Evaluation of the Public Health Risks Associated with Semivolatile Metal and Dioxin Emissions from Hazardous Waste Incinerators

by Richard M. Sedman* and John R. Esparza*

The public health impacts associated with stack emissions from hazardous waste incinerators have become a major concern in recent years. Most evaluations of incinerator stack emissions have focused on three classes of compounds: metals, semivolatile, and volatile compounds. These investigations have been complicated by the difficulty and expense of analyzing the emissions and the limited amount of toxicity information for many of the compounds that have been detected.

The results of over 20 trial burns at hazardous waste incinerators were assembled in an attempt to determine which compounds may pose a significant threat to the public health. The risks associated with semivolatile emissions were found to be inconsequential, although further study of dioxins and dibenzofurans emissions appears to be warranted. The risk associated with the emission of cadmium and perhaps chromium (VI) may pose a significant risk to public health at certain facilities. Controls on waste feed or air pollution control devices should be employed to reduce the emission of these metals. Any monitoring of metal emissions from hazardous waste incinerators should focus on cadmium and chromium (VI).

Introduction

Hazardous waste disposal practices have undergone major changes during the past decade. As new Federal and State statutes have become effective, the disposal of hazardous wastes into unsecured landfills has been curtailed (1,2). These new statutes have mandated many changes in hazardous waste disposal practices (3,4). Within a few years, the disposal of most types of hazardous wastes to any landfill will be virtually prohibited unless the wastes have been suitably treated. Only the residuals from an accepted waste treatment process will be permitted to be disposed of into a hazardous waste landfill.

The new Federal and State hazardous waste treatment standards provide for what constitutes an acceptable waste treatment practice (5,6). These standards designate either a minimum level of treatment or a specific technology that must be employed to treat each class of hazardous waste. Both Federal and California treatment standards are based primarily on the best demonstrated available technology that can be employed to treat the waste.

Incineration is a very effective technology for destroying organic wastes (7-9). Federal regulations require that hazardous waste incinerators achieve a minimum of 99.99% destruction and removal efficiency (10). Facilities that process certain wastes containing polychlorinated dibenzodioxins are required to achieve a 99.9999% destruction efficiency (10).

Even efficient hazardous waste incinerators emit small quantities of organic compounds from the stack (7,11-14). Organic compounds in stack emissions are usually attributed to three sources: uncombusted wastes and fuel, waste or fuel constituents that are only partially combusted, and compounds formed due to chemical reactions occurring during the combustion process. While only a small portion of thermally stable organic compounds survive the combustion process, the metallic components of hazardous wastes are not susceptible to thermal destruction. Metals can be oxidized and transformed.

Compounds emitted from the stack that have resulted from fragments or the recombination of fragments produced from waste or auxiliary fuel constituents are known as products of incomplete combustion (PICs). They include the polychlorinated dibenzodioxins (PCDDs) and dibenzofurans (PCDFs). The PCDDs and PCDFs are two classes of compounds that have received considerable public attention in recent years. The notoriety associated with these substances stems from animal bioassays that demonstrate that these compounds are potent carcinogens and reproductive toxicants (15-17). PCDDs and PCDFs have been detected in the emissions from certain types of incinerators (7).

Trial Burns

Federal, State, and local statutes and regulations govern permitting hazardous waste incinerators in California (18-20).
number of requirements are stipulated before a permit is issued to operate a hazardous waste incinerator. Trial burns are usually conducted at facilities to determine the incinerator’s efficiency in destroying certain designated constituents, the principal organic hazardous constituents, in a waste stream.

During a trial burn, a representative waste, which is often augmented with thermally stable compounds, is processed under normal operating conditions. Samples of the waste, emissions from the stack, and perhaps ash and air pollution control equipment blowdown streams are collected and analyzed to determine the levels of the designated constituents of concern. Using the results of the trial burn, the efficiency of the incinerator is determined by comparing the amount of a principal organic hazardous constituent that is emitted from the stack with the amount processed during the trial burn.

Of late, the results of trial burns have also been employed to evaluate the impact of incineras on public health (21,22). The emission rates of various constituents of concern are monitored during a trial burn. Air dispersion modeling is employed to estimate the impact of the incinerator’s emissions on ambient air adjacent to the facility. Dose-response relationships are then employed to evaluate the public health impacts associated with the stack emissions.

Semivolatile Compounds and Metals

As the number of trial burns at different facilities has increased, more information has become available that can be employed to delineate which toxic constituents emitted from an incinerator’s stack pose a substantial threat to the public health. This report will evaluate the potential impact on public health associated with the emissions of metals and semivolatile compounds from the stacks of hazardous waste incineras.

Methods

Facilities

Trial burns representing a wide range of incineras technology were included in this study. The emissions of metals and semivolatile compounds from five liquid injection incinerators, five liquid injection/rotary kilns, two rotary kilns, one fixed hearth, two fluidized bed incinerators, and six industrial boilers, a cement kiln, and an aggregate kiln were evaluated for potential impact on the public health (Table 1). Volatile emissions from these facilities were evaluated separately in a companion study (23). Descriptions of the waste feeds used and the air pollution control equipment associated with the incinerators that were the subject of a trial burn are found in Table 1.

Stack Sampling and Analytical Procedures

Since the results of many independent studies were used, the analytical procedures employed varied at the different facilities. However, stack gases were sampled for metals, dioxins, and semivolatile compounds using a similar procedure, a modified method 5 sampling train (MM5). Using a modification of EPA method 5 sampling train, stack gases are drawn through a series of filters and XAD-2 resin traps. Semivolatile constituents were determined in the various studies using gas chromatography/mass spectrometry methods. The levels of metals in particulates captured by filters were determined using inductively coupled argon plasma, atomic absorption, or visible spectroscopy. The emission rates from the stack were then determined, as described previously, from the level of each constituent captured by the MM5 (23).

Air Dispersion Modeling

Using the stack emission rates determined for the various constituents, air dispersion modeling was employed to determine the impact of the facility had it been located at an urban coastal setting or an inland rural location in California. Meteorological data from Los Angeles International Airport (urban) and Edwards Air Force Base (rural) were employed to model the air emissions. The approach employed to model the stack emissions has been previously described (23).

Health-Based Criteria

Criteria developed by the California Department of Health Services or the EPA were employed to evaluate the potential public health impacts associated with the maximum annual average concentration of toxicants in air adjacent to each facility. The compilation and use of the criteria to estimate the cumulative risk associated with the emission of individual compounds has been previously described (23). When available, ambient air criteria were employed to evaluate the risk associated with exposure by the inhalation pathway. Otherwise, a modified drinking water criterion was employed to evaluate the exposure. If more than one criterion was available, the most conservative criterion was employed.

Statistical Analysis

Regression analyses were employed to identify significant correlations between the emission rates of Cd, As, or Cr and the cumulative risk associated with the emission rates of these metals. Statistical analyses were preformed using the SYSTAT statistics software package on an IBM PS/2 model 60 (38).

Results

Semivolatile Compounds

Although many of the waste streams processed by the facilities contained substantial quantities of semivolatile compounds, only low levels of this class of compounds were detected in the stack emissions. Eight carcinogenic semivolatile compounds were identified in the stack emissions from these incinerators (Table 2). Only three carcinogenic semivolatile compounds, benz[a] anthracene, 2,4,6-trichlorophenol, and bis(2-ethylhexyl)phthalate were detected at more than one facility. The risk associated with the emission of these carcinogenic semivolatile compounds appears to be inconsequential (Table 3).

Dioxins and Dibenzo[b,f]furan

Relatively few studies were located where dioxin emissions were monitored at a trial burn. Both the California Department of Health Services dioxin equivalance approach (39) and the EPA approach (40) were employed to ascertain the risk associated
Table 1. Waste feed and air pollution control equipment operating at various trial burns.

| Facility (reference) | Commercial off site | Type of waste feed | Air pollution control device |
|----------------------|---------------------|--------------------|-----------------------------|
| Liquid injection incinerators | | | |
| American Cyanamid (II) | No | Aniline and mononitrobenzene waste | None |
| Mitchell (II) | Yes | Liquid organics and aqueous waste | None |
| EPA research (24) | No | Askarel transformer liquid, solid PCBs wastes | Venturi scrubber followed by packed scrubber, high-efficiency particulate filter and carbon bed absorber |
| Chevron (25) | No | Agricultural chemicals and fuel additives | Quench section followed by a venturi scrubber, knockout chamber and mist eliminator |
| Mobay (26) | No | Aqueous waste feed containing metals | Venturi scrubber followed by packed scrubber and mist eliminator |
| Liquid injection/rotary kiln incinerator | | | |
| SCA Chemical Services 1983 (27) | Yes | Askarel transformer liquid, solid PCBs wastes | Packed scrubber followed by ionizing wet scrubber and celsicle demisters |
| SCA Chemical Services 1988 (28) | Yes | Askarel transformer wastes, PCBs sludge wastes | Same as SCA Chemical Services, 1983 |
| Rollins (29) | Yes | Liquid organic and solids containing organics | Quench section followed by a wet scrubber, packed tower condensers, and a venturi scrubber |
| Du Pont (II) | No | Liquid organic and coke waste | Quench section followed by a cyclone and HCl scrubber system |
| Energy Systems Company (30) | Yes | Liquid and solid RCRA waste, including solid PCBs | Packaged scrubber, followed by mist eliminator |
| Fixed hearth incinerator | | | |
| Trade Waste Incinerator (II) | Yes | Liquid organic and aqueous waste; solids containing chlordane and hexachlorocyclopentadiene | Quench section followed by a venturi scrubber and mist eliminator |
| Aggregate or lime kiln | | | |
| Florida Solite (37) | Yes | Liquid organics including solvents, alcohols, ethers, still bottoms, and chlorinated hydrocarbons | Cyclone section followed by wet scrubbers and a knockout chamber |
| Rockwell (32) | Yes | Waste fuel consisting of solvents, lacquer thinners, alcohols, still bottoms, paint wastes, and chlorinated hydrocarbons | Radiator coolers followed by an eight-module baghouse |
| Boiler | | | |
| Site B (33) | Yes | Oil products waste | None |
| Site C (33) | Yes | Primarily α-methyl styrene dimers and phenolic/benzene residues | None |
| Site D (33) | Yes | Solvents consisting primarily of methanol, toluene, and xylene | None |
| Site E (33) | Yes | Fluxing oil | None |
| Site F (33) | Yes | Purge thinner from the purging of paint spray guns | None |
| Site G (33) | Yes | Highly halogenated organics | Dual scrubbers columns |
| Fluidized bed incinerator | | | |
| Ogden, Alaska (34) | No | PCB-contaminated soil | Addition of limestone for the control of chloride acid gases plus a flue gas cooler, followed by a fabric filter |
| Ogden, California (35) | No | Acid refinery sludge/sand | Identical to Ogden, Alaska |
| Rotary kiln incinerator | | | |
| EPA mobile (36) | No | Dioxin-contaminated soil | Quench section followed by high efficiency filter and alkaline scrubber system |
| EPA pilot (37) | No | Toluene still bottoms | Venturi scrubber followed by packed scrubber, carbon bed filter and high-efficiency particulate filter |

Table 2. Carcinogenic semivolatile compounds detected in incinerator stack emissions.

| Compound | Number of facilities reporting this emission |
|----------|---------------------------------------------|
| bis(2-Ethylhexyl)phthalate | 9 |
| Chrysene | 1 |
| Benzo[a]anthracene | 2 |
| bis(Chloroethyl)ether | 1 |
| 1,4-Dichlorobenzene | 1 |
| 2,4,6-Trichlorophenol | 1 |
| Hexachlorobenzene | 1 |
| Polychlorinated biphenyls | 1 |

with dioxin emissions. Unless information was provided concerning the dioxin congeners, all tetra through hepta forms were assumed to be chlorinated at the 2, 3, 7, and 8 positions. Based on this assumption, a highly conservative estimate of risk was ascertained. At only two of nine incinerators did the risk associated with dioxin emissions exceed the benchmark of $10^{-6}$ risk (Table 3).

**Metals**

Nine facilities were identified where metal emissions were
Table 3. Aggregate risk associated with carcinogenic semivolatile compounds.

| Facility                  | Semivolatiles<sup>a</sup> | DHS method<sup>b</sup> | EPA method<sup>c</sup> |
|---------------------------|---------------------------|------------------------|------------------------|
|                           | Rural/urban               | Rural/urban            | Rural/urban            |
| American Cyanamid         | ND/ND                     | —                      | —                      |
| Du Pont                   | ND/ND                     | —                      | —                      |
| Mitchell                  | 0.00005/0.0001            | —                      | —                      |
| Trade Waste Incinerator   | 0.00005/0.0003            | —                      | —                      |
| Site B                    | ND/ND                     | —                      | —                      |
| Site C                    | 0.0001/0.002              | —                      | —                      |
| Site D                    | 0.0008/0.003              | 0.2/0.8                | 0.03/0.1               |
| Site E                    | 0.0007/0.003              | 0.04/0.1               | 0.004/0.01             |
| Site F                    | 0.00005/0.0002            | —                      | —                      |
| Site G                    | 0.03/0.1                  | —                      | —                      |
| EPA research              | 0.002/0.006               | —                      | —                      |
| Rollins                   | ND/ND                     | —                      | —                      |
| Energy Systems Company    | —                         | 4/30                   | 0.7/4                  |
| SCA Chemical Services, 1983 | 0.0/0.05                | 4/20                   | 0.4/2                  |
| SCA Chemical Services, 1988 | 20/60                  | —                      | 2/7                    |
| Ogden (Alaska)            | 0.0002/0.001              | 0.04/0.2               | 0.004/0.01             |
| Ogden (California)        | ND/ND                     | —                      | —                      |

<sup>a</sup>Risk associated with semivolatile compounds excluding dioxins and dibenzofurans.
<sup>b</sup>Estimate based on California Department of Health Services dioxin equivalence method.
<sup>c</sup>Estimate based on EPA equivalence method.
<sup>d</sup>Results based on air dispersion modeling using meteorological data from Edwards Air Force Base.
<sup>e</sup>Results based on air dispersion modeling using meteorological data from the Lennos air station (Los Angeles Airport).
<sup>f</sup>ND, not detected.
<sup>g</sup>No analysis for these constituents.
<sup>h</sup>Risk ($\times 10^{-6}$).

monitored during the course of a trial burn. Four carcinogenic metals were detected in the emissions from these facilities. The maximum risk associated with the stack emissions ranged from $400 \times 10^{-6}$ to $0.2 \times 10^{-6}$ (Table 4). Cadmium and chromium were responsible for virtually all of the carcinogen risk associated with metal emissions at these facilities (Table 4).

Only the hexavalent form of chromium is considered to exhibit carcinogenic activity. Since only total chromium was measured in the stack emissions, the evaluation employed the highly conservative assumption that all the chromium emitted from the stack is in the hexavalent form. The actual risk associated with exposure to this metal is probably considerably lower than that displayed in Table 4.

The emissions of cadmium, chromium, and arsenic were evaluated to identify correlations with the cumulative risk associated with metal emissions. Cadmium emissions strongly correlated with metal emissions, with a coefficient of determination ($r^2$) of 0.98 (Fig. 1). Arsenic and chromium did not significantly correlate with the cumulative risk associated with metal emissions (data not shown).

Other noncarcinogenic metals were also evaluated to determine if they pose a significant threat to the public health. Exposure to lead and mercury occurred only at a fraction of a percent of the applicable ambient air criteria. However, mercury, a volatile metal, was not expected to be effectively sampled by the methods used in these trial burns ($4l$).

Table 4. Risk associated with metals emissions.

| Facility                  | As  | Cd  | Cr  | Be  | Total          |
|---------------------------|-----|-----|-----|-----|----------------|
| American Cyanamid         | ND/ND | 200/400 | —    | 200/400 |
| Du Pont                   | ND/ND | 1/7 | ND/ND | 3/0 |
| Trade Waste Incinerator   | 9/40 | 20/100 | 6/30 | 0.01/0.06 | 40/200 |
| SCA Chemical Services, 1983 | 1/5 | 10/40 | —    | 10/50 |
| rockwell                  | ND/ND | 4/20 | 0.004/0.01 | 4/20 |
| Chevron                   | 0.004/0.02 | 0.07/0.3 | 0.2/0.8 | 0.0001/0.006 | 0.2/1 |
| Ogden (California)        | 0.02/0.06 | 0.1/3  | 0.2/0.4 | —    | 2/6 |
| Mobay                     | 0.08/0.3 | 0.5/1  | 1/4   | —    | 2/6 |
| Florida Solite            | 9/50 | 30/100 | 0.03/0.1 | 30/200 |

<sup>a</sup>No analysis for this metal.
<sup>b</sup>Results expressed as risk ($\times 10^{-6}$) in a rural/urban area. ND, not detected.

![Cadmium Emission Rate (g/min)](image-url)
Discussion

The results of 20 trial burns were evaluated to determine if the emission of semivolatile compounds or metals could be a source of significant risk to the public health. Dioxins and dibenzofurans were evaluated separately from other semivolatile compounds.

Dioxin and Dibenzofurans

Dioxins and dibenzofurans were detected in the stack emissions of five hazardous waste incinerators in this study. Only after employing the highly conservative assumptions that all forms of the tetra through hepta dioxins and dibenzofurans that were detected are chlorinated in the 2, 3, 7, and 8 positions (if not otherwise specified), using the maximum average annual concentration projected by the air dispersion modeling and using the California Department of Health Services equivalency procedure was it demonstrated that the risk associated with these compounds substantially exceeded $10^{-6}$ at two of the facilities. Estimates of risk based on the EPA equivalency approach did not markedly exceed $10^{-6}$ at any facility. Had information been available concerning the actual distribution of the dioxin and dibenzofuran congeners, it is likely that the estimates of risk at all of the facilities would have been much lower.

Much higher levels of dioxin emission have been detected at other types of incinerators (42). However, lower combustion temperatures, less uniform mixing of the wastes, and lower oxygen levels in the combustion chamber are thought to be responsible for the higher level of dioxins detected at these types of incinerators. Although dioxins have been monitored at relatively few facilities, it appears that the monitoring of this class of compounds may be unnecessary at hazardous waste incinerators. Clearly, more studies are needed to determine if the emission of this class of compounds from hazardous waste incinerators can pose a significant threat to public health.

Semivolatile Compounds

Although semivolatile compounds composed a significant portion of the wastes processed during the trial burns, only very low levels of these compounds were detected in stack emissions. Several of these trial burns were conducted specifically to evaluate the combustion of certain semivolatile compounds such as PCBs and pentachlorophenol.

The risk associated with stack emissions of this class of compounds appears to be inconsequential. Semivolatile compounds tend to be less thermally stable than volatile compounds (43). Based on this study, there does not appear to be a need to monitor the emission of semivolatile compounds from hazardous waste incinerators.

Metals

The results of this study demonstrate that the emission of cadmium and perhaps chromium may pose a significant risk to public health near certain hazardous waste incinerators. Based on the extremely conservative assumption that all chromium is in the $6^+$ oxidation state, the cumulative risk associated with the emission of cadmium and chromium substantially exceeded $10^{-6}$ for five of seven facilities. However, only cadmium emissions were found to correlate with the cumulative risk associated with metal emissions.

The highest risk was associated with the American Cyanamid facility, an incinerator with no air pollution equipment. The Trade Waste Incinerator facility produced the next highest risk. The significant amount of sand and gravel processed during the trial burn at this facility probably contributed to the high metal emissions.

The Du Pont, Chevron, and SCA Chemical Services facilities were equipped with air pollution control equipment. Although this equipment did not appear to be a type that is highly efficient in removing Cd, Cr, or As, the lowest risks due to metal emissions were associated with the Du Pont and Chevron incinerators. The air pollution control equipment operating during the SCA Chemical Services 1983 trial burn was not functioning optimally; it was reported that much lower emissions of metals would be anticipated during future operations.

An aggregate and a lime kiln were included this study. While the risk associated with metal emissions from the Rockwell lime facility was relatively low, a relatively higher risk was associated with metal emissions from the Florida Solite incinerator. The operation of a baghouse during the trial burn, an efficient air pollution control device for removing Cd, Cr, and As, probably accounts for the lower risk associated with metal emissions from the Rockwell incinerator. Florida Solite was not equipped with effective air pollution control equipment for particulate emissions.

The emission of metals are governed by the level of metals in the waste feed, the nature of the combustion process, and the type of air pollution equipment operating at the facility. Many of the trial burns processed solid wastes or wastes containing sizable amounts of metals. Only one of these facilities was equipped with an efficient air pollution control device for reducing the emissions of cadmium, chromium, and arsenic (44).

Most of the trial burns were conducted at a time when the emissions of metals were not of particular concern. The level of metal emissions observed in the study may not be representative of facilities equipped with air pollution control devices designed to minimize the emission of particulates. This study is valuable for delineating which metals should be targeted in managing and monitoring the operation of hazardous waste incinerators. The emissions of cadmium and perhaps chromium (VI) should be controlled by managing the types of waste processed by the facility or by installing adequate air pollution control equipment. Any monitoring of metal emissions from these facility should be focused on these metals.

While mercury emissions did not appear to pose a significant threat to the public health, the analytical procedures employed in the trial burns did not appear to be capable of detecting volatile mercury emission. Volatile emissions may compose the major portion the mercury emissions from hazardous waste incinerators. Further studies are necessary to better quantify mercury stack emissions and determine if the emissions can pose a threat to public health.

Efforts to determine which constituents in stack emissions may pose a significant risk to public health prompted a study aimed at identifying which operating conditions are associated with changes in the emission of these compounds (45). The results of over 20 trial burns were included in this study. Few significant correlations between emissions rates and most operating
parameters were identified. This finding is probably due to the inherent differences in facility design, operating conditions, sampling locations, waste feeds, and air pollution control devices, which resulted in high variability in the emissions from the various facilities.

For the incinerators included in this study, the risk associated with volatile emissions correlated with the number of volatile carcinogens evaluated and the heat input of the facility. These results suggest that the size of the facility (as indicated by its heat input) can be correlated with the risk associated with stack emissions. These findings also suggest that the determination of risk associated with volatile emissions is dependent on the number of carcinogenic volatile compounds employed in the assessment.

The only operating parameter that significantly correlated with the risk associated with metal emissions was excess oxygen. This finding could be due to the entrainment of particulates resulting from increases in air flow through the combustion chamber or decreases in the residence time in the air pollution control equipment. Further studies are needed to determine if either mechanism is responsible for the apparent correlation between the risk associated with metal emissions and excess oxygen.

Efforts to construct hazardous waste incinerators are often hampered by public concerns that these facilities pose a substantial risk to public health. The ability to effectively monitor these facilities to ensure that they do not pose a significant risk to public health should aid in addressing these concerns. The routine monitoring of toxic emissions from hazardous waste incinerators is not currently practical due to technical difficulty and the expense of sampling and analysis. Focusing the monitoring on total hydrocarbon emissions and selected metal emissions should facilitate routine stack monitoring.

The authors thank Andrew Ranzieri and Richard Miller of the California Air Resources Board for assistance with the air dispersion modeling; Bill Vance, Julio Salinas, John Hart, Guido Franco, Dick Erickson, Kathryn Barwick, and Bruce La Belle for their valuable suggestions; and Watson Gin and Jan Rudimsky for their valuable support for this project. The views expressed here are not the official policy of the California Department of Health Services.

REFERENCES

1. California Department of Health Services, Toxic Substances Control Division. Alternative Technology for Recycling and Treatment of Hazardous Wastes. California DHS, Sacramento, CA, 1986.

2. California Department of Health Services, Toxic Substances Control Division. Economic Implications of Waste Reduction, Recycling, Treatment and Disposal of Hazardous Wastes. California DHS, Sacramento, CA, 1988.

3. 42 USC Sections 6901 et seq.

4. California Health and Safety Code. Division 20, Chapter 6.5.

5. 40 CFR part 148 et al.

6. Title 22. California Administrative Code articles 30 and 31.

7. Oppelt, E. T. Incineration of hazardous waste. A critical review. J. Air Pollut. Control Assoc. 37: 559-586 (1987).

8. Sittig, M. Incineration of Industrial Hazardous Waste and Sludges. Noyes Data Corporation, Park Ridge, NJ, 1979.

9. Bruner, C. R. Handbook of Hazardous Waste Incineration. Tab Books Inc., Blue Ridge Summit, PA, 1989.

10. 40 CFR 264.343.

11. U.S. Environmental Protection Agency. Performance Evaluation of Full Scale Hazardous Waste Incineration. NTIS PB85-129500, 1984. National Technical Information Service, Springfield, VA.

12. Trenholm, A., Hathaway, R., and Oberacker, D. Products of incomplete combustion from hazardous waste incinerators. In: Incineration and Treatment of Hazardous Waste, Proceedings of the Tenth Annual Research Symposium at Fort Mitchell, Kentucky, April 3-5, 1984. National Technical Information Service, PB85-116291, Springfield, VA, pp. 84-94.

13. Lee, C. C. A model analysis of metal partitioning in a hazardous waste incineration system. J. Air Pollut. Control Assoc. 38: 941-945 (1988).

14. Trenholm, A., and Lee, C. C. Analysis of total mass emission from an incinerator. Nuclear Chem. Waste Manag. 7: 33-36 (1987).

15. National Toxicology Program. Carcinogenesis Bioassay of 2,3,7,8-Tetrachlorodibenzo-p-dioxin in Osborne-Mendel Rats and B6C3F1 Mice (Gavage Study). NTP-80-31, NIH Publication No. 82-1765, NTP, Research Triangle Park, NC, 1982.

16. National Toxicology Program. Bioassay of a Mixture of 1,2,3,7,8,9-Hexachlorodibenzop-dioxins for Possible Carcinogenicity. NCI Trial No. 198, NTP 80-12, DHHS Publication No. (NIH) 80-1754, NTP, Research Triangle Park, NC, 1980.

17. Smith, F. A., Schetz, B. A., and Nitschke, K. P. Teratogenicity of 2,3,7,8-tetrachlorodibenzo-p-dioxin in CF-1 mice. Toxicol. Appl. Pharmacol. 38: 517-523 (1976).

18. Title 22 California Administrative Code, Sections 67450-67418.

19. 40 CFR 264.340 through 264.351.

20. California Health and Safety Code, Section 42300 et seq.

21. Kelly, K. E. Methodology for assessing the health risks of hazardous waste incinerators stack emissions to surrounding populations. Hazard. Waste 1: 507-531 (1984).

22. Taylor, C. C., Cook, C., and Holton, G. A. Health risk assessment for metal emissions from hazardous waste incinerators. In: Proceedings of the 79th Annual Meeting of Air Pollution Control Association, Minneapolis, MN, June 22-27, 1986. Air Pollution Control Association, Pittsburgh, PA, 1986, pp. 2-9.

23. Sedman, R. M., and Esparza, I. R. The evaluation of organic emissions from hazardous waste incinerators. Environ. Health Perspect. 94: 189-190 (1990).

24. Lee, J. W., Backhouse, T. H., and Ross, R. W. PCB Trial Burn for the U.S. EPA Combustion Research Facility Liquid Injection Incineration System. EPA/600/2-87/051, PB87-208799, July, 1987, EPA, Washington, DC.

25. Midwest Research Institute. Trial Results for the Chevron Chemical Company Hazardous Waste Incinerator Richmond, California, Vol. 1, Revision 1. July 18, 1988, MRI.

26. U.S. Environmental Protection Agency, Office of Solid Waste. Measurements of Particulates, Metals, and Organics at a Hazardous Waste Incinerator. Draft Final Report. November 15, 1988, EPA, Washington, DC.

27. Midwest Research Institute. Determination of Destruction of PCBs at SCA Chemical Services, Inc., Chicago Incinerator. Final Report, January 21, 1983, MRI, Kansas City, MO.

28. Midwest Research Institute. TSCA Trial Burn Results for the SCA Incinerator in Chicago II. Final Report, Vol. 1, February 26, 1988, MRI, Kansas City, MO.

29. Alliance Technologies Corporation. Res (TX) Annual Stack Test Program Emission Test Results (EPA) Final Report, February, 1988. Alliance Technologies Corporation, Bedford, MA.

30. Kawahata, M., and Bailey, G. Source Test of the Incinerator Emissions During the RCRA Trial Burn at ENSCO's Facility Located at El Dorado, Arkansas. April 21-23, 1987. Submitted to EPA Region 6, September, 1987, Dallas, TX.

31. Day, D. R., Cox, L. A., and Peters, J. A. Evaluation of Hazardous Waste Incineration in an Aggregate Kiln: Florida Solite Corporation. EPA/600/2-85/030, April, 1985, EPA, Washington, DC.

32. Day, D. R., and Cox, L. A. Evaluation of Hazardous Waste Incineration in a Lime Kiln: Rockwell Lime Company. EPA/600/2-84/132, August, 1984, EPA, Washington, DC.

33. Castaldini, C., Unnasch, S., and Mason, H. B. Engineering Assessment Report Hazardous Waste Co-firing in Industrial Boilers, Vols. 1 and 2. EPA/600/2-84/177b, November, 1984, EPA, Washington, DC.

34. Ogden Environmental Services. Process Demonstration Test Report for Demonstration Test of PCB Contaminated Soils PCB Destruction Unit: Circulating Bed Combustor Unit No. 1. Ogden Environmental Services, Inc., Swanson River, AK, December 14, 1988.

35. Alliance Technologies Corporation. Sampling and Analytical Results for the Preliminary Test Burn Treatability Study of McColl Superfund Waste in Ogden's Circulating Bed Combustor Plant in San Diego, CA. Vols. 1 and 2. Revised Final Report, 1989. Alliance Technologies Corporation, Bedford, MA.
36. Mortersen, H., Sherman, A., Troxler, W., Milled R., and Pfomer C. Destruction of Dioxin-Contaminated Solids and Liquids by Mobile Incineration. EPA/600/2-87/033, May, 1987, EPA, Washington, DC.
37. Ross, R. W., Backhouse, T. H., Vocque, R. H., Lee, J. W., and Waterland, L. R. Pilot-Scale Incineration Test of TCDD-Contaminated Trichlorophenol Production Waste. EPA/600/2-86/121, December, 1986, EPA, Washington, DC.
38. Wilkinson, L. SYSTAT: The System for Statistics. Systat, Inc., Evanston, IL, 1988.
39. California Department of Health Services. Technical Support Document, Report on Chlorinated Dioxins and Dibenzofurans. Part B-Health Effects on Chlorinated Dioxins and Dibenzo-furans. California DHS, Berkeley, CA, 1986.
40. U.S. Environmental Protection Agency. Updating of Toxicity Equivalency Factors for Estimating Risks Associated with Exposures to Mixtures of Chlorinated Dibenzo-p-Dioxins and -Dibenzofurans (CDDs and CDFs).
Draft Report. December, 1988, EPA, Washington, DC.
41. Wallace, D. D., Trenholm, A., and Lance, D. D. Assessment of metal emissions from hazardous waste incinerators. In: Proceedings of the 78 APCA Association Annual Meeting. Detroit, MI, 1985. Air Pollution Control Association, Pittsburgh, PA, 1985, pp. 2–20.
42. U.S. Environmental Protection Agency, Office of Air Quality and Standards. Dioxin Study. Tier 4 Combustion Sources, Project Summary Report. PB 88-877743, EPA, Research Triangle Park, NC, 1987.
43. U.S. Environmental Protection Agency, Office of Research and Development. Guidance on Setting Permit Conditions and Reporting Trial Burn Results. EPA/625/6-89/019, EPA, Washington, DC, 1989.
44. Burning of hazardous waste in boilers and industrial furnaces: supplement to proposed rule. Fed. Reg. 54: 43761 (1989).
45. Esparza, J. R., Mahmood, R. J., and Sedman, R. S. Hazardous waste incineration: a correlation of operating parameters with risk and emission rates. Hazard. Waste, in press.