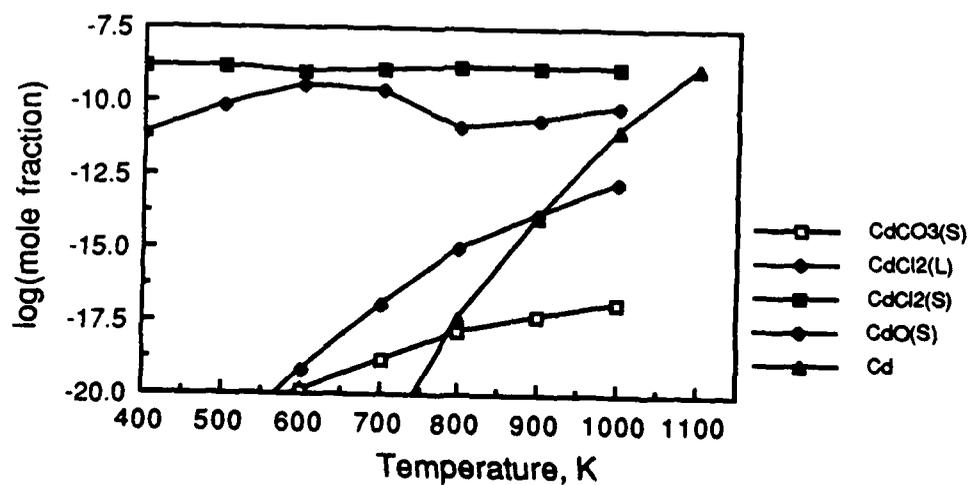


Figure 4-10

Equilibrium Product Distributions of  
Cadmium Compounds for C:H:Cl ratio 1:2:2,  
Stoichiometric Ratio = 113%

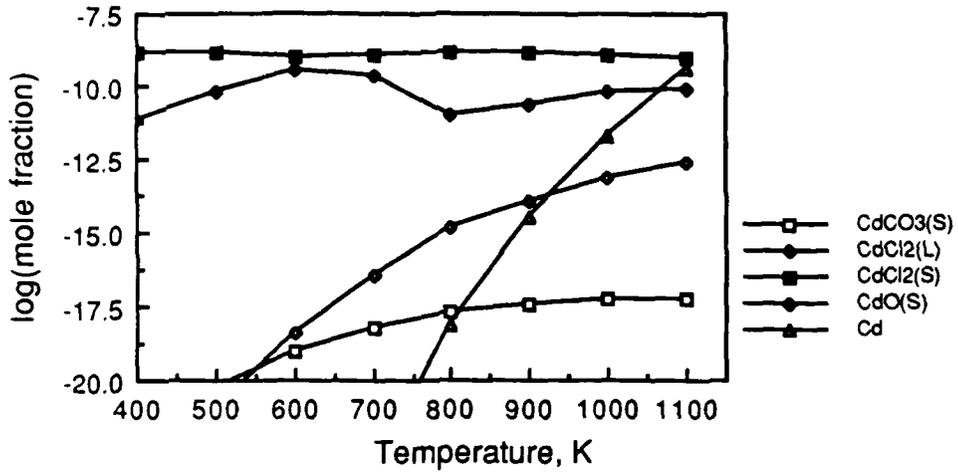


Figure 4-11

Equilibrium Product Distributions of Cadmium Compounds for C:H:Cl ratio 1:1:3, Stoichiometric Ratio = 113%

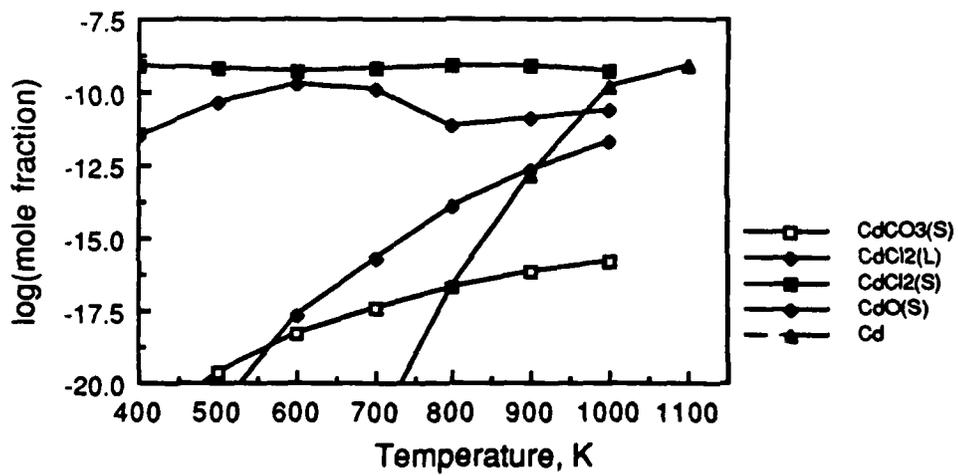


Figure 4-12

Equilibrium Product Distributions of Cadmium Compounds for C:H:Cl ratio 1:1.5:0.5, Stoichiometric Ratio = 105%

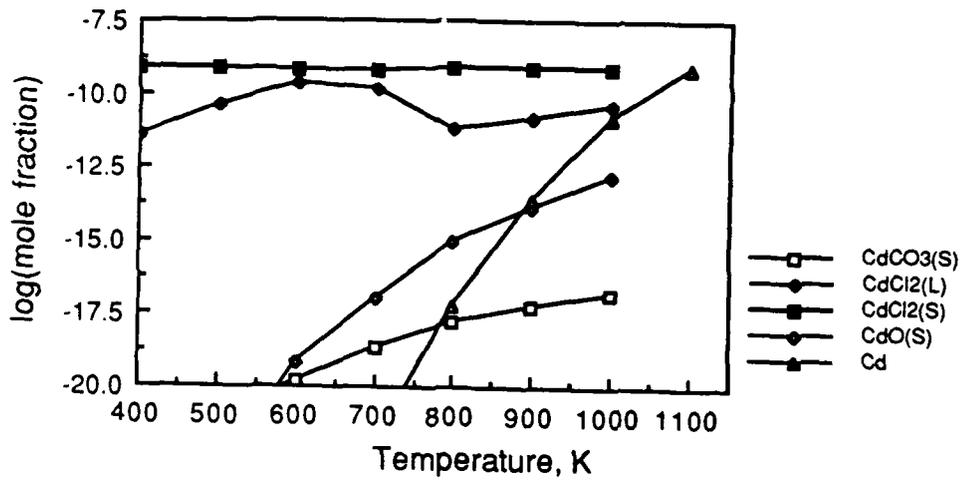


Figure 4-13

Equilibrium Product Distributions of Cadmium Compounds for C:H:Cl ratio 1:1:1, Stoichiometric Ratio = 106%

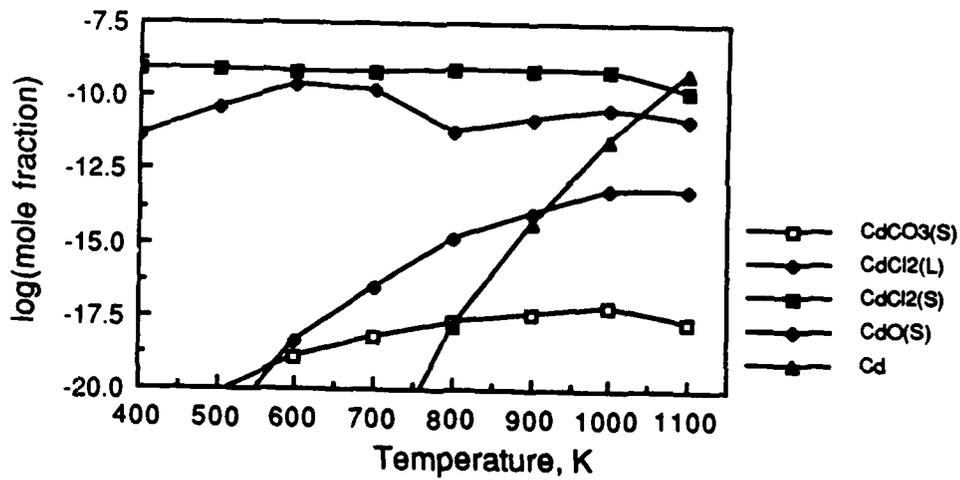


Figure 4-14

Equilibrium Product Distributions of Cadmium Compounds for C:H:Cl ratio 1:0.5:1.5, Stoichiometric Ratio = 106%

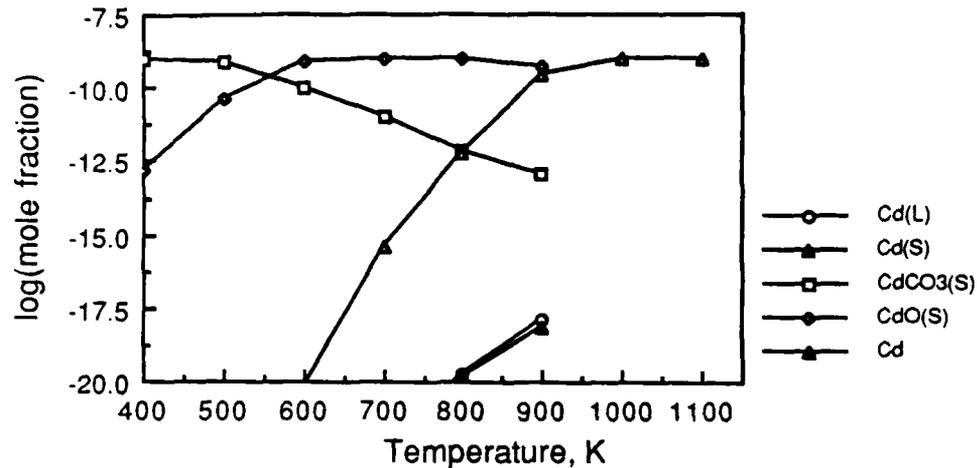


Figure 4-15

Equilibrium Product Distributions of  
Cadmium Compounds for C:H:Cl ratio 1:4:0,  
Stoichiometric Ratio = 106%

## Lead

Graphs of the results of the equilibrium analyses for lead compounds are presented in Figures 4-16 through 4-29. All species with a mole fraction greater than  $10^{-20}$  are shown. The reader is reminded that lead was input at  $10^{-7}$  moles relative to 1 to 4 moles of carbon and hydrogen (see Table 4-7), which is why the maximum lead concentration is so low (on the order of  $10^{-7}$ ).

**Reducing Environment** For all ratios C:H:Cl except 1:4:0,  $\text{PbCl}_2$ , both solid and liquid phases, was the dominant lead species (see Figures 4-16 through 4-21). Solid  $\text{PbCl}_2$  dominated to 700 to 800 K, and liquid  $\text{PbCl}_2$  above that temperature range. Lead sulfide dominated all other species, and its concentration became significant at higher temperatures. The concentration of

atomic Pb, both the solid and gas phases, was significant at higher temperatures.

Results of ratio 1:4:0 were not similar to those of other ratios (see Figure 4-22). Lead sulfide dominated the reducing environment up to 700 K. Solid Pb then dominated until the calculation failed at 800 K. Lead carbonate was important at the lowest temperatures.

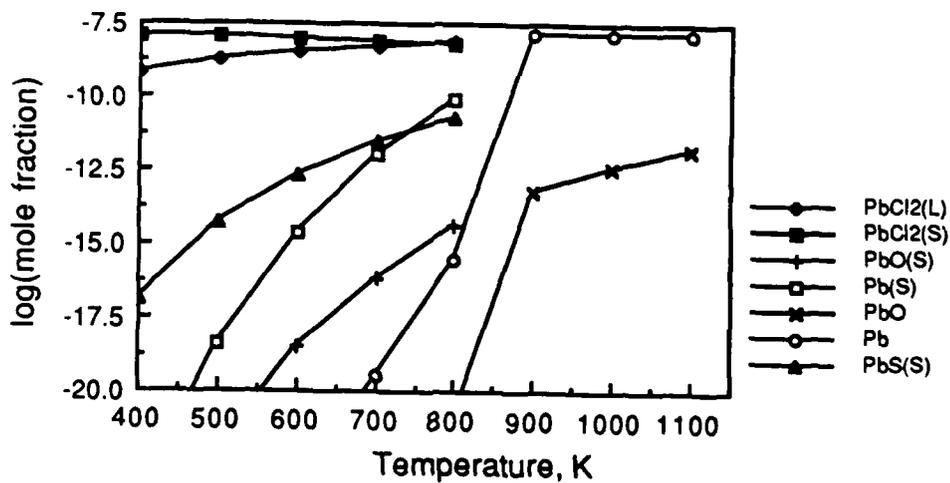


Figure 4-16

Equilibrium Product Distributions of  
Lead Compounds for C:H:Cl ratio = 1:3:1,  
Stoichiometric Ratio = 83%

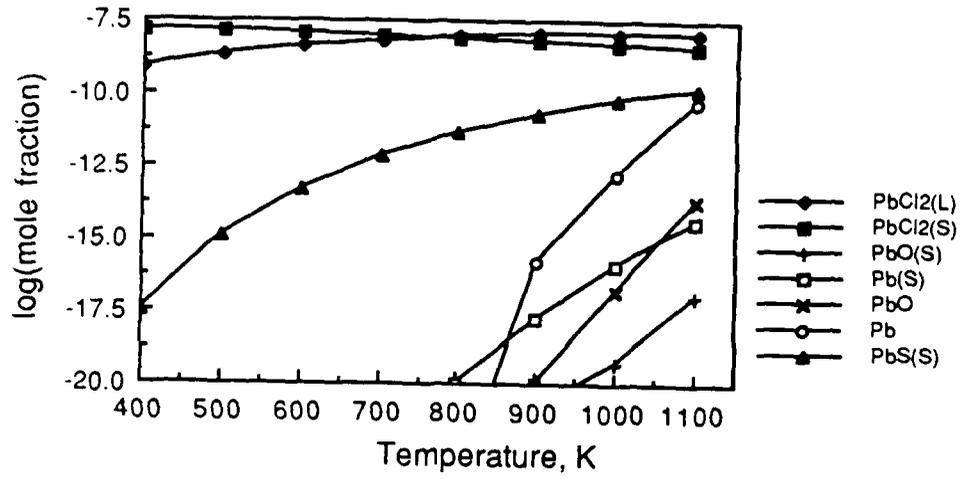


Figure 4-17

Equilibrium Product Distributions of  
Lead Compounds for C:H:Cl ratio 1:2:2,  
Stoichiometric Ratio = 88%

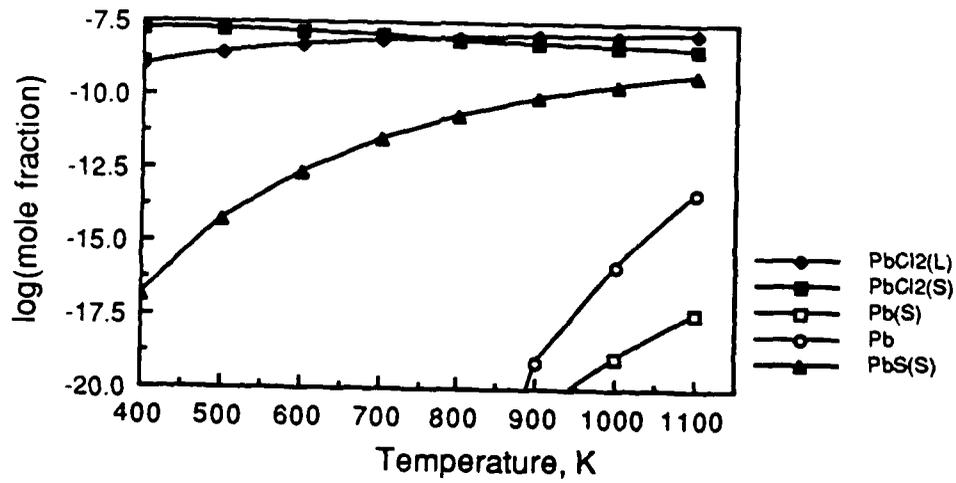


Figure 4-18

Equilibrium Product Distributions of  
Lead Compounds for C:H:Cl ratio 1:1:3,  
Stoichiometric Ratio = 75%

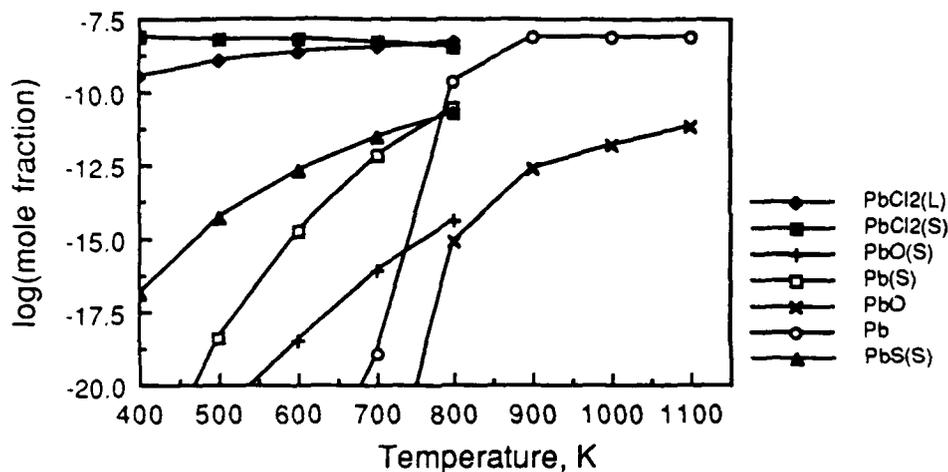


Figure 4-19

Equilibrium Product Distributions of  
Lead Compounds for C:H:Cl ratio 1:1.5:0.5,  
Stoichiometric Ratio = 90%

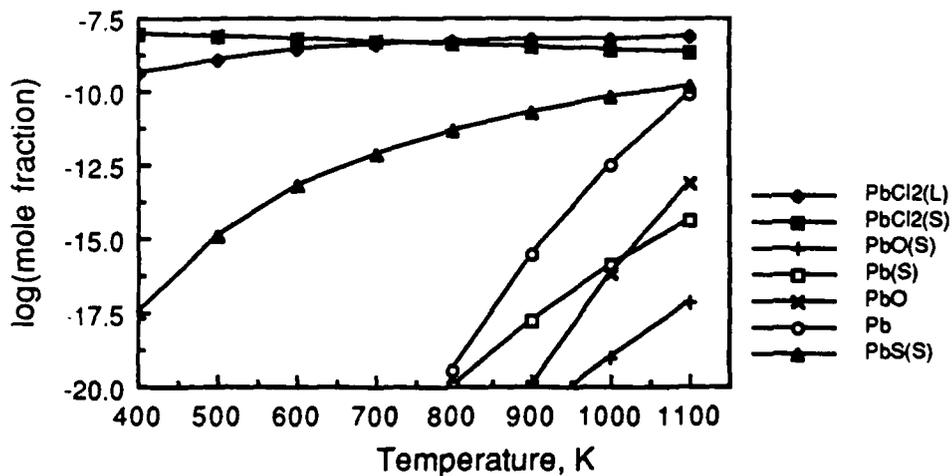


Figure 4-20

Equilibrium Product Distributions of  
Lead Compounds for C:H:Cl ratio 1:1:1,  
Stoichiometric Ratio = 94%

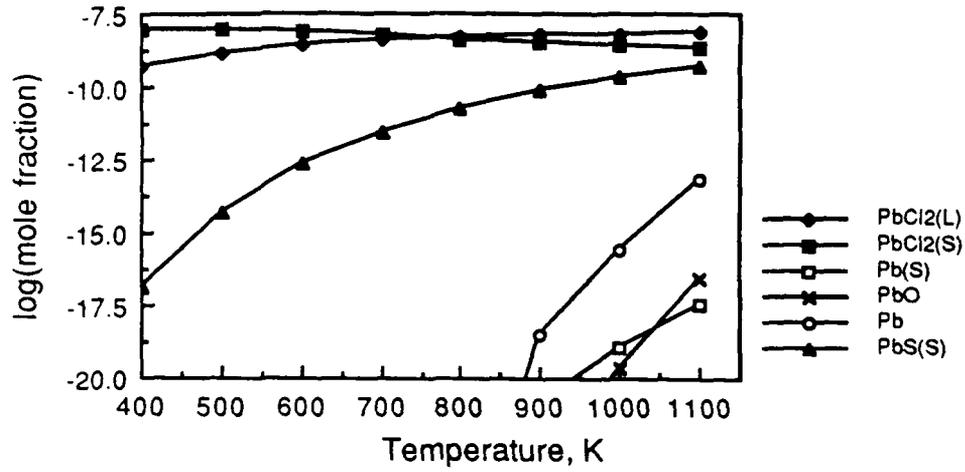


Figure 4-21

Equilibrium Product Distributions of  
Lead Compounds for C:H:Cl ratio 1:0.5:1.5,  
Stoichiometric Ratio = 88%

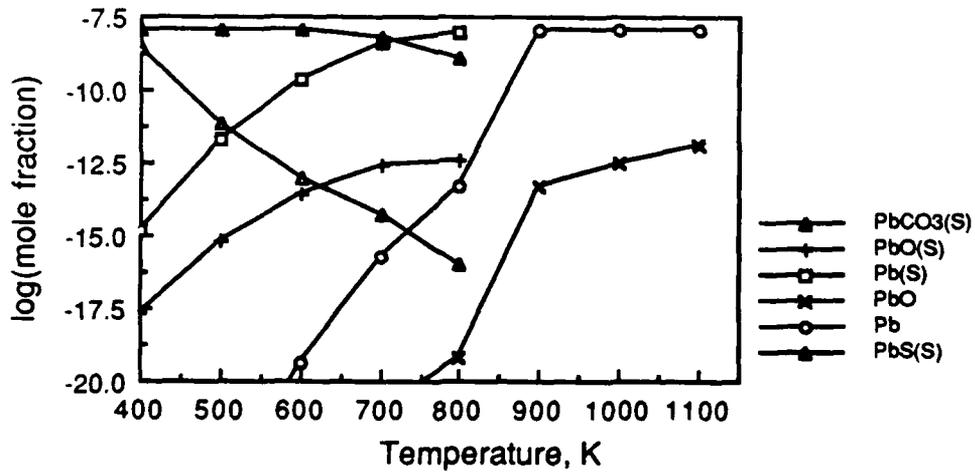


Figure 4-22

Equilibrium Product Distributions of  
Lead Compounds for C:H:Cl ratio 1:4:0,  
Stoichiometric Ratio = 94%

**Oxidizing Environment** Lead sulfate was the dominant species for all C:H:Cl ratios (see Figures 4-23 through 4-28). The concentration of  $\text{PbCl}_2$ , both solid and liquid phases, was 3 to 4 orders of magnitude less than that of  $\text{PbSO}_4$ . Lead oxide vapor became important at higher temperatures. Solid  $\text{PbO}$  and  $\text{Pb}$  vapor appear in lower concentrations at higher temperatures.

Results of ratio 1:4:0 were similar to those of the other ratios (see Figure 4-29). Lead sulfate dominated across the entire temperature range, and  $\text{PbO}$  vapor was important at higher temperatures. Solid  $\text{PbO}$  and  $\text{Pb}$  vapor were present at higher temperatures.

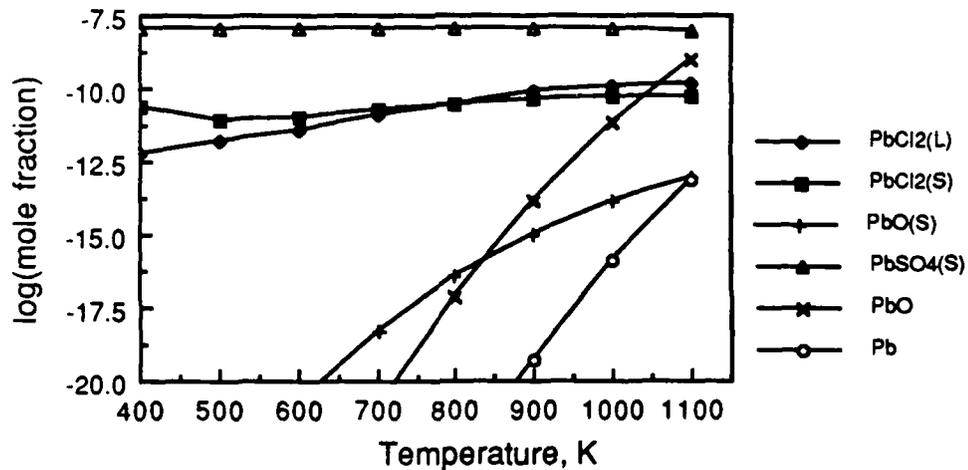


Figure 4-23

Equilibrium Product Distributions of  
Lead Compounds for C:H:Cl ratio 1:3:1,  
Stoichiometric Ratio = 108%

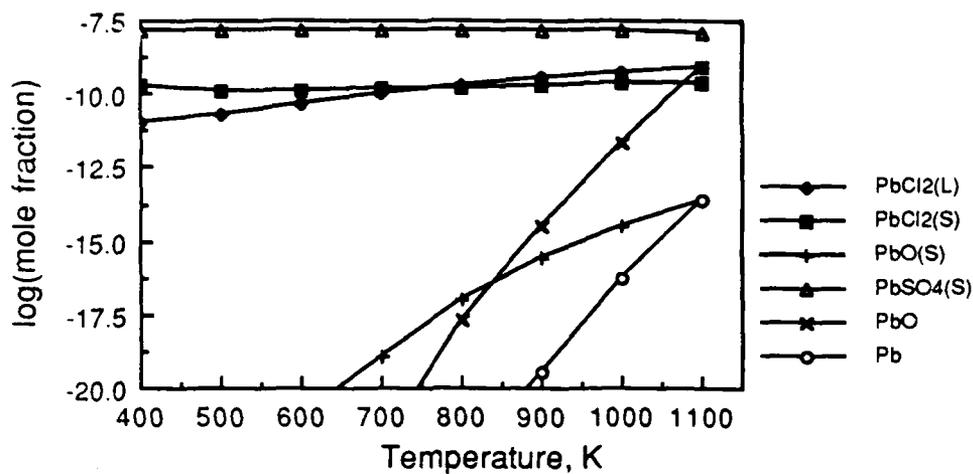


Figure 4-24

Equilibrium Product Distributions of  
Lead Compounds for C:H:Cl ratio 1:2:2,  
Stoichiometric Ratio = 113%

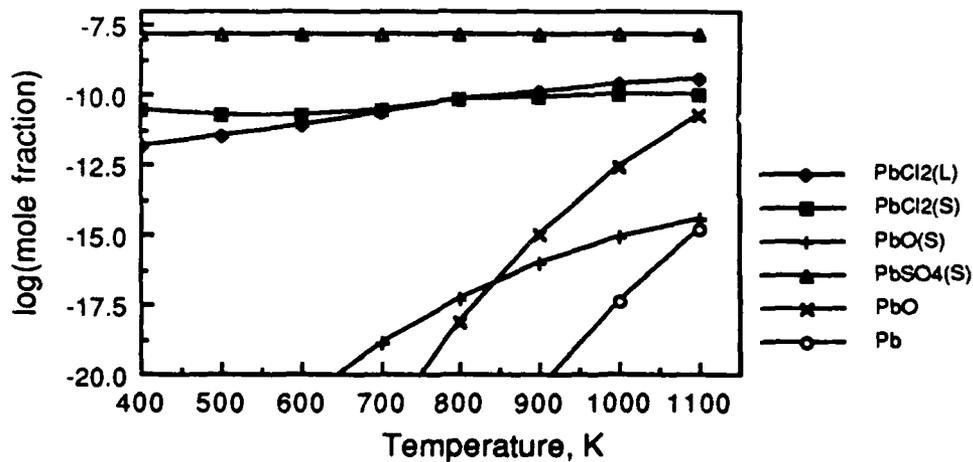


Figure 4-25

Equilibrium Product Distributions of  
Lead Compounds for C:H:Cl ratio 1:1:3,  
Stoichiometric Ratio = 113%

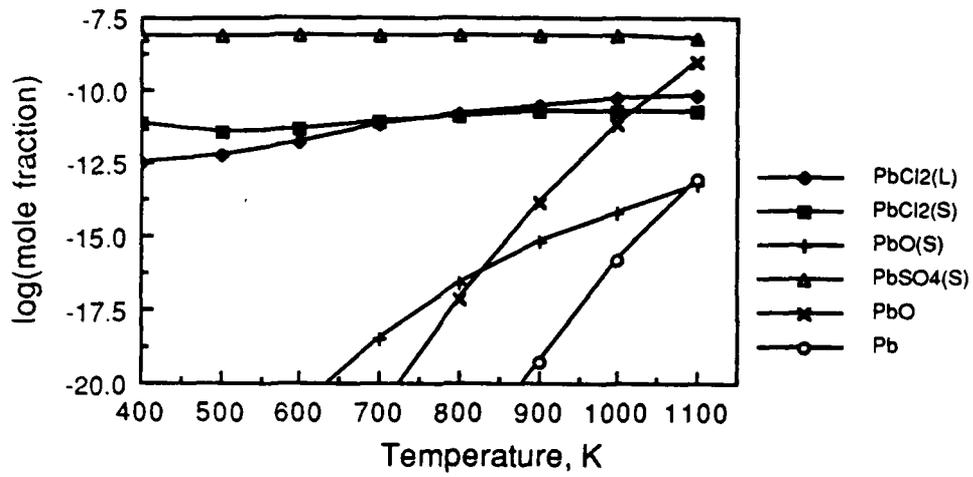


Figure 4-26

Equilibrium Product Distributions of  
Lead Compounds for C:H:Cl ratio 1:1.5:0.5,  
Stoichiometric Ratio = 105%

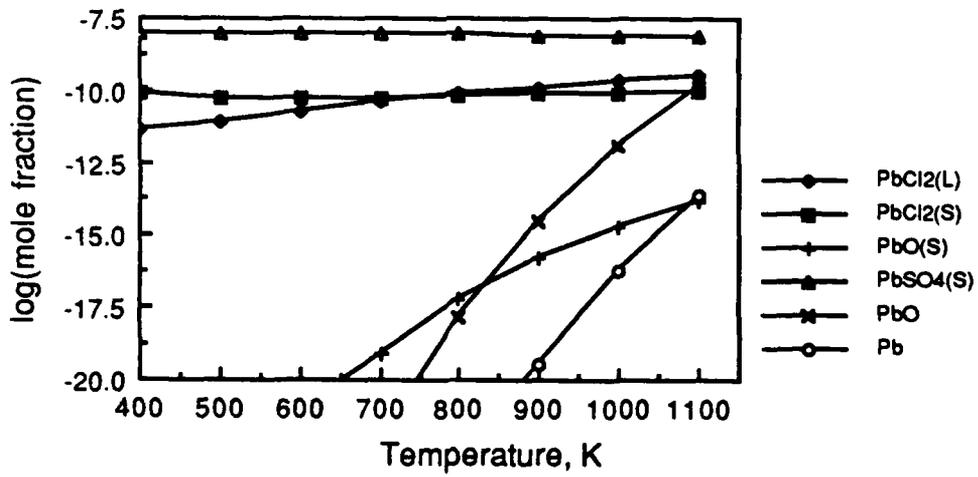


Figure 4-27

Equilibrium Product Distributions of  
Lead Compounds for C:H:Cl ratio 1:1:1,  
Stoichiometric Ratio = 106%

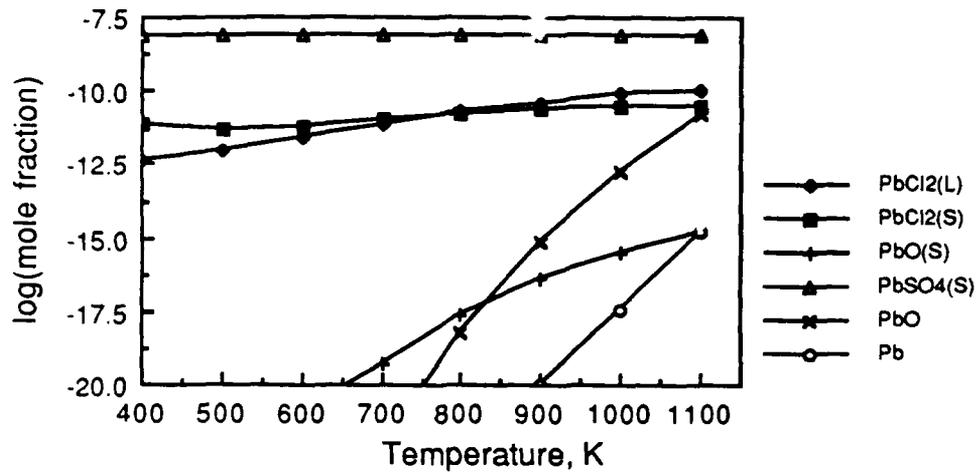


Figure 4-28

Equilibrium Product Distributions of  
Lead Compounds for C:H:Cl ratio 1:0.5:1.5,  
Stoichiometric Ratio = 106%

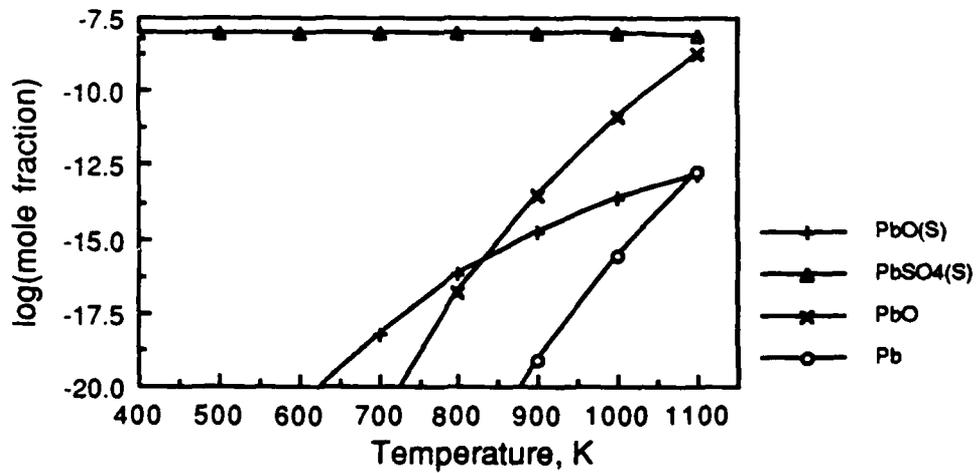


Figure 4-29

Equilibrium Product Distributions of  
Lead Compounds for C:H:Cl ratio 1:4:0,  
Stoichiometric Ratio = 106%

### Sulfur Absent

Cadmium speciation was analyzed under no sulfur conditions. Cadmium chloride, both solid and liquid phases, dominated all other cadmium species throughout the temperature range and in both reducing and oxidizing environments (see Figures 4-30 through 4-35). The concentration of Cd vapor increased with temperature, and became important at high temperatures.

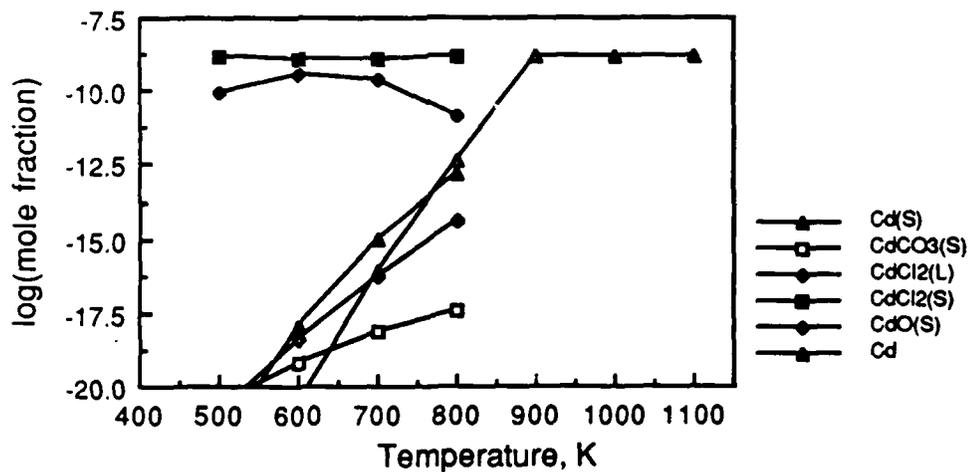


Figure 4-30

Equilibrium Product Distributions of  
Cadmium Compounds for C:H:Cl ratio 1:3:1,  
Stoichiometric Ratio = 67% (No Sulfur)

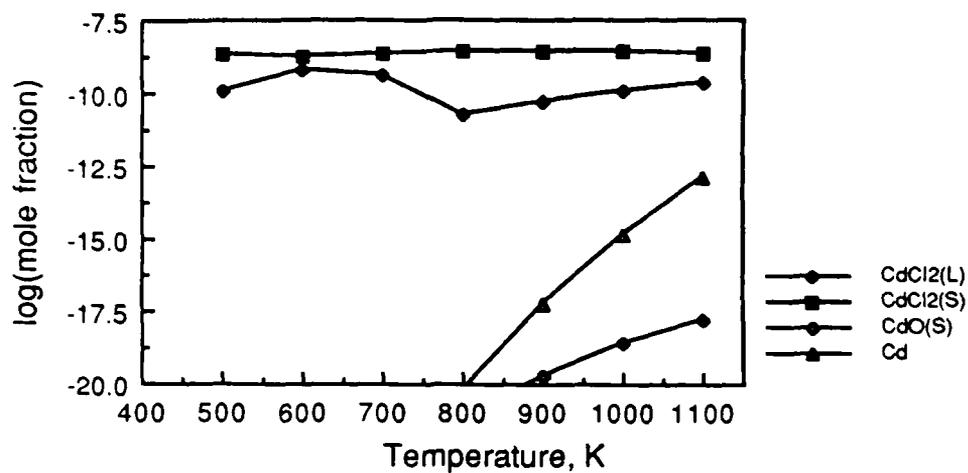


Figure 4-31

Equilibrium Product Distributions of  
Cadmium Compounds for C:H:Cl ratio 1:2:2,  
Stoichiometric Ratio = 25% (No Sulfur)

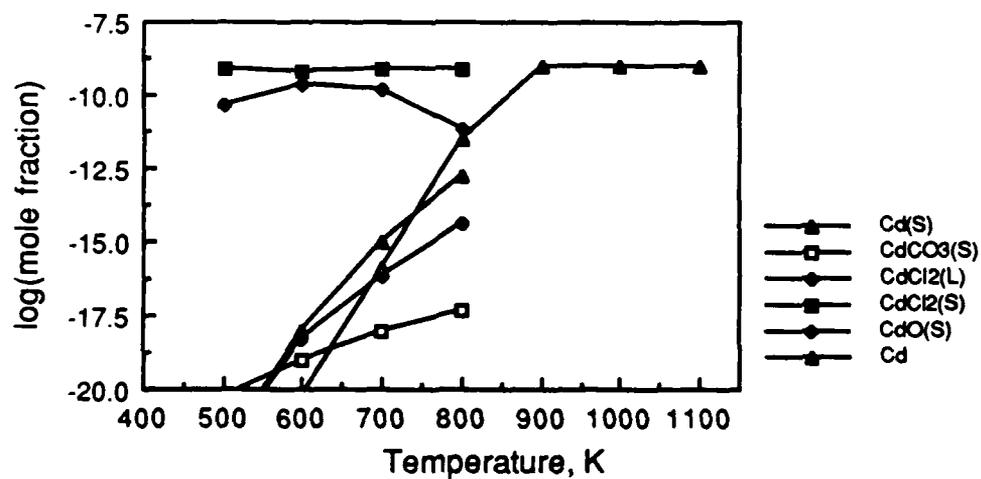


Figure 4-32

Equilibrium Product Distributions of  
Cadmium Compounds for C:H:Cl ratio 1:1.5:0.5,  
Stoichiometric Ratio = 80% (No Sulfur)

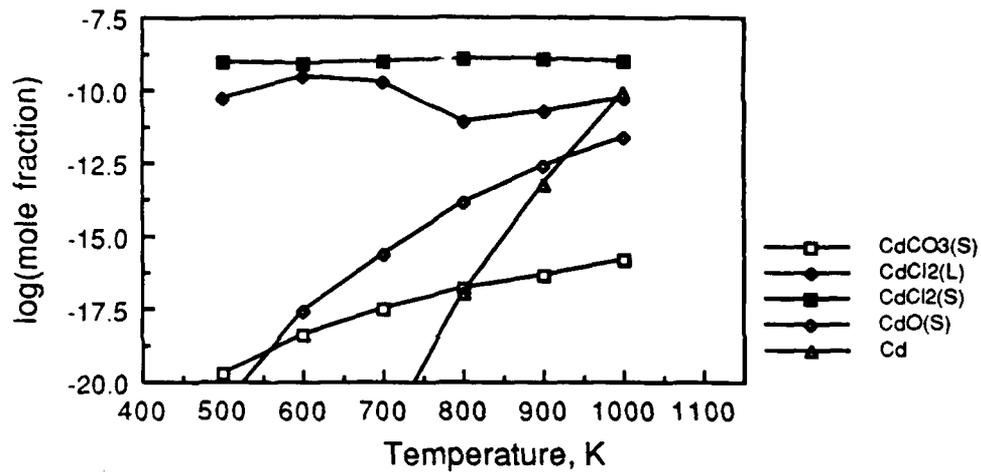


Figure 4-33

Equilibrium Product Distributions of  
Cadmium Compounds for C:H:Cl ratio 1:3:1,  
Stoichiometric Ratio = 108% (No Sulfur)

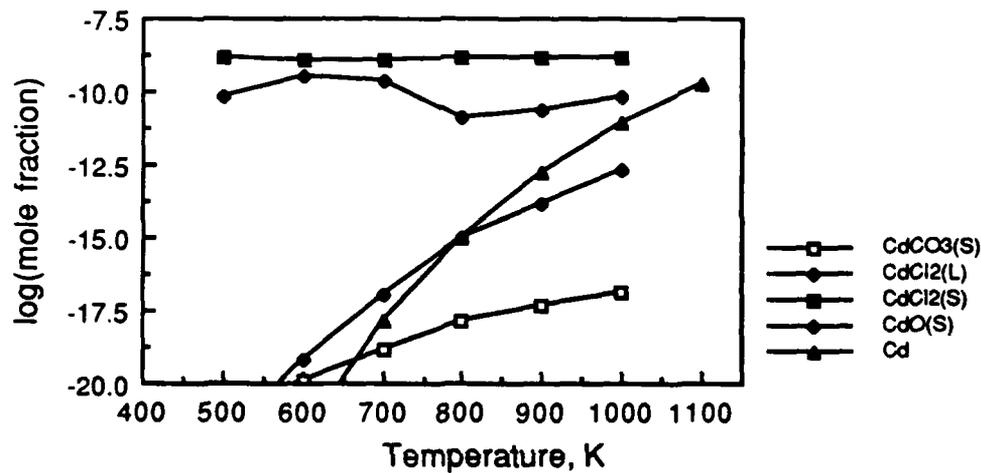


Figure 4-34

Equilibrium Product Distributions of  
Cadmium Compounds for C:H:Cl ratio 1:2:2,  
Stoichiometric Ratio = 113% (No Sulfur)

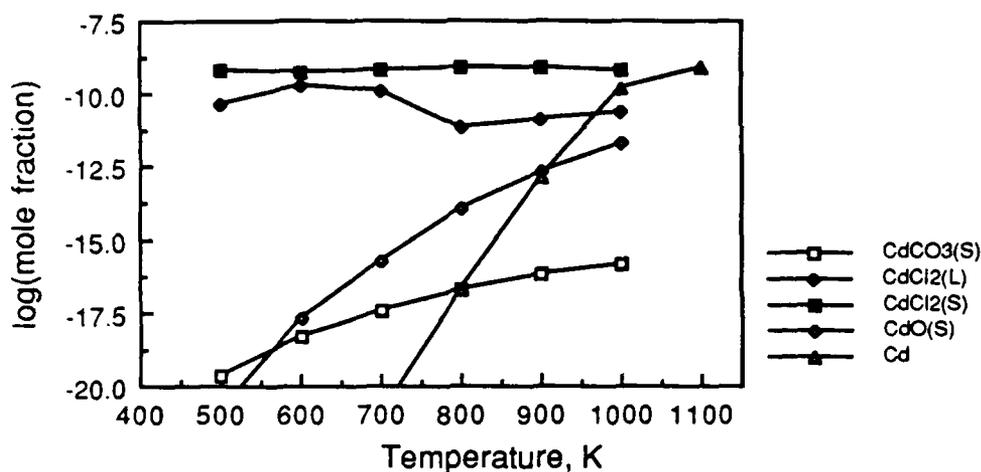


Figure 4-35

Equilibrium Product Distributions of  
Cadmium Compounds for C:H:Cl 1:1.5:0.5,  
Stoichiometric Ratio = 105% (No Sulfur)

## DISCUSSION OF RESULTS

Under reducing conditions such as those found in the primary chambers of controlled air incinerators, CdS and PbCl<sub>2</sub> dominated all other forms of both metals. In the absence of chlorine CdS remained the dominant cadmium species; PbS replaced PbCl<sub>2</sub> as the dominant lead species up to 800 K, where solid Pb dominated. When sulfur was not present, CdCl<sub>2</sub> and PbCl<sub>2</sub> were the dominant metal species. Addition of sulfur to the reducing environment appeared to be a possible mechanism for sequestering cadmium. As indicated in the review of cadmium toxicity, CdS does not appear to be taken up as readily as CdO by the body. However, sulfur effects on lead partitioning in reducing environments were minimal. Carbonates of cadmium and lead were not thermodynamically favored forms so that addition of carbonates, as might be

used in spray drying processes for acid gas control, would not sequester cadmium or lead.

Oxidizing environments are not likely in primary chambers of controlled air incinerators. However, it is possible for localized oxidizing regions to form if the chamber gas is not well mixed. Additionally, an incinerator may be fed excess air, which would result in oxidizing conditions in the secondary chamber. Cadmium chloride and  $\text{PbSO}_4$  dominated all other metal species under oxidizing conditions. Under no chlorine conditions  $\text{CdCO}_3$  (<500 K),  $\text{CdO}$  (500 - 900 K) and atomic Cd (>900 K) along with  $\text{PbSO}_4$  were the dominant species. Cadmium chloride dominated all other cadmium species when sulfur was absent. Effects of sulfur on cadmium partitioning appeared to be minimal in oxidizing environments.

From the perspective of controlling emissions of toxic metal forms by combustion modifications, it appears that either sulfur in the waste or sulfur addition might result in  $\text{CdS}$  and  $\text{PbS}$  (at high temperatures) formation in the primary zone. Two possibilities exist; early condensation and retention with the bottom ash or carry through to the secondary chamber. In the secondary chamber oxidation kinetics would determine the subsequent fate of  $\text{CdS}$ . If the kinetics of oxidation are sufficiently slow, cadmium might remain in the sulfide form, thereby reducing the bio-availability of cadmium by the inhalation route. The catalytic activity of cadmium and lead and their chlorides toward formation of PCDDs and PCDFs is not known at present. However,  $\text{CdS}$  and  $\text{PbS}$  are unlikely as catalysts. Control of cadmium and lead emissions by carbonate species does not appear to be feasible.

## 5. CONCLUSIONS AND RECOMMENDATIONS

Insight into the sources of cadmium and lead in BMWS was gained through the literature review and elemental analysis of bio-medical waste samples by PIXE and XRF. Thermodynamic equilibrium calculations of partitioning behaviour indicated that chemical forms of cadmium and lead are highly dependent on local chemical and environmental conditions.

### SOURCES OF CADMIUM

Several likely sources of cadmium were determined from the literature review. The primary source of cadmium in municipal waste streams is plastics, particularly PVC. A class of heat and light stabilizers are made from salts of cadmium and organic acids. Additionally, cadmium compounds exhibit a range of colors (from yellow to deep maroon) and are non-bleeding and alkali resistant. These compounds are found as pigments in a variety of plastic and paper products.

Because plastics are responsible for the majority of cadmium in MWS, and the plastic content in BMWS is from 3 to 10 times as great as in MWS, plastics are a likely source of the elevated cadmium emissions from BMWI. A cross section of potential cadmium-containing plastic products from a hospital was subjected to an elemental analysis by PIXE and XRF. Cadmium was not positively identified by either method in any plastic sample.

Two PVC samples were analyzed: a slide cover by PIXE and IV tubing by XRF. Neither sample was shown to contain cadmium. A hypodermic needle was also tested by XRF and cadmium was not found. Disposable alkaline batteries probably contain cadmium as an impurity in their zinc casing. The

presence of a small concentration of cadmium relative to zinc in the casing of a battery from a disposable penlight was detected by XRF.

### **SOURCES OF LEAD**

The literature review yielded several likely sources of lead in bio-medical waste: Stabilizers and pigments in plastics, and as pigments in paper and inks. Lead stabilizers (salts of lead and organic acids) are used in electrical cable insulation and rigid extruded PVC such as pipe. However, cable insulation and piping are not consistent components of the BMWS. Most lead in bio-medical plastics should be found as pigments, with colors ranging from yellow and orange to green.

The presence of lead in several plastic items was indicated in elemental analyses by PIXE and XRF. Lead was found in a yellow linen bag, yellow bedpan and red Sharps-tainer® by PIXE. Lead was detected in a red infectious waste bag, yellow bedpan, yellow linen bag and yellow top to a urine container. It appears that lead is used as a pigment in a variety of yellow and red plastics. Lead may also be present in uncolored plastics, as evidenced by its presence in a transparent PVC slide holder. Lead was not observed in the hypodermic needle, IV tubing or alkaline battery by XRF analysis. Additionally, PIXE analysis of newsprint and photocopy inks were not shown to contain lead.

### **THERMODYNAMIC EQUILIBRIUM ANALYSIS CONCLUSIONS**

Reactions with chlorine and sulfur determined the partitioning of cadmium and lead. Cadmium sulfide and  $PbCl_2$  were dominant in reducing (carbon and hydrogen rich) environments. Cadmium chloride and  $PbSO_4$  dominated in oxidizing (oxygen rich) environments. Under no chlorine conditions (ratio 1:4:0), CdS and PbS dominated the reducing environment.

Under oxidizing conditions  $\text{CdCO}_3$  dominated below 550 K,  $\text{CdO}$  dominated from 550 to 900 K, atomic Cd dominated above 900 K, and  $\text{PbSO}_4$  dominated across the entire temperature range. Under no sulfur conditions,  $\text{CdCl}_2$  and  $\text{PbCl}_2$  dominated both reducing and oxidizing environments.

## RECOMMENDATIONS

Elevated concentrations of cadmium and lead in the stack gas of BMWI pose a potentially significant health risk to the adjacent community. Possible catalytic mechanisms of cadmium and lead in the formation of PCDD and PCDF serve to strengthen the necessity of reducing inputs of these metals to BMWI. To reduce inputs (and lower stack gas concentrations) of cadmium and lead to BMWIs, the bio-medical industry should implement the following recommendations:

1. Reduce or eliminate the use of cadmium and lead as heat and light stabilizers in all plastic disposables likely to reach the bio-medical waste stream (BMWS). Calcium/zinc, organo-tin, or some other stabilizers should be substituted for cadmium and lead.
2. Reduce or eliminate the use of cadmium and lead as pigments in disposable plastic and paper products which are likely to reach the BMWS. Yellow bedpans (and similar items), urine containers and bags, and red Sharps-tainers<sup>®</sup> and bags contain lead.

Individual facilities can reduce emissions of lead, and possibly cadmium, by taking the following steps:

1. Reduce or eliminate the use of disposable yellow and red plastics.
2. The American Hospital Association should require manufacturers to certify that items produced do not contain metals known to be toxic.

Individual facilities can reduce emissions of cadmium by educating personnel to not discard penlights or other batteries into the BMWS.

Development of operating procedures : . BMWIs which limit emissions of cadmium and lead may be possible. Addition of sulfur and/or sulfate may help to sequester cadmium and lead in less volatile or biologically available forms. Control of local environments (reducing or oxidizing) is difficult at best, and probably would not be an efficient means of reducing emissions. Addition of sulfur to control emissions of cadmium from controlled air BMWIs is not a viable option. The concomitant sulfur emissions would pose air pollution and additional corrosion problems. Nevertheless, CdS is non-volatile and might prevent concentration of cadmium on fly ash. It is also relatively insoluble and its uptake through the lungs may be lower than other forms of cadmium.

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**APPENDIXES**

**APPENDIX A**  
**Results of PIXE Analysis**

MC DAVIS PIXE ANALYSIS

CROCKER NUCLEAR LABORATORY

PROCESS FILE NUMBER- 913 DESCRIPTION- MEDICAL BURNING; HICKMAN CE  
 UNITS- NANOGRAMS PER CM<sup>2</sup> SITE- PAPER1

June, 1988

ID SAMPLE CODE	MA	MF	LR	MC	MT	H	NA	HG	AL	SI	P	S	CL	K
24 REDBAG	0.0	0.0	0.0	0.0	0.0	0.0	-301.9	-109.0	310.2	-49.0	-56.9	255.5	-49.5	-43.9
25 REDBAG	0.0	0.0	0.0	0.0	0.0	0.0	-434.4	-170.0	1476.0	2609.0	-103.4	1443.9	589.3	519.2
26 BROWN	0.0	0.0	0.0	0.0	0.0	0.0	-1033.1	-401.3	-252.8	5043.8	-261.7	-221.0	-257.6	1667.8
27 BEIGE	0.0	0.0	0.0	0.0	0.0	0.0	-1062.7	-414.7	-252.4	3846.9	-250.6	2585.3	1784.8	-234.0
28 YEL LIN	0.0	0.0	0.0	0.0	0.0	0.0	-552.5	-210.3	-128.2	4156.2	-125.6	-102.2	-113.6	-100.0
29 A CLAVE	0.0	0.0	0.0	0.0	0.0	0.0	-500.8	-200.4	-124.7	760.2	487.3	330.8	345.2	305.9
30 A CLAVE	0.0	0.0	0.0	0.0	0.0	0.0	-622.0	-254.2	-160.6	-133.5	-163.3	5196.2	-151.3	208.4
31 GLOVE	0.0	0.0	0.0	0.0	0.0	0.0	-1926.3	-835.1	-600.4	-556.2211814.1205941.7			-775.0	-724.9
32 BL COPY	0.0	0.0	0.0	0.0	0.0	0.0	-842.6	-351.7	-229.7	-197.1	1997.2	-279.8	-229.6	2330.2
33 POLY	0.0	0.0	0.0	0.0	0.0	0.0	1617.0	-124.2	-72.9	-57.1	-66.7	218.3	107.7	-50.6
34 LATEX	0.0	0.0	0.0	0.0	0.0	0.0	-1047.4	-427.1	-272.1	-228.8	-281.7	31986.9	-266.3	18848.1
35 GLPKG	0.0	0.0	0.0	0.0	0.0	0.0	-726.1	-301.1	-193.1	-167.1	856.0	-162.3	-182.0	1361.6
36 SL COVER	0.0	0.0	0.0	0.0	0.0	0.0	-24307.2	-10286.1	-6914.3	-5989.1	-7703.3	-6578.5	*****	-6739.2
37 PAPER	0.0	0.0	0.0	0.0	0.0	0.0	-689.0	-272.6	702.3	1152.1	1389.1	445.9	377.5	-144.1

ID SAMPLE CODE	CA	BA	TI	V	CR	MN	FE	CO	NI	CU	ZN	PT	AU	HG
34 REDBAG	-36.9	0.0	25.8	79.3	-31.4	-30.7	6234.6	-10.9	-8.7	9.8	-5.1	-12.0	9.8	-11.0
35 REDBAG	3666.2	0.0	271.5	75.6	-58.9	-58.1	25155.8	-22.5	-18.0	-13.6	-10.2	-23.9	-21.8	-22.3
36 BROWN	15913.0	0.0	-189.4	-190.4	434.7	-166.5	91632.8	-63.3	-49.0	29.9	-27.2	-62.6	-57.2	-57.8
37 BEIGE	13362.4	0.0123853.6	8197.1	-164.1	-137.9	56544.6		-53.7	-43.1	-33.1	66.4	-61.9	-55.1	-56.1
38 YEL LIN	269.9	0.0	4863.4	509.5	5611.0	-61.0	-25.6	-21.7	-17.4	-13.4	412.7	-29.1	-29.7	-32.7
39 A CLAVE	-82.8	0.0	-64.5	-63.0	-54.1	-47.3	-14.9	-12.7	-10.1	4.4	-5.7	-13.2	-12.0	-12.1
40 A CLAVE	363.0	0.0	-102.1	-101.6	-88.1	-72.8	46.5	-20.6	-16.3	-12.4	-9.4	-22.2	-20.1	-21.0
41 GLOVE	-596.0	0.0	-457.0	2962.5	-402.8	-353.8	542.7	-26.5	-22.2	131.9	480.7	-48.4	-47.9	-51.4
42 BL COPY	-203.2	0.0	-171.3	-164.6	-133.6	-116.1	3268.1	-28.6	23.6	18.7	407.2	232.7	-28.4	-28.7
43 POLY	-42.6	0.0	-33.1	56.2	-27.6	-24.2	63.5	-8.0	-6.4	14.7	-3.8	-8.8	-8.0	-8.1
44 LI	6892.0	0.0	-160.4	388.9	-118.7	-99.9	-60.5	84.3	-41.7	-33.5	81031.3	-81.4	-73.0	-73.4
45 GLPKG	-148.4	0.0	-120.4	-115.9	-94.7	-81.1	467.3	-24.7	-19.8	1082.8	-11.6	60.1	-24.7	-25.1
46 SL COVER	8772.4	0.0	88987.1	-5140.0	-4660.5	-4098.6	-493.5	-436.0	-372.0	1418.8	2738.4	-845.9	-844.9	-939.2
47 PAPER	-122.4	0.0	-96.3	-90.9	-75.0	-62.4	168.0	17.9	55.9	45.6	76.7	71.3	-21.5	-21.7

ID SAMPLE CODE	AS	PB	SE	BR	RB	SR	Y	ZR	MO
4 REDBAG	-3.1	244.5	-2.7	-2.9	45.8	119.3	0.0	-1.9	-1.5
5 REDBAG	-6.4	-19.3	-5.5	-5.7	-7.0	146.1	0.0	-7.4	-8.7
6 BROWN	-16.1	-48.8	-15.0	-13.1	0.0	0.0	0.0	0.0	0.0
7 BEIGE	-16.3	-49.4	-15.0	-18.5	-14.3	0.0	0.0	0.0	0.0
8 YEL LIN	-11.2	39113.8	149.9	-14.5	-15.2	-7.3	0.0	-6.0	-4.5
9 A CLAVE	-3.5	63.8	-3.0	-3.1	-3.8	-3.4	0.0	-3.5	-4.0
10 A CLAVE	-6.7	16342.5	89.0	-7.7	-7.8	-6.1	0.0	168.1	865.7
11 GLOVE	-16.0	-48.4	-14.9	189.8	38.8	192.5	0.0	-7.9	-9.3
12 BL COPY	-8.3	84.1	-7.0	-7.4	-9.5	59.3	0.0	88.7	-10.3
13 POLY	-2.3	-7.0	-2.0	-2.1	-2.5	-2.3	0.0	-2.5	-3.0
14 LATEX	-16.4	-49.7	-13.7	-16.8	-13.0	0.0	0.0	0.0	0.0
15 GLPKG	-7.2	-21.9	-6.1	-6.6	-7.7	-7.0	0.0	-7.6	407.3
16 SL COVER	-285.4	47874.8	401.6	-295.5	-310.1	-237.7	0.0	0.0	0.0
17 PAPER	-6.3	-19.1	-5.3	-5.8	-7.7	-6.8	0.0	-8.3	-9.8

C DAVIS PIXE ANALYSIS

CROCKER NUCLEAR LABORATORY

PROCESS FILE NUMBER= 91006 DESCRIPTION= HICKMAN HOSPITAL INCINERATOR STUDY  
 UNITS= NANOGRAMS PER CM\*\*2 SITE= ASGL1

July, 1988

D	SAMPLE CODE	MA	MF	LR	MC	MT	H	NA	MG	AL	SI	P	S	CL	K
2	HOS-N-TUBE	0.0	0.0	0.0	0.0	0.0	0.0	21205.0	-594.5	7511.5	17842.7	-481.6	20939.5	53583.6	29321.0
3	HP YTR	0.0	0.0	0.0	0.0	0.0	0.0	6009.8	-580.3	31611.5	42122.1	-418.8	31776.5	-376.1	56085.1
4	YLW BEDPAN	0.0	0.0	0.0	0.0	0.0	0.0	-352.1	-159.4	-116.7	781.2	-127.2	-109.8	-125.9	350.3
5	SHARP CONT	0.0	0.0	0.0	0.0	0.0	0.0	-559.1	-258.3	-192.9	2100.1	1979.3	-191.6	384.4	-199.7
6	HYPO TOP	0.0	0.0	0.0	0.0	0.0	0.0	-762.6	-330.8	-238.4	5703.0	2444.6	1890.4	-272.8	-235.1
7	YLW BEDPAN	0.0	0.0	0.0	0.0	0.0	0.0	-2037.3	-849.3	-582.3	-516.1	-685.9	-616.2	2618.7	860.6
8	SHARP CONT	0.0	0.0	0.0	0.0	0.0	0.0	-407.0	954.6	-138.9	-122.0	1430.4	147.9	391.4	906.1
9	SHARP CONT	0.0	0.0	0.0	0.0	0.0	0.0	-5806.5	19708.0	-1674.8	67662.7	-1890.1	32701.0	17897.1	11763.5
0	SHARP CONT	0.0	0.0	0.0	0.0	0.0	0.0	-635.4	1628.9	-211.9	4372.1	1659.4	993.0	1452.4	2605.8
1	ASB GLOVE	0.0	0.0	0.0	0.0	0.0	0.0	-133.6	3689.7	-38.7	4327.8	-39.0	1633.8	91.9	142.4

D	SAMPLE CODE	CA	BA	TI	V	CR	MN	FE	CO	NI	CU	ZN	PT	AU	HG
2	HOS-N-TUBE	14794.2	0.0	10514.3	-246.9	-221.0	430.7	75190.6	-103.0	-83.6	8198.8	58943.6	-216.7	-210.6	-216.4
3	HOS-ENTR	57221.8	0.0	44817.3	4959.2	-209.2	747.7	13852.9	-73.9	-61.5	3612.2	48984.2	-158.0	-155.4	-161.1
4	YLW BEDPAN	269.0	0.0	10577.0	1853.8	1340.9	-62.1	119.0	-19.8	-15.8	-12.0	584.7	-25.6	-24.5	-25.1
5	SHARP CONT	-180.4	0.0	2273.4	-150.9	201.1	-118.3	59072.3	-78.8	-61.3	809.6	1774.2	-69.6	-81.0	-78.2
6	HYPO TOP	-210.0	0.0	-166.9	467.4	-141.3	186.8	997.4	-54.3	17.8	117.1	3953.6	-64.3	-58.4	-56.1
7	YLW BEDPAN	1932.1	0.0106948.5	16568.2	10890.3	-422.6	4595.9	-128.5	-101.2	471.1	7007.5	-178.1	-171.9	-178.0	
8	SHARP CONT	1282.3	0.0	1459.9	-101.1	-88.6	71.8	41241.4	-52.2	-40.8	57.8	1297.1	-58.9	-53.5	-51.5
9	SHARP CONT	17272.0	0.0	13306.8	1157.0	1521.2	-1083.4478880.8	-671.6	-637.3	1350.7	13510.4	-1896.0	-1923.5	-2062.8	
0	SHARP CONT	3004.5	0.0	2961.1	202.4	-131.2	143.6	57869.5	-82.5	-64.8	122.2	1876.8	-93.4	-84.7	-81.0
1	ASB GLOVE	175.4	0.0	-16.9	-16.9	27.9	-12.8	594.7	-7.3	67.4	29.8	79.7	-9.8	24.9	-8.3

D	SAMPLE CODE	AS	PB	SE	BR	RB	SR	Y	ZR	MO
2	HOS-N-TUBE	-69.0	39617.1	-64.4	1158.8	-57.6	-30.8	0.0	0.0	0.0
3	HOS-ENTR	-50.9	50677.6	87.3	-54.1	-60.6	678.9	0.0	-31.5	0.0
4	YLW BEDPAN	-8.0	14267.2	49.1	-9.4	-10.9	-8.0	0.0	85.0	0.0
5	SHARP CONT	-22.2	154.3	-20.5	-22.8	-30.3	-27.6	0.0	-31.6	0.0
6	HYPO TOP	-16.2	-48.7	26.3	-16.2	15.0	-20.0	0.0	-23.1	0.0
7	YLW BEDPAN	-57.3121970.6	-58.2	-67.3	-75.6	-68.0	0.0	-61.4	0.0	
8	SHARP CONT	-14.7	44.2	60.0	-14.7	-19.3	-17.8	0.0	-21.3	0.0
9	SHARP CONT	-664.3	1148.9	1712.4	-708.4	-752.6	-614.9	0.0	-337.0	0.0
0	SHARP CONT	-23.1	150.2	102.2	-23.8	-30.5	-26.5	0.0	1123.5	0.0
1	ASB GLOVE	-2.2	30.5	87.4	-2.2	-2.9	-2.7	0.0	-3.5	0.0

MC ANALYSIS FIVE ANALYSIS

ROCKEY NUCLEAR LABORATORY

PROCESS FILE NUMBER- 99001 DESCRIPTION- CHWAG-HICKMAN UCD CIVIL ENGR--OPTIMIZE FOR CAIUMIUM September, 1988  
 UNITS- NANOGRAMS PER GMS SITE-

ID SAMPLE CODE	NA	NF	LR	NC	NT	H	HA	HG	AL	SI	P	S	CL	K
1 H E INSIDE	0.0	0.0	0.0	0.0	0.0	0.0	4398.4	-243.4	2122.1	4106.8	-194.1	4180.5	11346.7	7360.0
2 H E ENTRAM	0.0	0.0	0.0	0.0	0.0	0.0	4693.3	-393.4	18199.6	23085.9	-269.9	18120.0	3352.6	33560.0
3 SAMPLE	3	0.0	0.0	0.0	0.0	0.0	-840.5	-346.9	-242.7	-222.1	-289.7	-260.1	773.1	918.5
4 SMOKE	6	0.0	0.0	0.0	0.0	0.0	-1317.4	5987.9	-372.6	12957.3	-425.8	6748.2	3118.4	3433.5

ID SAMPLE CODE	CA	NA	TI	V	CR	MN	FE	CU	NI	CO	ZN	PT	MI	HM
1 H E INSIDE	3219.5	0.0	2262.6	273.3	-98.3	-96.9	10334.8	-25.6	-21.0	972.3	6779.2	-46.8	-47.4	-52.0
2 H E ENTRAM	34368.3	0.0	25266.3	2436.5	-159.4	642.3	7912.3	-61.1	-50.7	2437.9	31254.3	-118.3	-120.3	-151.6
3 SAMPLE	3	885.7	0.0	32571.0	7263.1	4872.6	-190.8	695.3	-63.7	-51.3	146.7	1517.5	-84.9	-83.3
4 SMOKE	6	4289.7	0.0	3231.0	-323.5	479.7	-248.5	34513.3	-95.8	-76.7	189.9	1159.1	-110.3	-104.3

ID SAMPLE CODE	AS	PB	SE	BR	RB	SR	Y	ZR	HD	CD	AG	TE	
1 H E INSIDE	-16.5	4890.1	-14.8	242.0	-14.0	-15.5	-18.0	-21.6	-33.5	-97.1	-79.4	0.0	
2 H E ENTRAM	-42.1	31369.0	82.1	-45.5	-54.0	-50.9	-47.5	715.8	-54.8	2794.4	-122.2	0.0	
3 SAMPLE	3	-28.7	27096.4	135.0	-35.2	-38.5	-36.7	-35.8	-43.0	-64.2	140.5	-153.5	0.0
4 SMOKE	6	-32.7	1080.2	171.9	-34.2	240.9	-61.7	-55.4	-53.9	0.0	-110.2	0.0	0.0

yellow halpen  
sharps-tanner

**APPENDIX B**  
**Results of XRF Analysis**

X-RAY FLUORESCENCE  
Operator: Dr. Ken Severin

Sample Identification	Presence of ?				
	Cd	Pb	Fe	Zn	Ti
Date: October 20, 1988					
Yellow Bedpan	no	yes			
Red Infectious Waste Bag	no	yes	yes		
Yellow Linen Bag	no	yes			maybe
Alkaline Battery	yes	no		yes	
Hypodermic Needle	no	no	yes	yes	
Yellow Cap of Urine Container	no	yes			yes
Red Sharps-tainer®	no	no	yes		
Biege Bag	no	no	yes		yes
Autoclave Bag	no	yes			
Ash from Entrance to Heat Exch.	yes	yes		yes	
Ash from Inside Heat Exchanger	yes	yes	yes	yes	yes
Date: December 12, 1988					
Light Blue Cover of Injection Point	no	no			yes
IV Tubing	no	no		maybe	
Blue Box Material	no	no		yes	
White Box Material	no	no	yes		yes
Cut IV Tubing	no	no		maybe	