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April, 1988
Final Report

Report of the Environmental Effects, Transport and Fate Committee

SABEETFC882

Evaluation of Scientific Issues Related to Municipal Waste Combustion

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D C 20460

April 26, 1988

The Honorable Lee M. Thomas
Administrator
U.S. Environmental Protection Agency
401 M. Street, S.W.
Washington, D.C. 20460

OFFICE OF
THE ADMINISTRATOR

Dear Mr. Thomas:

The Municipal Waste Combustion Subcommittee of the Science Advisory Board's Environmental Effects, Transport and Fate Committee has completed its report entitled "Evaluation of Scientific Issues Related to Municipal Waste Combustion". The evaluation was initiated at your request, along with two other charges related to municipal waste combustion, all of which are now complete. The Subcommittee began gathering information in April of 1986 and has achieved consensus on a number of conclusions and recommendations in the intervening time. These findings are summarized below.

The Subcommittee recognizes that regardless of the technologies a society employs to reduce or dispose of municipal waste, there will always be a degree of residual risk to both the public and the environment. Members of the Subcommittee do not attempt to evaluate all of the issues that municipalities must weigh as they consider incineration as a waste management option, but instead strive to inform citizens and decision makers of current risks and uncertainties accompanied by recommendations for increasing knowledge to reduce such risks and uncertainties. The report examines a series of generic scientific issues that policy makers must address in an order that reflects the movement of potential pollutants through and from a municipal waste combustion facility. In particular, such issues as combustor feedstocks; the design and operation of municipal incinerators; the performance of incinerators with various degrees of pollution control equipment; stack emissions; ash disposal; operator training and certification; environmental transport and fate of combustion residues and by-products; pathways to and potential for exposures of humans and ecosystems; and potential public health and environmental effects are addressed.

The Subcommittee concludes that, in general, the performance side of the technology, including design and pollution control, has greatly improved, and is likely to continue to improve. In the Subcommittee's judgment, two critical needs at present are expanded and more rigorous operator training requirements, and

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data collection and analyses aimed at enabling scientists and decision makers to better estimate health and environmental exposures from this technology.

Since technological improvements have created highly efficient stack emission control systems, fly ash with relatively smaller particle size and increased concentrations of pollutants such as heavy metals and trace organics has resulted. The Subcommittee recommends that EPA develop a series of alternative techniques for: 1) analyzing ash samples and the compounds present in ash extracts; 2) assessing the toxic potential of ash; and 3) managing ash disposal.

The Subcommittee also recommends that the potential for health and environmental effects be addressed by developing a more comprehensive data base through field studies. Little information is presently available on the fate of chemicals from MWC facilities, and information is needed to estimate deposition of particulate and gaseous emissions, to model transport and diffusions operations, and to understand environmental transformation and dispersal of technology by-products that may pose risk.

Finally, the Subcommittee recommends that EPA assist local decision makers and the public by developing ways to collect and analyze data that will allow more informed choices regarding the management of municipal solid waste. Approaches should be developed for assessing exposure and risk and these tools should be transferred to the parties responsible for making the decisions. Appropriate tools may include guidance for evaluating waste management options, and means for comparing exposure and risk between available options.

The Subcommittee appreciates the opportunity to conduct this scientific review. We request that the Agency formally respond to the scientific advice transmitted in the attached report.

Sincerely,

Norton Nelson, Chairman
Executive Committee
Science Advisory Board

Rolf Hartung, Chairman
Municipal Waste
Combustion Subcommittee

Enc, cc: A. James Barnes
J. Winston Porter
Vaun Newill
Donald E. Barnes

SAB-EETFC-88-25

EVALUATION OF SCIENTIFIC ISSUES RELATED TO MUNICIPAL WASTE COMBUSTION

REPORT OF THE MUNICIPAL WASTE COMBUSTION SUBCOMMITTEE ENVIRONMENTAL EFFECTS, TRANSPORT AND FATE COMMITTEE

SCIENCE ADVISORY BOARD
U.S. ENVIRONMENTAL PROTECTION AGENCY

APRIL 1988

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I. EXECUTIVE SUMMARY

The present problem of safely disposing of municipal solid waste (MSW) stems from practices of modern industrial society that emphasize storage of wastes over disposal methods that destroy wastes or minimize them at the source. Regardless of which technologies a society uses to reduce or otherwise dispose of municipal solid wastes, there will always be a degree of residual risk to the public and the environment. Incineration offers particular environmental advantages and disadvantages as a waste disposal option, and may be applied as a technology with varying degrees of safety and effectiveness. Safe and effective application requires well designed plants, state-of-the-art pollution control equipment and appropriately skilled operating personnel.

Because different technological options exist for municipal waste disposal, EPA has an important task -- prior to establishing a comprehensive strategy for regulating municipal waste combustion -- to generate and evaluate data, and develop methodologies, for assessing the relative risks resulting from incineration and other municipal waste disposal processes. EPA needs to perform this task to enable citizens, scientists and public officials to compare risks across various environmental media for each waste disposal and management option. Such comparative analysis can provide the technical basis for choosing among technological options.

Communities must evaluate available technological alternatives for waste disposal and choose the technology (or combination of technologies) that presents acceptable levels of public health and environmental risk. Given the local differences in waste composition, available landfill capacity, urban and rural locations, population density, cost, and other factors, no single disposal technology is likely to be uniformly efficient or safe in all regions of the country. Thus, the overall goal, for individual communities and for society in

general, is to choose the particular technological option(s) that is both cost-effective and presents the least risk to the population and the environment.

The Municipal Waste Combustion Subcommittee of the Environmental Effects, Transport and Fate Committee of the Science Advisory Board has evaluated a series of technical issues related to the performance of waste combustion technologies. It has examined, in particular, such issues as combustor feedstocks; the design and operation of municipal incinerators; the performance of incinerators with various degrees of pollution control equipment; stack emissions; ash disposal; operator training and certification; environmental transport and fate of combustion residues and by-products; pathways to and potential for exposures of humans and ecosystems; and potential public health and environmental effects.

Evaluating the human health and environmental impacts of municipal waste combustion is a difficult task. This is true for a number of reasons including: 1) difficulty in identifying and/or obtaining a representative or "average" sample of municipal waste; 2) variability in the conditions of combustion; 3) limited information on the identity of emitted compounds; 4) lack of validation of transport and fate models; 5) the relative lack of data on the environmental loadings contributed by incinerators compared to other combustion sources (including coal and oil fired power plants, automobiles, and wood stoves and fireplaces); and 6) large uncertainties in estimating human health and environmental effects from municipal incineration in comparison to other combustion sources.

In evaluating the issues identified above, the Subcommittee has reached the following major conclusions and recommendations:

A. Municipal Waste Combustion: Process and Technology

o Municipal solid waste (MSW) is heterogeneous in composition. MSW composition is heavily dependent on location, time of year and patterns of consumption. Even simple constituents such as moisture content may fluctuate widely. Because of the inherent variability of the MSW feedstock, it is difficult to predict the composition of stack emissions that may result from combustion. Wide variations in feedstock composition can affect combustion conditions in the incinerator furnaces, and can cause cycles of poor combustion. Poor combustion conditions have a direct impact on emissions. It is important to design incinerators with state-of-the-art features that will provide operators with the ability to accommodate wide variations in feedstock composition to reduce the potential for poor combustion and increased emissions.

o Organic materials containing only carbon and hydrogen are completely combusted or burned in an oxygen-containing atmosphere theoretically producing water vapor and carbon dioxide as the products of combustion. Municipal solid waste, however, is not composed entirely of organic materials or carbon and hydrogen, and, therefore, many other products of combustion are released to the environment. In addition, combustion is not always complete, resulting in release of products of incomplete combustion (PIC). Proper or complete combustion depends not only on sufficiently elevated temperatures but also on the residence time needed for the materials to burn fully, and the need for turbulent conditions in the furnace in order to achieve proper mixing of air and the gases evolved from the burning fuel, which all vary with the composition of the waste.

o Increased competition for the growing market for incinerators is leading to improvements in engineering design and especially to an increased understanding and sophistication of the technology of combustion. Recognition of environmental problems has also been a key factor motivating the development of

improved combustors and emission control equipment. Earlier designs of mass burners did not incorporate the flexibility for controlling the location and amount of introduced combustion air, or the sophistication of instrumentation for control of feedback combustion air that newer plant designs provide. Thus, older plants generally do not achieve the efficiency of combustion attainable in modern plants.

o The Subcommittee concludes that EPA should investigate the hypothesis that polychlorinated dibenzodioxins (PCDD) and polychlorinated dibenzofurans (PCDF) can result from free radical reactions that take place in fuel-rich zones of incinerator flames. These reactions may yield polycyclic aromatic hydrocarbons (PAH), oxygenated compounds such as phenol and perhaps, in the presence of chlorine, some PCDD and PCDF.

These compounds may also be present in MWC feed stock since they are by-product contaminants in a number of chemicals, most notably chlorinated phenols and polychlorinated biphenyls (PCB). These compounds may persist beyond combustion only if temperatures are sufficiently cooled by excesses in local air flow. Condensation reactions involving the chlorinated phenols, phenol ethers, and biphenyls may also produce PCDD and PCDF.

o The design and operation of an incinerator combustion chamber has major impact on the concentration of the pollutants entering the air pollution control devices. In well-designed and operated incinerators, the emissions of organic compounds currently measured can be reduced to levels close to the limits of detection with existing analytical methods.

Recommendations

o EPA and private vendors should fund research to gain a better understanding of 1) municipal solid waste composition; 2) the affects of furnace design and operating conditions on the combustion process; 3) the relation between inorganic and organic

emissions and; 4) PCDD and PCDF formation. To obtain this information, research on full-, pilot-, and laboratory-scale units is needed.

o Well-planned field testing that evaluates different operating conditions will generate a realistic correlation of emissions with operations, and will provide data for establishing emission indices. Pilot-plant and laboratory-scale testing can be used to critically investigate hypotheses derived from field studies. Small-scale equipment facilitates such testing because of the greater ease of independently varying design parameters, operating conditions, and feed composition.

o Research on the relationship between the composition of MSW and emissions should be carried out over a wide enough temperature range to be useful in testing the various hypotheses for formation of PCDD and PCDF. Specific research is required to understand post-combustion formation of PCDD/PCDF by condensation reactions that occur as the flue gas cools in the heat recovery process.

o Continuous monitors to detect upsets in operating conditions should be developed. Carbon monoxide and hydrocarbons are currently being explored as potential indicators of emissions of PCDD and PCDF. Alternatives such as polycyclic aromatics, detectable by their fluorescence or ultraviolet irradiation, may be more appropriate surrogates.

B. Operator Training and Certification

o The combustion of municipal solid wastes at resource recovery facilities is exempt from the Subtitle C requirements of the Resource Conservation and Recovery Act, provided that the owners or operators take precautions to ensure that hazardous wastes are not burned. Because of this exemption, no national policy related to operator training and/or certification is required for municipal solid waste combustion facilities.

However, proper operation of municipal incinerators requires a thorough understanding of the complexities of the combustion process. An understanding of the composition and variability of the feedstock, fundamentals of the combustion process, requirements and consequences of adequate emission controls, procedures for handling upset conditions, and elements of safe operator practice are required for efficient and effective municipal waste disposal. At present, there are no recommended criteria for selecting MWC staff nor is there an existing pool of trained, experienced personnel to operate municipal waste combustion facilities.

o New facilities planned and/or under construction are much more complex than existing facilities. The need for proper operation of new plants is made even more critical by the rapidly increasing complexity of regulatory requirements and the need for increases in capacity and efficiency of pollutant control devices to ensure environmentally safe plant operations.

Recommendations

o EPA, the states and private vendors should support and promote efforts to ensure that adequate training programs are developed to provide a reservoir of technically competent personnel to staff municipal waste combustors. Training programs should be readily available, developed with appropriate expertise, and tailored to the specific technology being utilized, and the programs should lead to certification when sufficient expertise is demonstrated.

C. Air Pollution Control Technologies

o There appear to be trade-offs between the influence of combustor design and operation and the technology of emissions control. For example, higher incinerator temperatures more thoroughly destroy organic compounds; but at those higher temperatures certain metals volatilize more readily creating the

potential for emissions with greater metal concentrations. Increased nitrogen oxide production can also result at higher temperatures.

o Until about 1985, stack sampling of only very limited scope was conducted at several scrubber/fabric filter installations in Europe, principally for emissions of particulates, acid gases (hydrochloric acid and sulfur dioxide) and certain metals. These studies generated a narrow data base of somewhat limited use, since trace organic compounds were often not studied or, at best, only PCDD/PCDF were. Moreover, the operating conditions of the incinerators and the identities of the pollution control devices were often not well documented, and the studies did not examine a range of different operating conditions.

In 1985, Environment Canada completed an extensive testing program providing the first thorough data base for evaluating the performance of these control systems for a wide range of pollutants of concern. Testing of more limited scope conducted in Denmark paralleled these efforts. The results are encouraging and indicate that, at appropriate temperatures, scrubber/fabric filter technology can significantly reduce not only particulates and acid gases, but also a range of trace organics (e.g., PCDD, PCDF, chlorophenols, chlorobenzenes, PCB, and polycyclic aromatic hydrocarbons), and a host of metals (including cadmium, chromium, lead and mercury). Equipment design and operating conditions necessary to achieve high removal of these compounds were identified in these studies on a pilot scale.

o The scrubber/fabric filter is currently an effective technology and the data base is growing rapidly to substantiate its capability to reduce stack emission to low levels (in some cases approaching the analytical detection limits for compounds such as PCDD, PCDF, and certain metals). This conclusion does not represent a Subcommittee endorsement that the scrubber/fabric filter technology is the only one to use. Other technologies may

offer equal or even better performance with less associated capital cost. Furthermore, the capability for continued performance at such low emission levels under a variety of operating conditions remains to be demonstrated for full-scale municipal solid waste incinerators.

Recommendations

o EPA and the private sector should examine the long-term performance of air pollution control systems under a variety of operating conditions.

o EPA's determination of "Best Available Control Technology" should be sufficiently flexible to allow adoption of improvements in control technologies.

D. Ash Characterization and Disposal

o The concentration of various metals and organic compounds in ash is highly dependent on whether it is bottom grate ash, boiler hopper ash, or ash from emission control devices. Most compounds of concern appear to become progressively more concentrated in the ash sampled or removed from the flue gas stream further downstream in the process. Highly efficient stack emissions control systems result in fly ash with relatively higher concentrations of pollutants, e.g. heavy metals and trace organics, since those substances tend to concentrate on the smaller particles that are more efficiently removed by these systems.

o EPA has considered requiring compliance with RCRA Subtitle C if ash residues from municipal waste combustion contain waste constituents defined as "hazardous". Alternatives under consideration include regulating municipal incinerator ash as non-hazardous waste. Leachate tests on incinerator ash conducted by EPA and other organizations have identified lead and cadmium levels above the Extraction Procedure (EP) toxicity

limits. The EP test, originally developed by EPA for characterizing the toxicity of hazardous waste liquids, has not been validated as a test for municipal incinerator ash.

Recommendations

o State-of-the-art analytical chemical techniques should be employed on ash samples, and as many of the compounds in the extracts as feasible should be identified in order to provide a broad-scale data base.

o EPA should re-examine the appropriateness of using the EP test or its successor, the Toxicity Characteristic Leaching Procedure (TCLP), to assess the toxicity of municipal incinerator ash.

o EPA should evaluate a number of alternative techniques for managing ash disposal from municipal incinerators. These may involve solidification or vitrification of the waste material, or grouting of disposal trenches, sometimes in combination with liners. The Subcommittee recognizes that these techniques may need to be modified to meet the particular chemical characteristics of incinerator bottom ash and fly ash, although the experience of disposing of fly ash from coal-fired power plants may have relevance.

E. Environmental Transport and Fate

o The atmospheric transport and fate of emissions from municipal solid waste incinerators involve a broad spectrum of physical and chemical processes. The processes that need to be addressed include stack emission phenomenon, including plume rise and downwash; plume chemistry, involving changes of physical state and chemical reactions; atmospheric transport and diffusion; gravitational settling; dry deposition; and wet deposition due to in-cloud and below-cloud processes. A scientific basis exists to support model simulations of the

atmospheric transport of pollutants provided the emissions are properly characterized along with the atmospheric and topographic characteristics of each site. However, considerable uncertainty surrounds the ability to properly simulate both wet and dry deposition processes.

o Chemicals which are emitted to the atmosphere, or are deposited on soil or in water, undergo a variety of transformations. Such transformations can result in the destruction of the parent compounds and the simultaneous formation of one or more products. Some of the products may be toxic. The transformation may be photochemical, may proceed in the dark, or may be mediated by biological processes. For assessing potential effects, the identity, quantity and rate of destruction of the parent chemical in various environmental media and the identity, concentration, and persistence of the products are of great importance. Little information is presently available on the fate of chemicals from MWC operations because of the paucity of information on the parent compounds released and the absence of a research program to identify and quantify products formed from the parent substances. In some instances where the parent compounds have been identified, scientists can make reasonable predictions of fate based on published studies.

Recommendations

o EPA and the private sector should develop a more comprehensive data base through field studies at several representative MSW facilities. The data base should provide information that can be used to estimate deposition (wet and dry) of particulate and gaseous emissions, and also to evaluate mathematical and fluid models of transport, diffusion and deposition in urban and suburban environments. The data base should include measurements of MSW emissions (stack and fugitive), plume rise, dispersion, wet and dry deposition.

F. Assessment of Risk to Public Health and the Environment

o The Subcommittee concluded in a separate, previous report that the proposed EPA methodology for assessing risks from municipal incinerators through multiple environmental pathways represents a considerable improvement over other multi-media risk assessment methodologies previously developed by EPA and reviewed by the Science Advisory Board (See Appendix A). The current methodology is more comprehensive and, in general, provides a conceptual framework that should be expanded to other environmental problems. The Subcommittee identified areas in this methodology that need further consideration or improvement, including: the inappropriate use of the Hampton incinerator facility and associated data to represent typical mass burn technology; the failure to use data from current best available control technology facilities for model validation; separate treatment of particulate and gaseous emissions and their fate, i.e. downwash; the need to use best available kinetics in predicting soil degradation; exposure resulting from the disposal of ash; over emphasizing the maximally exposed individual (MEI) concept; and the treatment of plant (and herbivore) exposure.

II. INTRODUCTION

A. Charge and Scope of the Review

At the request of the Administrator of the U.S. Environmental Protection Agency (EPA), the Science Advisory Board (SAB) Executive Committee agreed on April 23, 1986, to review a number of scientific issues related to the incineration of municipal wastes. The Executive committee assigned the responsibility for conducting the review to its Environmental Effects, Transport and Fate Committee which, in turn, established a Municipal Waste Combustion Subcommittee.

The Subcommittee's review encompasses current municipal waste incineration technologies, the combustion process, and emissions to the atmosphere, including associated air pollution control equipment. In addition, it covers such issues as ash disposal, transport and fate of process residues, and assessment of potential effects on human and ecological receptors. The Subcommittee recommended research to reduce scientific uncertainties associated with incineration technologies.

The Municipal Waste Combustion Subcommittee reviewed several separate documents prepared by EPA on aspects of the municipal waste combustion problem. On November 10-11, 1986, the Subcommittee reviewed a methodology jointly prepared by the Office of Air Quality Planning and Standards (OAQPS) and the Environmental Criteria and Assessment Office (ECAO) entitled: Methodology for the Assessment of Health Risks Associated with Multiple Pathway Exposure to Municipal Waste Combustor Emissions. EPA intends that the methodology serve as a principal technical basis for its decision on whether to regulate municipal combustors. EPA was required by a court settlement to publish a decision on this issue in the Federal Register by July 2, 1987. Because the Subcommittee desired to advise the Administrator in a timely fashion, the review of this methodology was issued as a separate report on April 9, 1987 (reprinted in Appendix A).

During the course of the Subcommittee's review, the Assistant Administrator for Air and Radiation, J. Craig Potter, requested that the Science Advisory Board review a methodology prepared by EPA's Risk Assessment Forum entitled, "Interim Procedures for Estimating Risk Associated with Exposures to Mixtures of Chlorinated Dibenzo-p-dioxins and Dibenzo-p-furans (CDD and CDF)". The purpose of this methodology is to provide EPA with a tool for risk assessment, specifically to address the toxicity of various congeners of CDD and CDF in relation to 2,3,7,8- TCDD. The SAB Executive Committee, recognizing the relationship between this procedure and the issues undergoing review by the Municipal Waste Combustion Subcommittee, established a Dioxin Toxic Equivalency Methodology Subcommittee to conduct a review of the former, and provided for overlapping membership between the two Subcommittees. This enabled a joint consideration of information pertinent to assessing risk from exposure to CDD and CDF and municipal waste combustion. The executive summary of the Dioxin Toxic Equivalency Methodology Subcommittee's report is presented in Appendix B.

The Municipal Waste Combustion Subcommittee separately reviewed a research strategy prepared by EPA's Office of Research and Development (ORD). The ORD strategy document entitled Draft Municipal Waste Combustion Research Plan (February 1987), is a chapter in EPA's Comprehensive Report on Municipal Waste Incineration which was prepared for and submitted to Congress. The Subcommittee had access to various draft versions of EPA's comprehensive report, but reviewed only the research plan. A summary of the Subcommittee's review of the research plan is presented in Appendix C.

During its review, the Subcommittee held eight public meetings and solicited scientific testimony from a number of individuals, groups and organizations. State and local regulatory officials, private industrial firms, and environmental groups presented their views on a series of issues. These issues

included the evolution of municipal waste combustion technologies, projected scenarios of the growth in demand for municipal incinerators, problems encountered in permitting municipal waste combustors and the potential of public health and environmental risks resulting from the use of this technology. The Subcommittee made site visits to operating incinerators; in Hampton, Virginia on May 29-30, 1986, and in Baltimore, Maryland on July 28-29, 1986.

B. Major Assumptions and Limitations of the Review

Because of the complexity of the scientific issues under review, the data limitations for many of these issues, and the time constraints for providing advice to EPA, the Subcommittee adopted a number of assumptions and recognized several limitations in defining its charge. They included the following:

o The Subcommittee considered but did not evaluate information on alternatives to municipal waste combustion, such as landfilling, recycling, and waste minimization. Nor did it assess potential risks from these alternatives in a rigorous manner. In principle, the Subcommittee believes that MWC is one of several acceptable waste management techniques. However, it recognizes that some degree of risk or hazard is associated with the application of any waste management technology.

o The Subcommittee recommends that the potential effects of municipal waste combustion be compared with those associated with other common combustion processes. For example, emissions from coal-fired or oil-fired power generators, internal combustion engines, and wood-burning stoves and fireplaces should be compared to emissions contributed by waste combustors to better define no antecedents refers to what respective contributions to health and environmental risks. The Subcommittee did not compare potential emission characteristics from the various combustion sources in common use.

o The Subcommittee report presents an evaluation of a series of generic scientific issues that policy makers at the national level must address. This report is not designed to evaluate all the issues, such as optimal incinerator location, that municipalities typically encounter as they evaluate waste combustion as a part of their local or regional waste disposal strategy. The issues that the Subcommittee reviewed for the purpose of advising national policy makers may not be of equal relevance or importance for making local decisions or site-specific assessments.

This report analyzes issues in an order that reflects the movement of potential pollutants from a specific incinerator source. This analysis follows the process from combustion, through emissions resulting from the combustion process (either directly through the stack, or fugitive emissions), through environmental transport and fate of emissions through various media (e.g., air, land and water) and finally through potential human health and environmental effects.

o The Subcommittee did not initiate or conduct any economic analysis of alternatives for municipal waste disposal or management.

III. THE NATIONAL MUNICIPAL WASTE MANAGEMENT PROBLEM

All societies produce municipal solid waste as a by-product of their industrial activities and consumption patterns. In general, the larger and more complex the society, the greater and more complex its municipal wastes. One of the key technologies available for managing the growing amounts of garbage or trash is incineration. This is not a new technology; incinerator plants have been in use in both Europe and the United States for decades.

EPA estimates that the United States generated approximately 126-159 million tons of municipal solid waste (MSW) in 1980. Only about 6 million tons, or approximately 4 percent of such wastes, were incinerated in approximately 100 municipal waste combustors (MWCs) [1]. In comparison, Sweden currently incinerates approximately 50 percent of its municipal waste and Japan combusts approximately 70 percent.

Over 90 percent, or about 137 million tons of MSW are buried in the United States each year in about 10,000 municipal, and privately operated sanitary landfills. Currently, EPA estimates that 12.7 million tons/year of industrial solid waste is recycled and recovered as raw material for manufacturing. There is some potential for waste reduction due to waste minimization efforts.

In the past decade a number of intersecting events have combined to alter the nation's awareness, and the public policy framework, regarding municipal waste management. These include: growing amounts of municipal waste to be collected and disposed; limitations -- such as the need for greater efforts by government to provide technology transfer and consumer awareness and, in some areas, economic disincentives -- in the current potential for recycling waste and reducing the volume of waste generated; shrinking landfill capacity in many areas of the country; escalating costs for transportation and storage of municipal wastes; and stricter controls on landfills increasing operating

costs and owner's legal liability. Public health and environmental concerns over waste/management alternatives, such as landfilling, incineration, and ocean dumping, have also been heightened, as evidenced by difficulties in gaining public acceptance to new landfill or incinerator sites and concerns over the potential for groundwater contamination. Through the Hazardous and Solid Waste Act Amendments of 1984, Congress declared a national policy preference for more permanent methods of disposal, such as incineration, over the storage of wastes, such as landfilling. In general, these factors are stimulating a wider reliance upon incineration technologies and are encouraging expansion of this industry.

The present municipal waste problem stems in large part from the fact that, to date, the nation has chosen disposal methods that favor storage of wastes over methods that favor destruction. In the future, waste minimization and recycling can reduce the overall volume of waste, but ultimately there is a requirement for some form of disposal. Municipal waste combustion currently represents a technological alternative that can reduce the volume of waste by over 90 percent. In addition, it may provide a source of energy recovery under certain conditions.

EPA projects significant growth in the use of municipal waste combustion in the United States between 1985 and the year 2000. By that time the Agency estimates that as many as 311 additional MWCs may be in service with a design for total capacity of about 252,000 tons of MSW per day. This compares with 1985 design capacity of approximately 45,000 tons incinerated per day in more than 100 combustors [1]. Table I identifies currently operating incinerators by design type. Data on facilities now being planned or built suggest to EPA that MWCs with a design capacity of more than 1,000 tons per day will constitute more than 50 percent of the new facilities built by 1990.

During the course of its review, the Subcommittee became aware of the many changes under way in combustion technology as well as the improvements in emissions control technology. The Subcommittee is also aware that other related waste disposal technologies are under development or show promise for wider use, given favorable economics and ease of practice. Two of these developing approaches--preprocessing and resource recycling--have been considered but not fully evaluated by the Subcommittee. These approaches singly, or in combination, have the capability to further minimize the generation of potentially hazardous residues. Minimizing solid wastes will reduce the amount of land needed for disposal of waste, and will increase the potential for returning materials to the economic cycle, potentially reducing pressure on natural resources.

No matter which methods society uses to reduce and dispose of municipal wastes, it will encounter some degree of public health or environmental risk. In this respect, waste disposal, including combustion, is no different than most other technologies which serve our needs. It is important for EPA to develop the means for and to undertake comparative risk assessments across media for each waste management option. Such comparative analyses would provide a basis for selecting among the different options and would help to identify the option presenting the least adverse risk. State and local decision makers could also utilize this technique for site-specific assessments. Furthermore, comparative analysis would facilitate risk management, taking economic, societal, and other factors into account.

It is necessary for individual municipalities to evaluate all available technological alternatives for waste disposal, and to choose the technology(ies) that presents acceptable levels of risk to the local population and environment. It should be recognized that all technological alternatives (including the maintenance of the status quo) impose (voluntarily or involuntarily) some form of risk. The overall societal objective

is to select the most cost-effective technology that imposes the least adverse risk to the population and environment.

TABLE 1

EXISTING MWC FACILITIES BY DESIGN TYPE[a]

DESIGN TYPE	INSTALLED DESIGN CAPACITY (TONS/DAY)	NUMBER OF FACILITIES
MASS Burn[b]		
With Heat Recovery	20,900	25
Without Heat Recovery	9,800	16
Total	30,700	41
MODULAR INCINERATOR[c]		
With Heat Recovery	3,300	33
Without Heat Recovery	500	16
Total	3,800	49
RDF PROCESS[d]		
With Heat Recovery	10,700	9
Without Heat Recovery	0	0
Total	10,700	9
GRAND TOTAL	45,200	99

[a]Source: Radian Corp., [1]

[b]Mass burn - The burning of unprocessed MSW, typically in refractory or waterwall furnaces

[c]Modular incinerator - Factory preassembled mass burn units usually employing controlled air combustion technology to incinerate considerably lower volumes of waste than those employed by mass burn or RDF units

[d]RDF - Refuse derived fuel processes subject MSW to varying degrees of processing to improve fuel quality for better combustion efficiency and to achieve some material recycling or recovery (see Appendix D

IV. THE PROCESS AND TECHNOLOGY OF INCINERATING MUNICIPAL WASTE

A. Feedstock

Municipal solid waste is extremely heterogeneous in nature, and its composition is, in part, a function of consumption patterns that differ with geographic locations and vary significantly with time of the year. There is a substantial data base describing MSW by major constituents--paper, plastics, glass, wood, cardboard and ferrous and nonferrous metals (see Table 2). The data contain not only proximate and ultimate analysis, but also chemical analysis of ash. This information can be useful in making the standard combustion calculations, including combustion air requirements, inorganic stack gas emissions (such as acid gases and volatile metals), and bottom ash characterization.

TABLE 2

CURRENT AND PREDICTED COMPOSITION OF DISCARDED RESIDENTIAL AND COMMERCIAL SOLID WASTE (WEIGHT PERCENT)[a]

	Year		
Component	1980	1990	2000
Paper and Paperboard	33.6	38.3	41.0
Yard Wastes	18.2	17.0	15.3
Food Wastes	9.2	7.7	6.8
Glass	11.3	8.8	7.6
Metals	10.3	9.4	9.0
Plastics	6.0	8.3	9.8
Wood	3.9	3.7	3.8
Textiles	2.3	2.2	2.2
Rubber and Leather	3.3	2.5	2.4
Miscellaneous	1.9	2.1	2.1
TOTAL	100.0	100.0	100.0

[a]Source: Radian Corp., [1]

Due to the inherent variability of MSW, and shortcomings of current computer models of incinerator combustion, it is difficult to accurately predict the composition of stack emissions. Accordingly, it is important to consider the impact of variation in MSW composition when designing furnace and emission/control systems in order to minimize solid and gaseous emissions.

The American Society for Testing Materials (ASTM) has classified municipal solid waste used as a fuel as Refuse Derived Fuel (RDF-1, RDF-2, RDF-3, RDF-4, or RDF-5) based on the degree of MSW processing required. Appendix IV provides a further description of these categories.

B. The Incineration Process

Organic materials that are completely combusted or burned in an oxygen atmosphere will theoretically produce water vapor and carbon dioxide as gaseous products of combustion. This assumes that the organic materials contain only carbon and hydrogen.

Municipal solid waste, which is usually composed of 50-75 percent organic materials, is a fuel that contains many constituents other than organic materials, such as free moisture and inorganic materials including minerals and trace metals. Thus, the products of combustion, whether complete or incomplete, will leave the incinerator in various forms. These forms include stack emissions as flue gas and suspended particulates, bottom ash falling off the grate at the end of the burning fuel bed, or fly ash removed by pollution control devices.

Complete combustion depends on temperature, turbulence and residence time. The temperature required for proper combustion varies with the raw material. The turbulence required in the furnace to achieve the proper mixing of combustion air and product gases evolved from burning materials also varies and influences efficient combustion. Similarly, the amount of time

needed for materials to fully combust depends on the elemental and physical characteristics of the feedstock and has an influence on combustion efficiency.

Thermodynamic properties of chemical constituents in MSW indicate that, under excess air conditions and the temperatures typical of incinerators, emissions of organic compounds should be so low as to be considered zero. However, field sampling data show significant emissions of trace organic compounds.

Organic compounds, which include hydrocarbons, can be formed during MSW combustion. Some of these hydrocarbons may raise toxicological concerns or may be precursors to potentially toxic compounds. The heterogeneous characteristics of the fuel can prevent complete and uniform mixing of volatile gases and thereby prevent complete combustion. Fuel-rich pockets develop in the furnace leading to hydrocarbon formation. Chemical kinetic considerations indicate that these hydrocarbons should be destroyed rapidly in the presence of oxygen at elevated temperatures.

The objective of the combustion control process is to provide for effective mixing of the fuel with oxygen at a temperature sufficiently high and for a time sufficiently long to promote the destruction of all organic species. Thus, organic emissions can be eliminated or reduced to minimal amounts by the proper implementation of combustion control, which includes efficient furnace design, sufficient instrumentation for combustion air control and proper unit operation.

C. Descriptions of Combustion Systems

Increased competition in the growing incinerator market is a prime motivation for continued improvements in the engineering design of incinerators, especially in the combustion process. Both competitive pressures and concerns over environmental

performance are forces leading to improvements in the design of municipal waste combustors and emissions control equipment. Major municipal waste combustion systems can be grouped into several categories:

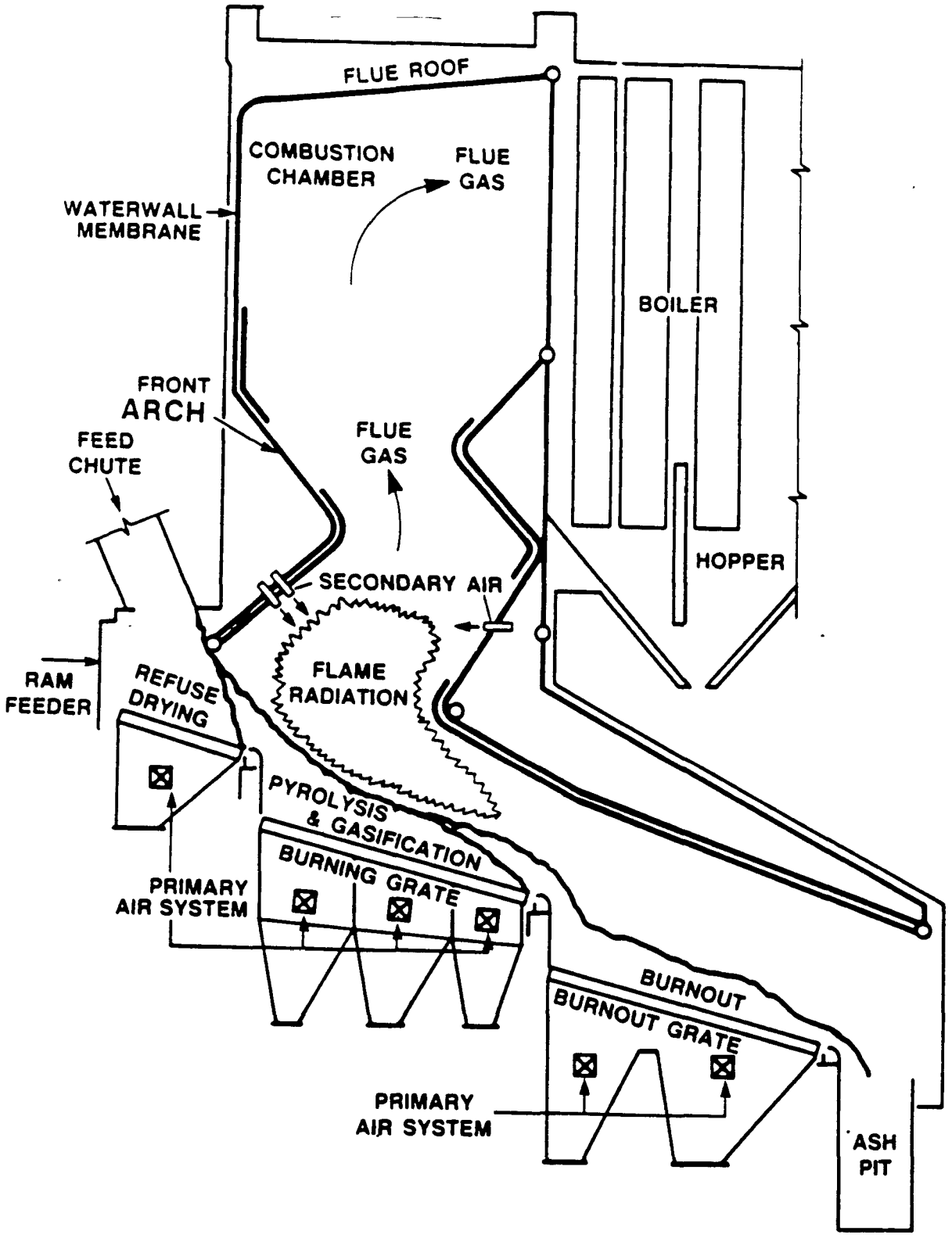
1. Mass Burning of Unprocessed Municipal Waste (RDF-1)

Mass burning usually implies an incinerator that employs a waterwall furnace enclosure positioned over the combustor grate. The flue gases that are products of combustion leave the furnace then flow through a convective (back-pass) heat recovery boiler (see Figure 1). Older systems may also consist of refractory furnace walls combined with a convective (back-pass) heat recovery boiler.

Early mass burning units introduced the waste into the furnace and onto the grate by gravity through a feed chute. Newer units utilize hydraulic rams to meter the fuel onto the grate. Grate designs use some form of fuel bed agitation through reciprocating, oscillatory or rotary motion or some combination of these movements. This bed agitation allows for more uniform burning and maximum burnup. Grate area is designed to maximize the heat release rate.

In such units combustion air is introduced as undergrate (primary) air and as overfire (secondary) air. Overfire air is introduced via nozzles positioned in the front, rear, and sidewalls of the furnace over sections of the grate. Excess air levels in such units usually range from approximately 80 percent for waterwall plants to 150 percent or more for refractory wall units. Flue gases exiting the furnace usually pass through a convection heat transfer boiler. The non-combustible matter in the fuel, along with unburned carbon, fall off the end of the grate as bottom (hopper) ash, or will be carried up as fly ash in the flue gases passing through the burning fuel bed. Bottom ash is the residue remaining after nearly complete combustion of the organic matter achieved in current design and operation. Bottom

Figure 1
MASS BURNING INCINERATION



ash usually drops off into a water-filled hopper (for quenching) and is usually transported to a landfill for disposal (see Figure 2).

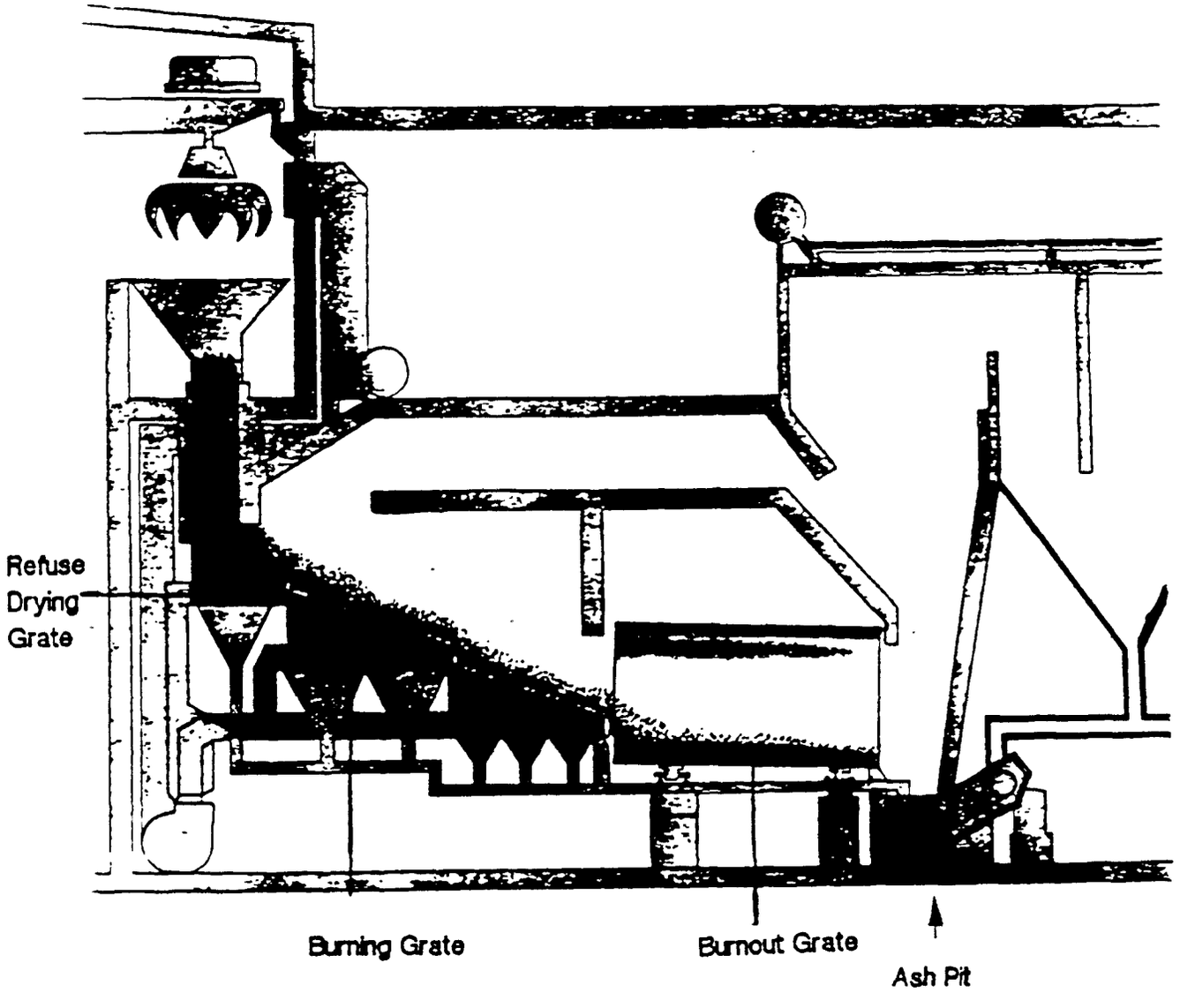
2. Modular/Starved Air Burning of Unprocessed Municipal Waste (RDF-1)

In small-scale facilities, starved air or controlled air combustors use two-stage or double combustion chambers (see Figure 3). Usually, sub-stoichometric air is supplied to the primary refractory lined chamber to control exit temperatures of gases and to reduce particulate entrainment by the flue gas from the burning bed. A variation in the system design of the two-stage combustor is known as a controlled-air incinerator. In this design, excess combustion air is supplied to both primary and secondary chambers. To minimize fly ash carry-over, the excess air in the primary chamber is relatively low. In either a starved air or an excess air unit, a heat recovery boiler is located downstream, followed by appropriate equipment for particulate removal.

3. Dedicated Stoker Boilers Burning Coarsely Processed Refuse (RDF-2)

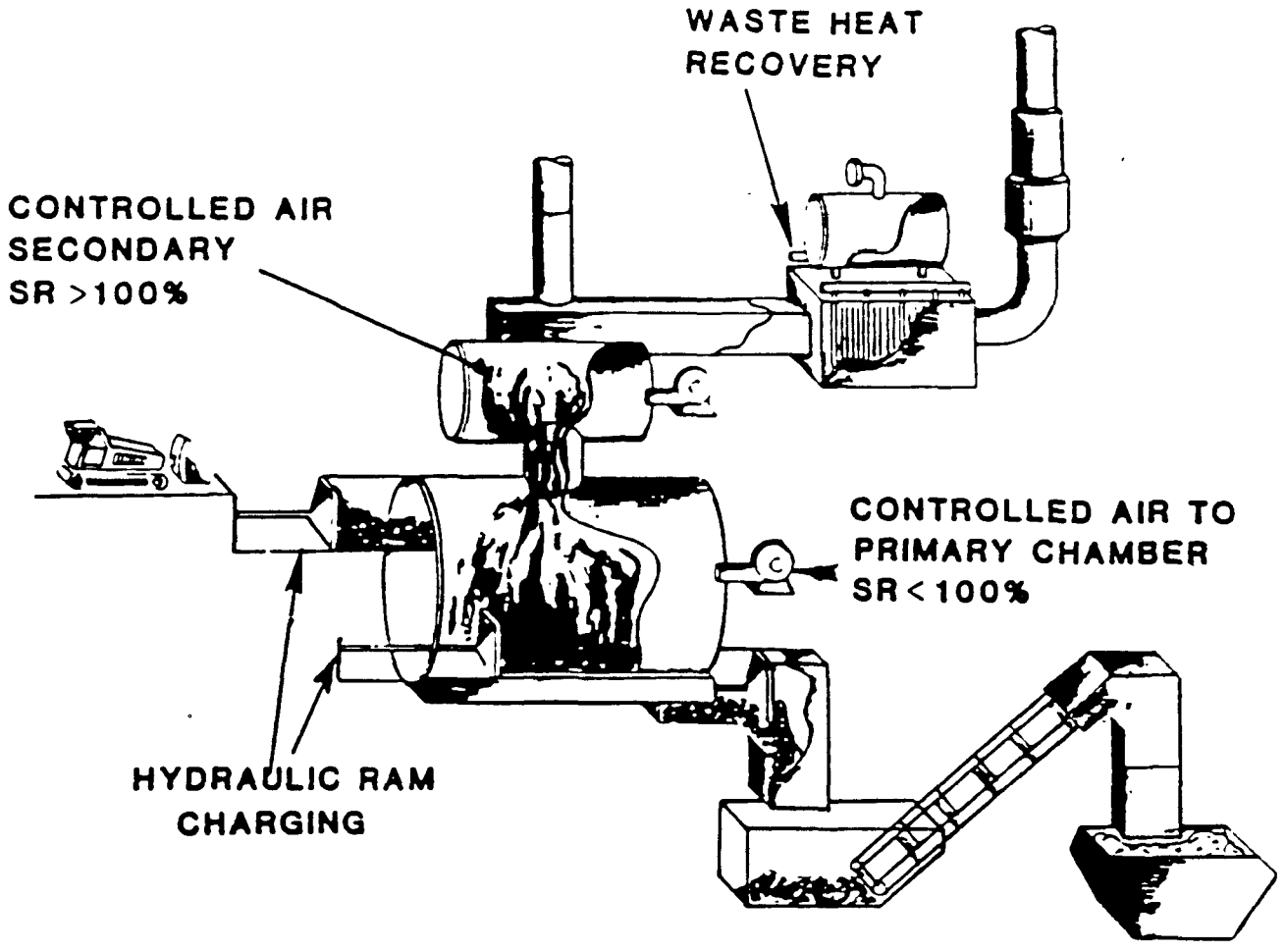
RDF-2 may be combusted in "conventional" stoker fired boilers which consist of a waterwall furnace and a convective back-pass heat recovery boiler (See Figure 4). Fuel is injected into the furnace by air swept spouts (or essentially pneumatic injection). Traveling grates drop the bed ash into hoppers as they move towards the front wall of the boiler. Optimum amounts of excess air range from 70-90 percent. Several levels of overfire air nozzles are normally positioned above the grate in the front and back waterwalls. These nozzles induce turbulence, providing the necessary mixing of partially combusted flue gas as it exits the grate bed. New units are also being designed with arches located in several of the waterwalls to promote further

Figure 2



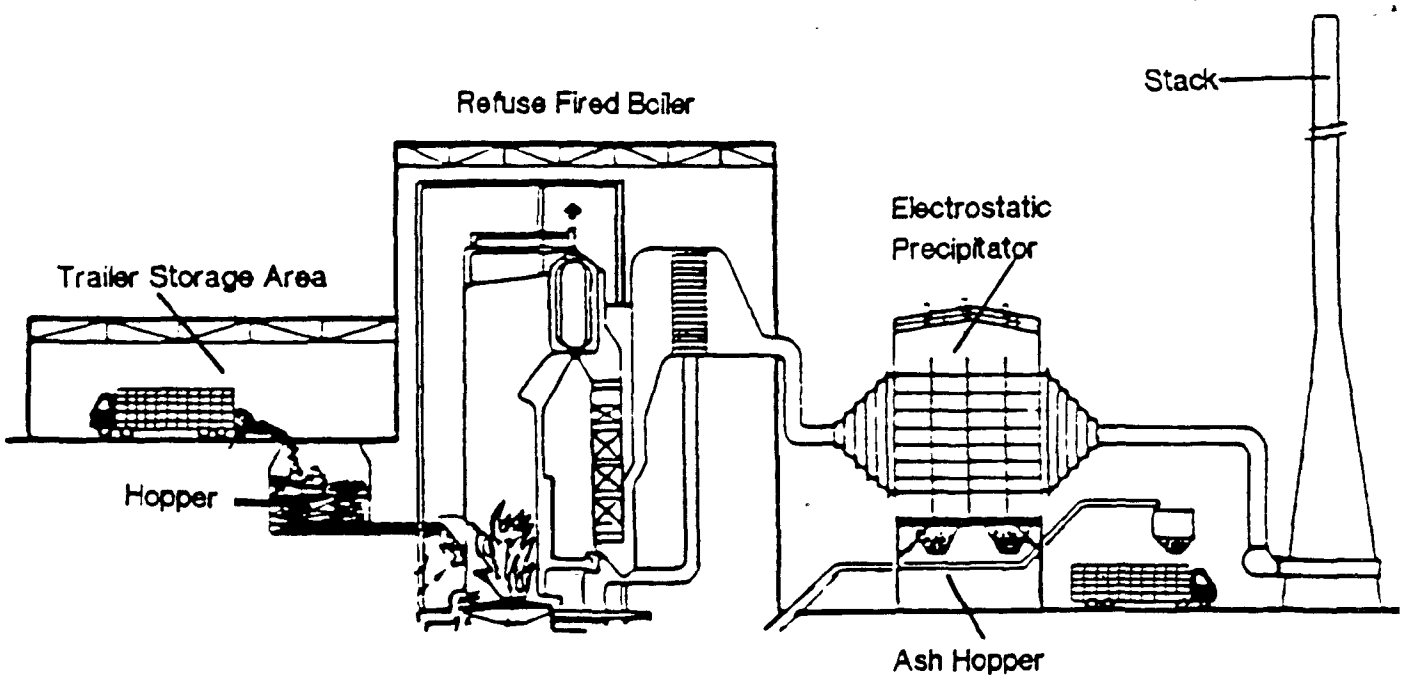
MSW Grate

Figure 3



Starved Air Combustors

Figure 4



RDF-Fired Combustors

turbulent mixing. Some volatile matter in the RDF-2 undergoes drying and ignition while in suspension.

4. Co-firing of Coal and Municipal Solid Waste Burning Processed Refuse (RDF-3, RDF-4, and RDF-5)

The practice of co-firing MSW with coal involves the use of processed fuel such as RDF-3, RDF-4, or RDF-5. Co-firing may be accomplished either in a spreader stoker or in a utility steam generator co-fired with pulverized coal.

Fluff RDF (RDF-3) is pneumatically injected into the furnace of stoker units at firing rates of up to 50 percent BTU of total heat input from fuel, or up to 20 percent BTU heat input in pulverized coal units.

D. Combustion System Design and Operation

1. Stages of Combustor Operation, Old and New Plant Designs

As previously stated, completeness of combustion depends on oxygen supply, time, temperature, and turbulence. Sufficient temperature and residence time are required for the fuel to undergo complete oxidation. Proper amounts of excess air aid in developing necessary furnace flue gas temperatures and turbulence.

Grate combustion of municipal solid waste takes place in three often overlapping stages. Multi-sectioned grates are used to accomplish these steps in both American and European designs for mass burn systems. These three stages are illustrated in Figure 1 and are described below:

o Drying-Volatilization: As the waste is heated, moisture and volatile matter is released, leaving a carbonaceous residue. The combustible content of the volatiles burns partially within

the refuse bed and partially in suspension over the grate (see "refuse drying, Figure 1).

o Fixed Carbon Combustion: The carbon residue produced by the devolatilization of the waste burns on the grate, leaving an inorganic residue (see "burning grate", Figure 1).

o Final Ash Burnout: Additional time on the burnout grate is required to reduce the remnants of carbon embedded in the ash to an acceptable (<5 percent) level (see "burnout grate, Figure 1).

In older units, undergrate combustion air was supplied by use of a single damper-controlled compartment (wind-box) for each section of the grate system. In the past, the incinerator operator often depended on visual inspection to achieve a "good-looking" fire, with the hope of maintaining "good" combustion. Modern designs use sectionalized undergrate air compartments to supply varying amounts of primary combustion air to different areas of the grate. Automatic controls on the combustion system integrate signals from CO, O_2, or CO_2, waste feed and/or steam production, as well as combustion air control to produce optimized burnout of the products of combustion.

Turbulent mixing of the flue gas leaving the grate in mass burners or dedicated boilers is essential and can be obtained by appropriate location of the overfire air nozzles. Proper combustion control yields the correct ratio of undergrate/overfire air. This ratio provides good flue gas mixing at a constant excess air setting. Too little combustion air will result in the generation of products of incomplete combustion including soot, while too much overfire air will result in a quenching of the combustion process causing formation of the products of incomplete combustion. Sometimes the emission of a white smoke will result from the condensation of the quenched, unburned hydrocarbons.

Earlier designs for mass burners did not incorporate flexibility in introducing combustion air, or the sophistication of combustion air control, used in newer plant designs. Thus, older plants generally did not achieve the efficiency of combustion attainable in modern plants.

Furnace designs feature arches over the grate in the front and rear walls to allow for faster drying and distillation of the fuel volatile matter, in fuel and also improve the mixing of stratified flue gases to permit more complete combustion and ash burnup (See Figure 1). Plugging or jamming of the drag conveyer for bottom ash has been the source of some boiler load upsets resulting in the release of products of incomplete combustion to the environment.

2. Emissions from the Combustion Chamber

Data on the identity and concentration of different pollutants emitted from the combustion chamber provide useful information in designing air pollution control devices, but such data are relatively scarce. The following information pertains primarily to mass-burn incinerators and is provided to illustrate the relationship among emissions, feed composition, and combustor design and operation.

a. Acid Gases

HCl and SO_2 are produced as a result of chlorine and sulfur containing materials in the feedstock. Approximately 60 percent of the chlorine in the waste ends up as HCl; the remainder occurs primarily in the solid residue as inorganic chloride and may be combined with trace amounts of gaseous organic compounds. The sulfur in the feedstock oxidizes to SO_2. Part of the SO_2 will react further, such as with alkali in the waste, to form sulfates. The ash residues may retain from 10 to 90 percent of the sulfur depending upon the alkali and sulfur content of the

waste. The remainder of the sulfur will be emitted with the combustion products, primarily as SO_2.

The oxidation of nitrogen, present either in the air or in organic compounds in the feed, produces nitrogen oxides (NO_x). The organically-bound nitrogen, found in high concentrations in proteins and some plastics, can be converted to NO_x with efficiencies of up to 50 percent. The NO_x produced from the oxidation of atmospheric nitrogen in combustion air increases markedly with increases in combustion temperature and strongly depends upon combustion conditions.

b. Fly ash and Residues

Unlike organic compounds, elemental or non-combustible materials are not destroyed during the incineration process. The composition of feedstock or incoming wastes, therefore, provides a measure of the total inorganic residue. Most of the inorganic residue and the products of incomplete combustion of organic compounds leave the furnace as either fly ash or bottom ash. Bottom ash drops off the end of the grate and is conveyed to hoppers, while fly ash is elutriated with the flue gas to be collected by air pollution control devices or emitted as particulate out of the stack. The distribution of elements between bottom ash and fly ash carried over to the air pollution control device(s) depends upon the design and operation of the incinerator and the composition of the feedstock. The amount of ash carried out with the flue gases leaving a burning refuse bed increases with increasing underfire air and with bed agitation. For this reason, starved air incinerators with low underfire air flow tend to have less particulate emissions than conventional mass-burn units. The amount of fly ash carried from the combustion chamber will be influenced by the particle size of the inorganic content of the MSW.

The distribution of elements between the different components of refuse has a strong influence on the their environmental fate. For example, TiO_2 used as a pigment in paper products has a particle size of about 0.2 um and will be carried off by the flue gases passing through the refuse bed, whereas TiO_2 in glass will accumulate in the bottom ash. Up to 20 percent of the total inorganic content of the waste will usually be entrained in the flue gas causing the burning refuse bed to form fly ash particles in the 1 to 20 um size range. The remainder will end up in the bottom ash.

c. Trace Metals

Volatile elements and their compounds, usually present in trace amounts in the feed, will vaporize from the refuse and condense in the cooler portions of a furnace. They will condense either as ultra fine aerosol (less than 1 um size) or on the surface of the fly ash, preferentially on the finer ash particles. A large fraction of the mercury, arsenic and selenium in the feed will be volatilized. Elements such as sodium, lead, zinc and cadmium will be distributed between the volatiles and the residues in amounts that depend on the chemical composition of the substances that contain the elements. For example, sodium in glass will be retained in the ash residue but that in common salt will be volatilized.

d. Organic Compounds

Relating characteristics of organic emissions to the composition of MSW and to the operation of a unit during upset conditions is very difficult. Some episodic releases of organic emissions can be related to operating upsets resulting from changes in feed composition. High moisture content of fuel delays ignition and yields lower furnace temperatures which, in turn, retards complete combustion. High concentrations of certain plastics, solvents or other highly volatile materials will result in surges in the emission of combustible gases from

the grate that may overwhelm the local air supply. The capability of modulating the air supply and changing the distribution of air can control the effects of such sudden surges in heat release. Mixing the MSW in the receiving or collection pit may also help control surges of heat release in the furnace.

As combustion takes place, polycyclic aromatic hydrocarbons (PAH) are formed during the fuel rich combustion of gas, oil, and coal, as a consequence of free radical chemical reactions in the high temperature flame. Quenching of partially combusted fuel due to interaction with cooled surfaces is another PAH formation mechanism that occurs with internal combustion engines, diesel engines and oil-fired home heating furnaces. In such circumstances a high fraction of the polycyclic compounds are oxygenated. Upset conditions leading to local air deficiency may also result in the emission of organic compounds such as PAH.

One hypothesis deserving further analysis is that similar free radical reactions take place in fuel rich zones of incinerator flames yielding PAH, oxygenated compounds such as phenols, dioxins and furans and, in the presence of chlorine, some PCDD and PCDF. This hypothesis is supported by the observation of PCDF in the combustion products of pine wood only when it had absorbed HCl. The argument for the high temperature synthesis of PCDD and PCDF is also supported by the demonstrated increase in the concentration of the pollutants across a heat recovery boiler.

The above free radical mechanism should be further investigated to determine if it is the dominant source of PCDD and PCDF in incinerators. These compounds may also be present as contaminants in a number of chemicals, therefore they may be present in MWC feedstock. The presence of chlorinated phenols, and polychlorinated biphenyls (PCB) may result from the use of these chemicals (uses that have been discontinued in some cases) as fungicides and bactericides (phenol derivatives), and as heat exchanger and capacitor fluids (PCB) contaminated with low levels

of PCDF. These compounds may persist beyond combustion only if process gases are cooled to temperatures below those required for their decomposition and reaction by large excesses in local air flow.

PCDD and PCDF may also be produced by condensation reactions involving the chlorinated phenols and biphenyls. The observed formation of PCDD when fly ash from MSW incinerators is heated to 250°-300°C suggests such catalyzed condensation reactions of chlorinated phenols. PCB can be a precursor to PCDF; pyrolysis tests with PCB in laboratory reactors at elevated temperatures have yielded PCDF.

E. Operator Training and Certification

The preceeding sections underline the importance of controlling combustion air flow rates, air distribution, and furnace operating temperatures for minimizing emissions. To minimize the potential for hazardous emissions, facilities must be operated properly. The proper operation of MWCs requires a thorough understanding of the complexities of incineration, including knowledge of the composition and variability of the feedstock, the fundamentals of the combustion process, and requirements and consequences of adequate emission controls. In addition, operators must be trained in procedures for managing upset conditions in order to prevent or mitigate the release of hazardous compounds.

The combustion of municipal solid wastes at resource recovery facilities is exempt from Subtitle C requirements of the Resource Conservation and Recovery Act (RCRA), providing that the owners or operators assure the permitting authorities that the burning of hazardous wastes will be prevented. Due to this exemption, no national policy on operator training and/or certification for MWC facility operators has developed.

Since many new resource recovery facilities are, or will soon be, under construction, there is an urgent need for appropriately trained, and technically qualified operators. Incinerators in the planning and/or construction stages are generally larger and much more complex than existing facilities. The performance of these newer plants is becoming more critical in view of the increasing complexity of regulatory requirements, the requirement for increased efficiency of pollutant control technologies in newly permitted facilities and the heightened public concern for environmentally safe disposal of residue from the combustion process.

There is no existing pool of trained plant operating personnel that private industry or municipalities can draw upon to staff MSW plants. Some states have promulgated regulations requiring plants to be operated by certified personnel, but these states do not have formal training programs leading to certification. At present, training courses for plant operating personnel are available only to a limited extent, and most of these are one week general training programs. Such programs do not provide the necessary understanding of the concepts and details of combustion system design and operation, and emissions control. Vendors must deal with the normal problems of plant startup while providing extensive on-the-job training for personnel who are basically unfamiliar with the facilities.

F. Conclusions and Recommendations

1. Conclusions

o The design and operation of combustion chambers has a major influence on the type and concentration of the pollutants entering air pollution control devices. In well-designed, well-operated incinerators with state-of-the-art systems for air pollution control, the emissions of organic compounds of concern

can be reduced to levels close to the limits detectable by currently available sampling and analytical methods.

o When high concentrations of organic compounds are emitted, it is usually a consequence of poor mixing of combustible volatiles generated in the burning refuse bed with air, or from quenching of the partially combusted products by excess quantities of air or contact with cold surfaces. Inadequacies of design and/or operation of overfire air jets or underfire air compartments may result in the improper distribution of air causing inefficient mixing and quenching before volatiles are combusted.

o Extensive field testing has been conducted to establish general emission concentrations. There are fewer data on systematic variation of operating and design parameters to provide insight into the mechanisms governing organic emissions. [2, 3, 4]

o The wide variety of polycyclic aromatic compounds and the large number of congeners of PCDD and PCDF observed in the emissions from incinerators appear to be consistent with the pyrosynthesis of these compounds in the high temperature flame zone.

o Feedstock composition has an important impact on the emissions of inorganic compounds. Chlorine, sulfur, and volatile trace metals will be transferred with relatively high efficiency to the gaseous and fine particulate matter carried out of the combustion chamber. In addition, particulate matter will be carried from the combustor in amounts that will depend upon the fineness of the mineral constituents in the refuse, bed agitation, and the underfire air flow rate.

o Municipal waste combustion is a complex process that depends on many factors that begin with initial feedstock variability and end with emissions control. Technologies under

development will add to this complexity. Operators are seldom trained to operate existing or new incinerators, nor are they required to be certified for incinerator operation. The lack of trained operators may slow the application of MWC technology and may compromise efficient and safe plant operation.

2. Recommendations

There is a need for better understanding of the relationship of inorganic and organic emissions, and PCDD and PCDF in particular, to MSW composition, furnace design, and operating conditions. This requires research on full-, pilot-, and laboratory-scale units. Well-planned field testing under different operating conditions will generate a more realistic correlation of emissions to operations, in addition to providing data for establishing emission indices. Pilot-plant and laboratory-scale testing can be used to critically test hypotheses on the routes and mechanisms of pollutant formation, because of the ability to independently vary operating and design parameters and feed composition in small-scale equipment. The following specific tasks need to be undertaken:

o The relationship between underfire and overfire air distribution and emissions needs to be understood in order to establish guidelines for adjustments in air flow rates that are responsive to changes in MSW composition and feed rate. A complementary study is needed on the emission of combustible volatiles from burning refuse beds since the overfire air distribution should be matched to the evolution of combustible volatiles. The effect of transient operation is of particular interest.

o The kinetics of pyrosynthesis and condensation reactions as they relate to the formation of PCDD and PCDF should be further investigated. An understanding of the factors governing the distribution of congeners and isomers of these compounds

would be useful for assessing health effects and as an aid in diagnosing the genesis of emissions. For example, the relationship of the composition of MSW to emissions should be studied over a wide enough temperature range to be useful in testing the various hypotheses for formation of PCDD and PCDF.

o EPA and the private sector should work cooperatively to develop continuous monitors to detect upsets in operating conditions. Carbon monoxide and total hydrocarbons are currently being explored as potential indicators of emissions of PCDD and PCDF. Alternatives, such as polycyclic aromatics, may be appropriate surrogates.

o Private industry and Federal, State and local governments should initiate efforts to plan and implement an operator training program leading to certification. This plan should provide the operator with a basic understanding of the combustion process, management of plant equipment, and impact of operational parameters on environmental emissions. EPA and state authorities should provide guidelines to facilitate operator training and to maximize assurance that hazardous materials will not be burned in MWC. Certification should be valid nationally and transferable from state to state. Implementation of this recommendation will provide a reservoir of appropriately trained personnel to staff the increasing number of MWCs.

V. PERFORMANCE OF AIR POLLUTION CONTROL TECHNOLOGIES

A. Potential Air Pollutants of Concern

As outlined in the previous chapter, the combustion process results in the generation of flue gases and particulates which contain various pollutants. These can be grouped into several categories:

- Particulates
- Heavy Metals
- Acid gases
- Trace Organics

To prevent or reduce emission of these compounds into the atmosphere, various air pollution control systems can be installed between the incinerator/boiler and the stack. These are discussed below.

For some pollutants, there appear to be trade-offs between combustor design, unit operation and emission controls. For example, higher incinerator temperatures can destroy trace organic compounds, but also cause an increase in NO_x production. In addition, metals like mercury volatilize more readily and are carried from the combustor to the control devices in greater amounts at higher incinerator temperatures.

B. Description of Air Pollution Control Systems

The following are the main types of air pollution control systems or devices that can be installed on municipal waste combustors:

1. Electrostatic Precipitators (ESP)

Electrostatic precipitators have demonstrated capability to remove particulate matter but do not remove gaseous pollutants.

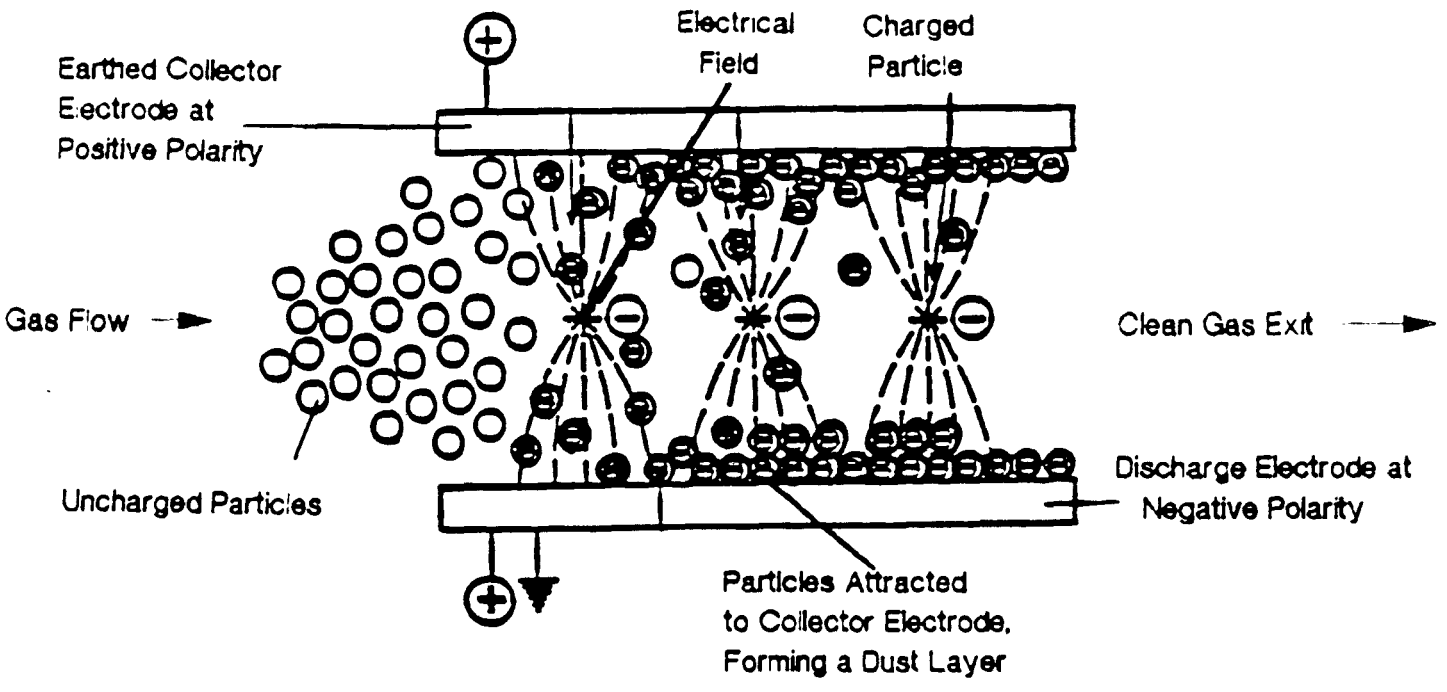
They can be used alone, linked in a series of 2 - 5 fields or linked with other pollution control devices such as scrubbers. The precipitation process follows these basic steps: (a) development of a current of negative ions from a high voltage corona discharge to charge dust particles in the gas stream; (b) the presence of an electric field in the gas space between the high voltage discharge electrode wires and the collection plate that propels the negatively charged particulate matter toward the positive collection plate; and (c) removal of the collected particulate matter into hoppers by use of a rapping mechanism. Figure 5 illustrates the basic principles of electrostatic precipitation.

Electrostatic precipitation occurs within an enclosed chamber. A high voltage transformer and a rectifier modify the electrical power input. Suspended within the chamber are the grounded collection electrodes (metal plates) connected to the grounded steel framework of the supporting structure. Suspended between the collection plates are the high voltage discharge (wire) electrodes (corona electrodes) insulated from ground and negatively charged with voltages ranging from 20 kV to 100 kVDC.

The last step of this process involves dust removal from the collection electrodes. In dry ESPs, this is accomplished by periodic striking of the collection plates and discharge electrode with a rapping device. Hoppers collect the fly ash and it is conveyed to storage or disposal points.

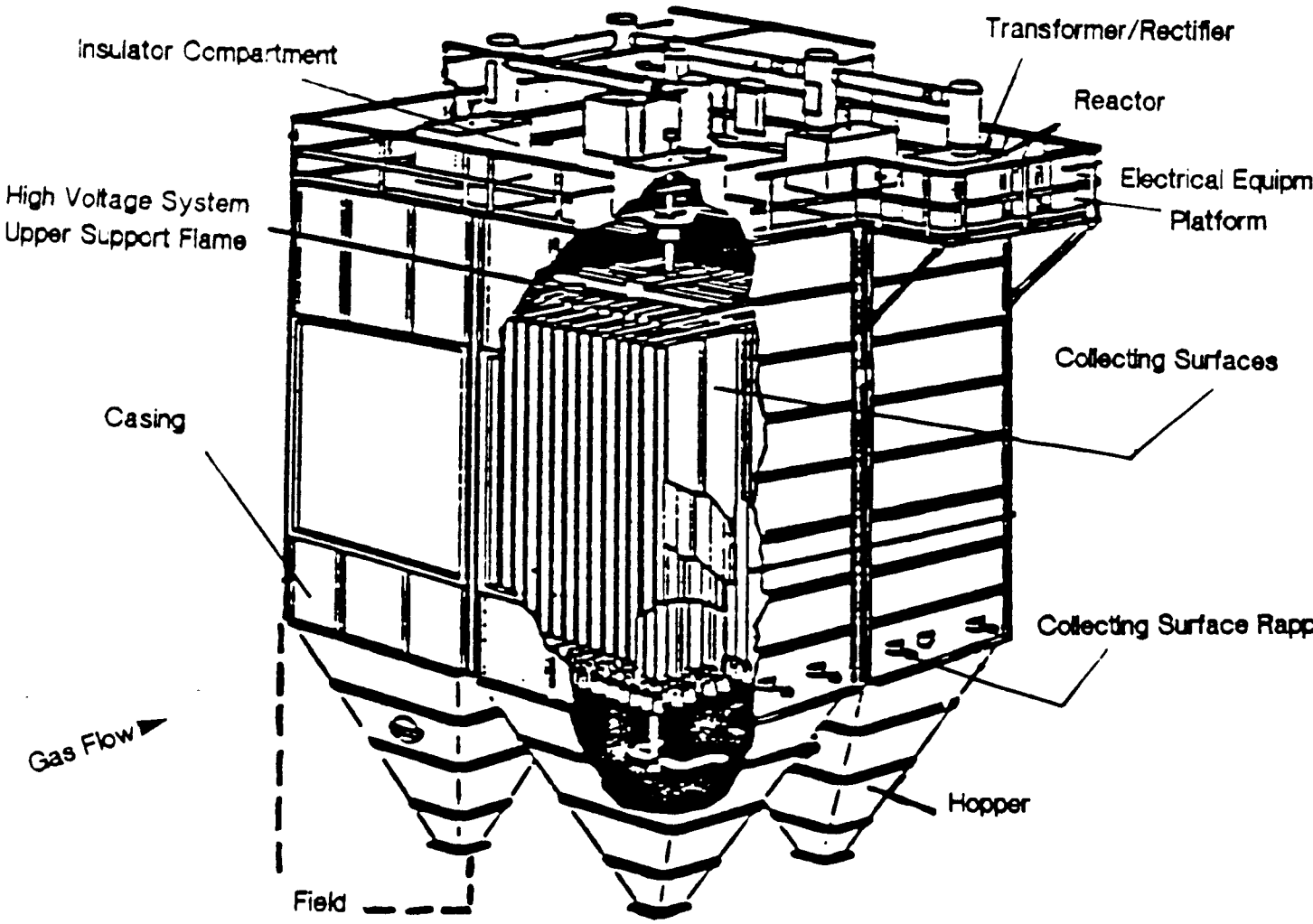
In North America, electrostatic precipitators have traditionally been used alone for particulate control. In Europe, several installations use a scrubber in combination with an electrostatic precipitator. The physical arrangement of a typical electrostatic precipitator having two independent electrical fields is illustrated in Figure 6.

Figure 5



Electrostatic Precipitation Process

Figure 6



Arrangement of Electrostatic Precipitators

2. Fabric Filters

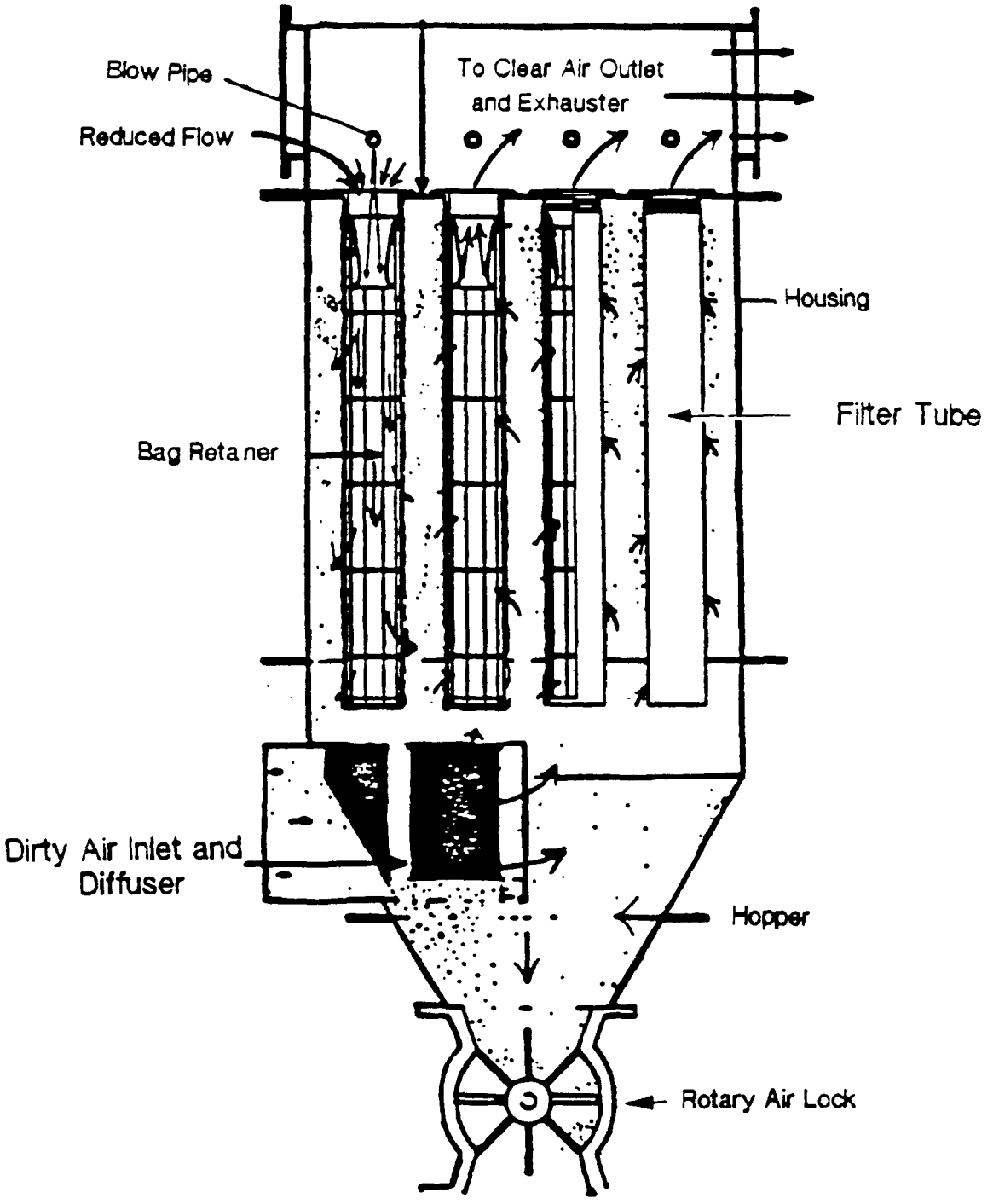
Operation of this technology involves impaction of dust particles on a fabric filter to form a dust cake on the cloth surface, with filtration of the gas as it passes through the cake and cloth. The fabric typically used is a woven or felted material. The dust cake formed on the filter plays a key role in the overall efficiency of particulate collection. Periodically the dust cake is removed from the filter surface via a cleaning cycle that may consist of shaking the bag, reverse air cleaning or blow-back by compressed air via pulse jets. The cake remaining after cleaning forms a base for collection of particles as the bag is put back on line.

The type of cleaning cycle used is a factor in distinguishing the different designs of fabric filter type dust collectors. Figure 7 illustrates a small pulse-jet cleaning fabric filter. Fabric filters have not been used alone on MSW incinerators, but are used in combination with lime injection scrubbers, described below.

3. Scrubbers

Three widely used types of scrubbers exist. These include wet, dry, and wet-dry scrubbers. A wet scrubber can be designed with several different configurations, but they have in common an underlying principle of intimate contact of a gas stream with a liquid that may also contain some absorbent and/or reagent for removal of acid gases. Although some wet scrubbers have been installed in the past, typically on older incinerators, these are not likely to be used in the future due to several disadvantages, including the generation of a liquid waste effluent and a wet plume from the stack.

Figure 7



Fabric Filter

Dry scrubbers are typically cylindrical vessels where powdered dry sorbent is injected into the gas stream by compressed air. Intimate mixing of the sorbent and gas occurs, then dry gases flow into a highly efficiency device for particulate removal, such as a fabric filter or an electrostatic precipitator. For temperature control, a dry scrubber is often preceded by a heat exchange system which may also involve a water spray system to cool the gases. Figure 8 depicts a dry scrubber system with water sprays and fabric filter.

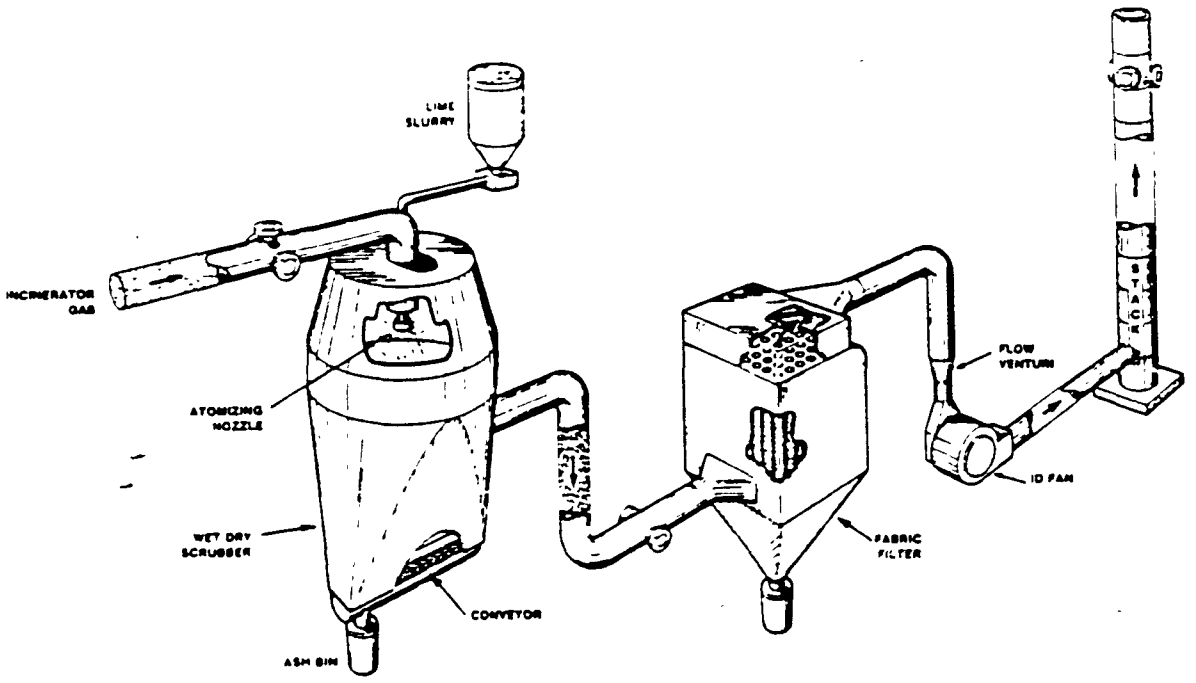
A wet-dry scrubber is also called a spray dryer or semi-dry scrubber, or even a dry scrubber. In a wet-dry scrubber a liquid sorbent stream is sprayed into a gas stream and the amount of liquid is carefully controlled so that all the liquid evaporates into the gas stream, yielding a dry fly ash product. A high efficiency particulate removal device, such as a fabric filter or an electrostatic precipitator, is required to remove the particulates from the gas stream prior to discharge up the stack. Figure 9 illustrates a wet-dry scrubbing system with a fabric filter.

C. Historical Perspective of Air Pollution Control for MSW Incinerators

The air pollution control systems used to reduce stack emissions from municipal solid waste incinerators are undergoing continued design improvement. In post-1980 North America, two-field electrostatic precipitators were succeeded by three, four and, more recently, five fields for enhanced removal of particulate matter from flue gas.

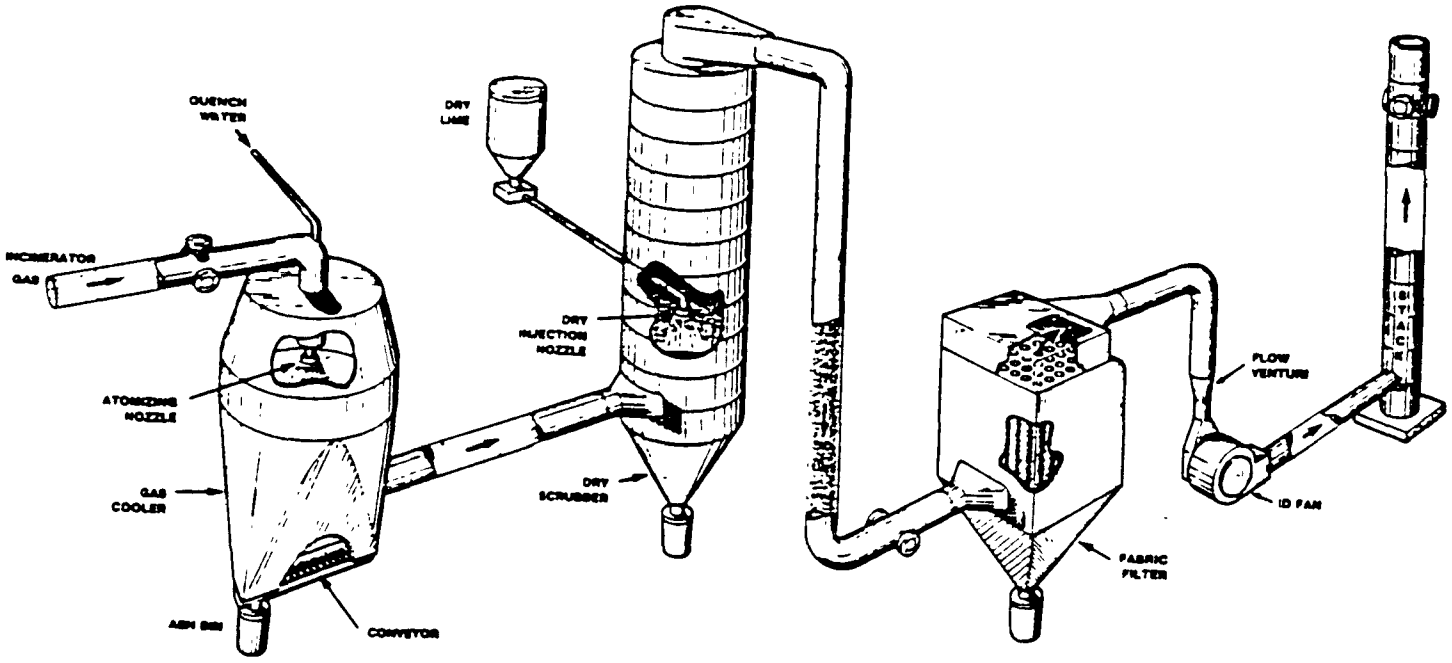
Beginning in the late 1970s, several air pollution control systems, consisting of a combination of a dry scrubber or a wet dry scrubber followed by either a fabric filter or an electrostatic precipitator, were installed in Europe and Japan. It appears that facilities adopting this technology initially

Figure 8



Wet-Dry Scrubber

Figure 9



Dry Scrubber

sought improved acid gas control. As concerns over trace organic compounds and toxic metals emerged during the past few years, questions arose regarding the capability of this equipment for removing these substances, as well as acid gases.

Up to 1985, limited sampling occurred at several scrubber/fabric filter installations in Europe, principally for emissions of particulates, acid gases (hydrochloric acid and sulfur dioxide) and certain metals. These studies generated a narrow data base of somewhat limited use, since the analysis of trace organic compounds was often omitted or, at best, confined to PCDD/PCDF or even TCDD/TCDF. In addition, the operating conditions of the incinerators and pollution control devices were often not well documented, and the studies did not examine a range of different operating conditions.

In 1985, Environment Canada completed extensive testing on a pilot-scale unit with pollution control equipment. This testing resulted in the first thorough data base for evaluating the performance of these control systems for a wide range of pollutants [4]. Testing of a more limited scope in Denmark [5] paralleled these efforts. The results of these tests indicate that, at appropriate temperatures, the scrubber/fabric filter technology can significantly reduce not only particulates and acid gases, but also a range of trace organics (PCDD, PCDF, chlorophenols, chlorobenzenes, PCB, polycyclic aromatic hydrocarbons), and a host of metals (including mercury, chromium, cadmium, and lead) in the stack emissions. Equipment design and operating conditions necessary to achieve high removal of these compounds were identified on a pilot scale in these studies.

The first full scale scrubber/fabric filter installation on a waste-to-energy incinerator in North America was tested and the stack data for PCDD/PCDF [6] show comparable concentrations to the emissions found in the pilot-scale studies discussed above. Several municipal solid waste incinerator facilities are now

operating in North American with this type of pollution control equipment.

The scrubber/electrostatic precipitator combination has been installed at several incinerators in Europe. However, data to evaluate this combination and compare its performance to that of the scrubber/fabric filter are currently limited to inorganic compounds. There is a reluctance on the part of regulatory agencies to permit such facilities because of the limited test data on scrubber/electrostatic precipitator installations. Equipment manufacturers and system suppliers also have some hesitation to guarantee that such facilities will meet very low emission levels required for some new plants. EPA may test a new scrubber/electrostatic precipitator installation at an incinerator in Massachusetts in 1988.

The scrubber/fabric filter technology reduces stack emissions to low levels approaching the detection limits for certain compounds, such as PCDD, PCDF and some metals. The data base to substantiate this capability is growing rapidly. Nevertheless, the reader should not construe that the Subcommittee endorses the scrubber/fabric filter as the only technology to use. Other technologies may offer equal or even better performance in the future. The potential development of other improved systems should not be hindered by undue insistence on the use of a scrubber/fabric filter.

D. Air Pollution Control Experience

1. Particulates

Tests on incinerators equipped with the conventional two-field electrostatic precipitator have shown a wide range of particulate emissions, varying from 50 to 300 mg/Nm^3. The three- and four-field electrostatic precipitators achieve emissions of 20 to 75 mg/Nm^3. An emission level below 20 mg/Nm^3 is technically possible. However, there is a high capital cost

associated with constructing a precipitator with a sufficient number of fields and adequate treatment area to consistently achieve such performance. Furthermore, the reliability of continued performance at such low emission levels remains to be demonstrated.

Scrubber/fabric filter control systems are capable of operating within a range of 2 to 20 mg/Nm^3. The material selected for the filter bags can have an important effect on filtering efficiency and the emission levels achieved. In general, test results to date for the scrubber/fabric filter indicate lower particulate emissions than those for electrostatic precipitators on municipal solid waste incinerators. However, there is considerable controversy that electrostatic precipitators can be as effective. The longer-term reliability and cost effectiveness of the various control processes also need to be considered.

2. Metals

Data exist on emission levels for approximately 30 different elements. Among those present in stack emissions from municipal waste incinerators are the following: lead, chromium, cadmium, arsenic, zinc, antimony, mercury, molybdenum, calcium, vanadium, aluminum, magnesium, barium, potassium, strontium, sodium, manganese, cobalt, copper, silver, iron, titanium, boron, phosphorus, tin, and others. (See Table 3)

A number of sampling studies for metal emissions were reviewed by M. Clarke [7]. Since the condensation point for metals such as lead, cadmium, chromium, and zinc is above 300°C, ultra fine aerosol particles will form for which removal efficiency depends largely on the efficiency of the particulate control system used. Efficient removal, defined as exceeding 99 percent, has been observed for most metals with the scrubber/fabric filter system. Conversely, relatively high metal emissions are associated with lower efficiency precipitators. Many existing

TABLE 3

CONCENTRATION OF STACK EMISSION COMPONENTS FOR MWC EQUIPPED WITH SCRUBBER/FABRIC FILTERS[a]

COMPOUND	CONCENTRATION IN (UNITS)
o TRACE ORGANIC COMPOUNDS	ng/Nm^3 @ 12% CO_2[b]
PCDD	1 - 5
PCDF	1 - 5
CB	100 - 1000
CP	200 - 1000
PAH	10 - 200
PCB	1 - 10
o METALS	ug/Nm^3 @ 12% CO_2
Zinc	5 - 10
Cadmium	0.5
Lead	1 - 6
Chromium	0.2 - 1
Nickel	1 - 2
Arsenic	0.02 - 0.1
Antimony	0.2 - 0.6
Mercury	10 - 40
o PARTICULATES	mg/Nm^3 @ 12% CO_2
All particulates	2 - 10
o ACID GASES	ppm
HCl	10 - 30
SO_2	10 - 40

[a] Source: Environment Canada [3]

[b] To convert to mass flow rates, use approximately 5000 nm^3 flue gas @ 12% CO_2 per ton of refuse as fired.

facilities have inefficient particulate control equipment, resulting in higher levels of metal emissions.

Since mercury is a relatively volatile metal, several studies indicate that both sufficient cooling of the flue gas (below 140°C, based on tests conducted to date) and a highly efficient particulate removal system are required to achieve high mercury removal. The scrubber/fabric filter system can achieve efficient mercury removal, provided that the flue gas is adequately cooled.

3. Acid Gases

Municipal solid waste incineration typically generates levels of 300-1000 ppm HCl, 50-200 ppm SO_2, 1-10 ppm HF, and 75 to 320 ppm NO_x. Lime injection into a scrubber/fabric filter system has resulted in removal efficiencies of 90-99 percent for HCl and 70-90 percent SO_2, provided that the flue gas temperature and the stoichometric ratio are suitable. This has reduced HCl to levels below 20 ppm and SO_2 to levels below 40 ppm. This technology has also been extensively used in other applications for acid gas removal [1, 2, 8].

The scrubber/electrostatic precipitator combination provides about 90 percent HCl removal, but typically less SO_2 removal (about 50 percent). Since precipitators and baghouses alone have no effect on HCl and SO_2 removal, lime injection into the furnace has been tested with some success (about 50-70 percent efficiency). Some sampling to determine HF removal has been reported. In general, HF removal of approximately 50 percent has been reported where HCl removal exceeded 90 percent.

The Commerce Waste-to-Energy facility in Los Angeles recently achieved significant NO_x reduction through the use of Selective Non-Catalytic Removal technology (SNCR). Start-up operation testing has shown NO_x reduction up to 50 percent. Most

MSW plants under permit review in California propose to use SNCR for NO_x control [9].

4. Trace Organics

Organic compounds for which emission data exist include PCDD, PCDF, chlorobenzenes (CB), chlorophenols (CP), PAH and PCB. Available test data identify a number of other organic compounds, including aldehydes, chlorinated alkanes, and phthalic acid esters. Since public perception has focused on PCDD and PCDF emissions, there are more data for these compounds, especially for the tetra homologues, and especially the 2,3,7,8 substituted isomers. The other compounds have been analyzed at only a few facilities.

Data clearly show that chlorinated dioxins and furans exit the boilers and, depending on the emission control devices employed, some fraction enters the atmosphere either as gases or sorbed onto particulates. In addition, the solids remaining behind in fly ash or bottom ash contain most of the same compounds, which become another potential source of environmental release of these substances.

Worldwide, there are data pertaining to PCDD/PCDF in stack emissions for about 35 incinerators. It is important to recognize that this data base was developed using somewhat inconsistent sampling and analytical techniques. Reported emission concentrations for PCDD fall into three ranges:

- low emissions, in the range of 20 to 130 ng/Nm^3,
- typical emissions, from 130 to 1000 ng/NM^3, and
- high emissions, over 1000 ng/Nm^3.

Average PCDD emissions from older plants may be expected to range from 500 to 1000 ng/Nm^3. Concentrations of the 2,3,7,8

isomers represent only small fractions of these levels. The "low emission" levels tend to be achieved by newer, well operated mass fired facilities such as waterwall plants and modular design incinerators. In most testing programs, adequate operating data were not collected to correlate emissions with incinerator operations. Researchers in the field theorize that combustion conditions can play a role in minimizing PCDD emissions [10]. Several studies are underway in Canada and the United States to define this role more exactly [11, 12].

Recently, Environment Canada has evaluated a scrubber/fabric filter system control for PCDD emissions, and has reported PCDD removal efficiencies exceeding 99 percent. This has resulted in PCDD concentrations at the stack that approach the analytical detection limit of the sampling and analytical equipment currently available. Emissions of PCDF exhibit a similar range of values, and the scrubber/high efficiency particulate removal combination can reduce PCDF to very low or non-detectable levels.

Some limited data on emissions of CB, CP, PCB, and PAH are available. Most sampling programs for PCDD/PCDF have unfortunately neglected to analyze for these compounds. Maximum levels from two Canadian studies follow in Table 4.

TABLE 4

SCRUBBER/FABRIC FILTER PERFORMANCE

COMPOUND EMITTED	INLET ng/m^3	OUTLET ng/m^3
CB	17,000	3,000
CP	30,000	8,000
PCB	700	Non-detectable
PAH	30,000	130

The scrubber/fabric filter technology generally achieved removal rates of 80-99 percent for these compounds in the Canadian studies. Very few studies report on other products in the flue gas. Some data from tests on older plants have been reported for aldehydes and certain volatile hydrocarbons [8]. Unfortunately, no data are available from newer plants.

5. Conventional Combustion Gases

The conventional combustion gas measurements include CO, total hydrocarbons (THC), CO_2, and H_2O. Both CO and THC have been considered as potential surrogates or indices of combustion efficiency for dioxin/furan production; however studies published before 1985 report no strong correlations. Nonetheless, a few authors have attempted to correlate CO and dioxin/furan data obtained from several different facilities [10]. From such comparisons, low CO levels (below 100 ppm) are associated with low dioxin/furan emissions. Higher CO levels, (ranging from 100 ppm to more than 1000 ppm), indicate high dioxin/furan emissions, but correlations are not consistent. During poor or upset combustion conditions, CO levels of 1000 ppm have been observed and THC levels have risen from a typical 1-5 ppm to 100 ppm and above.

A few studies have attempted to determine CO and dioxin emission data under varying operating conditions on the same incinerator, successfully demonstrate a direct correlation [4, 11]. Since one of the measures of optimized combustion that is available to incinerator operators is minimal CO production, one could hypothesize from the above noted correlations that dioxin/furan emissions could also be minimized. However, presence of high CO has been used more as an indicator of furnace upset, alerting the unit operator to take corrective action.

6. Ash Disposal

MSW incineration facilities generate several residues for disposal. These include incinerator bottom ash, boiler/economizer ash, electrostatic precipitator ash, scrubber ash, and fabric filter ash. The formation of the latter three types of ash depends upon the type of air pollution control equipment utilized.

Environment Canada studies report that the concentration of various organic and metallic compounds in ash greatly depends upon their source: bottom ash, boiler ash, or fabric filter ash. In general, most compounds present in ash appear to become progressively more concentrated in ash found further downstream in the combustion/pollution control process. For example, PCDD concentrations in fabric filter ash were reported as 200 - 700 ng/g, whereas 30 - 150 ng/g were detected in boiler/economizer ash, and PCDD were non-detectable in bottom ash. PAH have shown a mixed trend, with highest values in the bottom ash, lower values in the scrubber ash, and increased values in fabric filter ash. Most metals show a progressive increase in concentration (i.e. more in fabric filter ash than in scrubber ash); however, some metals such as chromium and nickel show the reverse trend. Highly efficient air emission control systems result in fly ashes with relatively higher concentrations of heavy metals and trace organics, since air pollutant removal is more efficient.

7. Ongoing Research and Development

Recent research results, based upon the more modern plant design and operation in the United States, Canada, Germany and Japan have contributed measurably to the existing knowledge base relative to emission control capabilities. Several ongoing studies in Canada, Germany, and the United States, will generate, during the next year, data that will provide additional information on the role of incinerator design in limiting

dioxin/furan emissions. A reduction of these emissions in the furnace will result in lower concentrations to be treated in subsequent air pollution control devices. This will result in lower concentrations of pollutants in the fly ash removed and, thus, can potentially reduce the concern with ash disposal.

E. Conclusions and Recommendations

1. Conclusions

o Recent studies of municipal waste incinerator particulate emissions indicate that state-of-the-art control devices reduce these emissions to levels of 20 mg/Nm^3 and less. It has yet to be demonstrated whether such levels of control can be maintained over long periods of time under all normal operating conditions.

o Acid gas control for HCl, SO_2, and HF can achieve 90-99 percent removal of HCL, and lower removal of SO_2 and HF where lime injection is used in conjunction with a wet scrubber, a dry scrubber or a wet-dry scrubber.

o Removal of heavy metals (over 99 percent) including mercury (over 95 percent), can be achieved provided that the flue gas temperature is maintained below 140°C and a highly efficient particulate control device is used (fabric filter or a properly designed electrostatic precipitator).

o Scrubber/high efficiency particulate removal technology offers the possibility of reducing PCDD/PCDF emissions to very low levels, well below 10 ng/Nm^3. This is 1 to 3 orders of magnitude below emissions data reported for incinerators lacking this type of control technology. In addition, this control technology is capable of removing a significant portion of CB, CP, PCB, and PAH.

Table 3 provides a summary of emission results from an Environment Canada study, using a pilot-scale scrubber/fabric

filter control system. These results provide further significant documentation of the low emission levels achievable with state-of-the-art air pollution control equipment.

o Currently, the only New Source Performance Standards [NSPS] for MSW incinerators relate to particulate control. There are no Federal standards directly controlling organic or metal emissions from MSW incinerators. Several states have established their own regulations and permit procedures as municipalities and private industry have proposed facilities. This inconsistency of emission requirements among various levels of government has contributed to public uncertainty regarding the use of this technology and has caused further complexities in the permitting process.

2. Recommendations

Adequate data may exist to begin to develop technology based emission standards for municipal incinerators. However, EPA and private industry should continue research to better define trace emissions, and the relationship between combustion, control technology and emission of these hazardous substances. Conducting this research will provide an improved data base for risk assessments that can lead to more scientifically informed decisions for adequate protection of public health and the environment.

VI. ENVIRONMENTAL TRANSPORT AND FATE

A. Dispersal and Persistence In Environmental Media

Pollutants emitted to the atmosphere, entering soils or waters, or deposited in landfills are subject to a variety of dispersal processes and fate mechanisms, including transformation. Transformations can result in the destruction of the parent compounds and the simultaneous formation of one or more chemical products. The parent compounds or the products may have long or short periods of persistence. The transformations may be photochemical as can occur via atmospheric processes in the airborne plume, on the surfaces of soil and vegetation, and near the top of water columns. They may be chemical reactions that can proceed in the dark. They may be mediated by physical and biological processes at or below soil surfaces and in surface waters. From the viewpoint of assessing potential effects, the degree of persistence or rate of destruction of the parent chemical in the various environmental media and the identity, quantity, and persistence of the products are of great importance.

Assessments of fate -- transformation being one of many fate processes -- clearly rely on knowledge of the identities and quantities of the parent compounds. Little information is available on the fate of chemicals from MWC operations because of the paucity of information on the parent compounds released in either stack emissions or ash. Furthermore, there is currently no substantive program designed to identify and quantify products formed from the parent substances. In some instances, in which the parent compounds have been identified, scientists can make reasonable predictions of fate based on published studies.

Assessments of the environmental transport and fate of chemicals also depend upon the availability of validated mathematical models which can make efficient use of the available data. The availability of such models is, in turn, dependent on

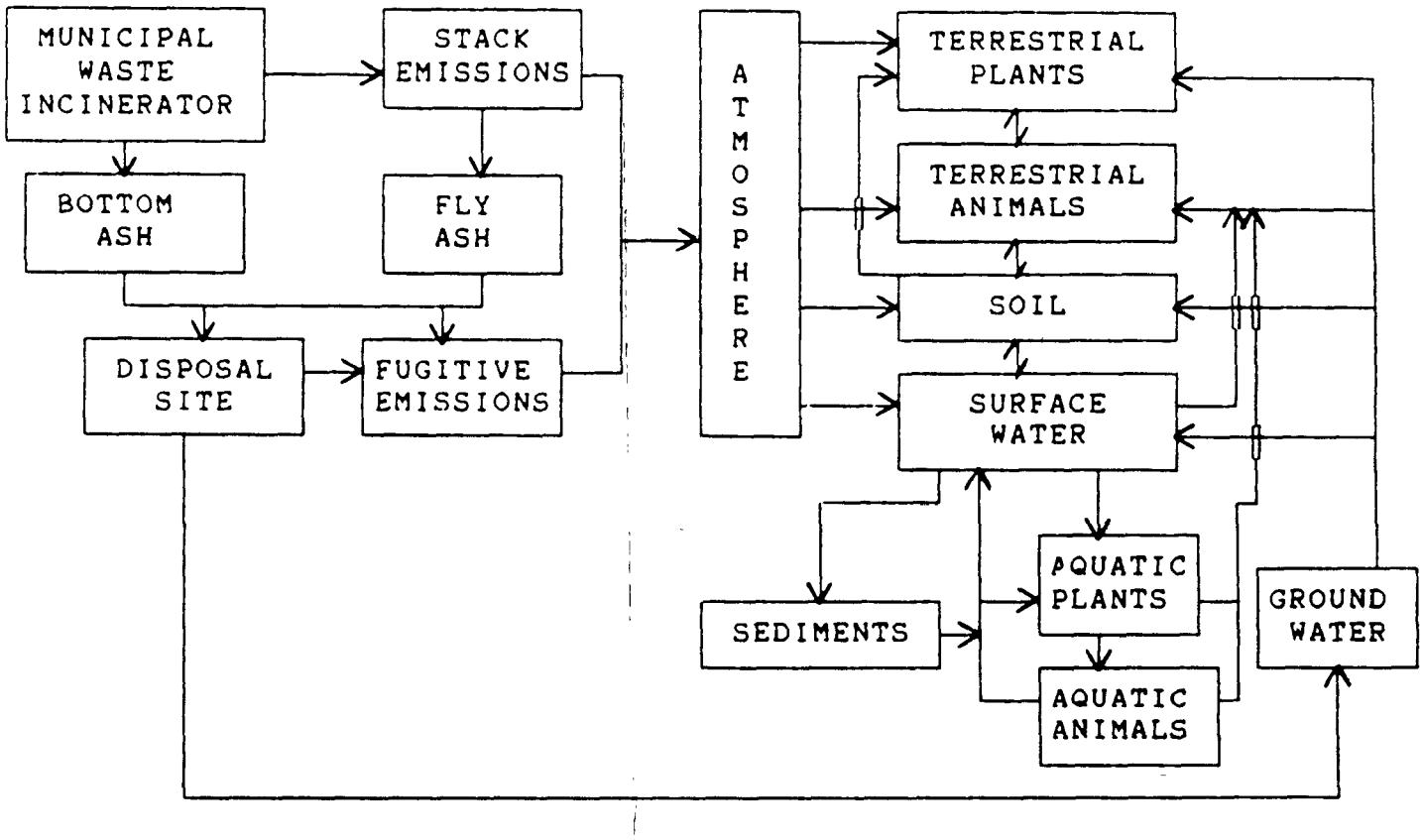
an understanding of the transport and fate processes occurring in different media. Unfortunately, current levels of knowledge regarding the transport and fate of chemicals vary greatly for different environmental media. In general, knowledge of atmospheric transport and fate processes is much more advanced than that for other media. This factor is reflected in the pages to follow where discussions relating to atmospheric transport and fate are more extensive than those for soil and water.

Figure 10 schematically depicts the major transport pathways that may disperse MWC emissions through the ecosystem. However, current understanding of complex terrestrial food webs, biotransformation and bioaccumulation processes, and the influence of these environmental processes on the quantitative transport and fate of chemicals, is rudimentary at best.

1. The Atmosphere

The atmospheric transport and fate of emissions from municipal solid waste incinerators are governed by a broad spectrum of physical and chemical processes. These include emission dynamics, such as plume rise and downwash; plume chemistry, involving changes of state and chemical reactions; atmospheric transport and diffusion; gravitational settling; dry deposition; and wet deposition, due to in-cloud and below-cloud processes. Model simulations are scientifically feasible provided the emissions are properly characterized along with the atmospheric and topographic structure of each site. The use of so-called generic conditions can result in model results that are not representative of realistic potential impacts. Model simulations are impeded further by the scarcity of information on combustion products and the atmospheric transformations of those products from any emission sources.

Figure 10



Transport of MWC Emissions From an Incinerator Facility Through the Ecosystem

a. Stack Emissions

Understanding emission products requires characterization of the plume constituents and the factors pertaining to their release, including temperature, velocity, and physical characteristics of the materials exiting the stack. Emissions need to be characterized according to chemical state, rate of release, and, for particulates, size distribution, density, and mass. The description of the release must take into account factors such as stack height and diameter, efflux velocity, and sensible and latent heat content in order to calculate plume rise and the effective release height. The latter also requires characterization of the vertical (and sometimes the horizontal) structure of the ambient atmosphere--winds, temperature, and humidity. Several algorithms are available which provide representative estimates of the effective plume rise [13].

Downwash can occur where the stack height is low with respect to the incinerator or adjacent buildings. This phenomenon occurs due to aerodynamically generated, horizontal-axis vortices or eddies in the lee of the stack/structure that transport the stack plume to the ground, thereby effectively creating a ground-level volumetric source. Case-specific analyses are required to assure the absence or prevention of adverse downwash effects in the vicinity of a given incinerator. In general, however, it is possible to estimate minimum stack-height requirements using the so-called "2.5 times rule" that suggests that stacks discharge their emissions at a height at least 2.5 times the height of the tallest nearby structure. "Nearby" is interpreted to include structures whose horizontal separation from the stack is less than five times the height or width of these structures (whichever is greater).

EPA's Administrator has promulgated regulations (40 CFR Part 51) that define the use of good engineering practice (GEP) to limit the stack heights that can be used to avoid downwash. EPA has developed guidelines for determining GEP stack height [14],

and to provide guidance for the use of fluid modeling (i.e. wind tunnel simulations) to determine GEP stack heights [15].

b. Atmospheric Dispersion and Transformation

The transport and diffusion of gaseous and particulate MWC emissions are governed by the magnitude and variability of the wind, the thermal stratification of the lower troposphere, and the aerodynamic characteristics of the ground surface (including manmade structures). These factors interact, and their characterization is frequently difficult (but tractable), especially in urban areas and complex terrain.

Well established and representative modeling techniques are available from the Agency, especially for determining long-term impacts rather than short-term case studies [16]. It is important, however, that the atmospheric measurements used as inputs to these models be representative of conditions both at the source and downwind. For example, wind and temperature profiles recorded from observing instrumented weather balloons located at airports are frequently not representative of the urban environment. Similarly, stability estimates based on airport surface weather observations may not be representative in urban areas, or when extrapolated to areas that are bounded by large water bodies. A useful overview of dispersion parameterization methods is provided by Hanna, Briggs and Hosker, 1982, [17] as well as many other sources.

c. Deposition

Removal of particulate emissions and gaseous constituents by atmospheric deposition is also an important fate process. The removal and deposition at the earth-air interface occurs by dry deposition and precipitation scavenging. Although there has been extensive theoretical and observational research on these fate mechanisms, there is still considerable uncertainty surrounding

both physical processes and modeling. Hosker and Lindberg, [18] have prepared a critical review and summary of these issues.

o Dry Deposition

Dry deposition of large particles occurs by gravitational settling. Several mechanisms remove small particles and gases at the surface, including impaction, electrostatic attraction, adsorption, and chemical processes. The fall velocity of particles is determined by the balance between gravitational forces and aerodynamic drag forces, and depends on particle size, density, and shape. Inert materials typically deposit more slowly than reactive materials or charged particles, and vegetated surfaces effect greater deposition than bare surfaces. Dry deposition estimates for MSW emissions are, therefore, subject to considerable uncertainty. Hanna, Briggs and Hosker, have estimated the distance from sources of several heights at which 50 percent of the plume is depleted through dry deposition for a wind speed of 1 m s^{-1} and a deposition velocity of 1 cm s^{-1} [17]. These data are summarized in Table 5, and they clearly show that dry deposition can be an effective removal process for certain combinations of source height and stability.

TABLE 5

DISTANCE IN km WHERE DRY DEPOSITION DEPLETES THE MASS OF A PLUME BY 50 PERCENT FOR A WIND OF 1 m s^{-1} AND A DEPOSITION VELOCITY OF 1 cm s^{-1}

Meteorological Stability Class	Source Height(m)			
	0	10	50	100
A-B	>10 km			
C	1.8	18	43	60
D	0.4	3.5	8.6	19
E	0.15	2.2	8.3	17
F	0.10	2.0	10.0	28

Source: Hanna, Briggs and Hosker, 1982 [17]

o Wet Deposition

Wet deposition of plume material occurs both as the result of in-cloud scavenging by cloud droplets (i.e. rainout) and below-cloud scavenging by rain or snow, called washout. Scavenging is a function of pollutant reactivity, solubility, size distribution (for particulates), rainfall intensity, and cloud residence time. Therefore, it is important that both clouds and pollutants be carefully characterized in order to provide accurate estimates of wet deposition.

Washout and rainout are typically combined and expressed in terms of either a scavenging coefficient or washout ratio. The scavenging coefficient is more appropriate to single episode events and is used to express the decrease of concentration with time. The washout ratio averages conditions over multiple precipitation events. It is defined as the effluent concentration in precipitation normalized by the effluent concentration in air, and tends to decrease with time of precipitation in a given storm and increases with the overall precipitation rate. Worst-case wet deposition rates and distributions could be obtained using data from specific events while long-term wet deposition amounts may be better estimated using the washout-ratio concept.

o Deposition on Soil

The Agency has presented a number of possible approaches to evaluate exposures to emissions from municipal waste combustion. However, literature available to the Subcommittee contained only a few examples that sought to predict environmental concentrations of chlorinated dioxins around municipal waste incinerators. These approaches, although simplistic and limited, may be helpful in indicating whether more sophisticated analyses should be undertaken. Beychok made an effort to calculate exposure of soil to PCDD based on air concentrations. He calculated a value of 7.5×10^{-10} g/g of soil [20]. The

Subcommittee also conducted its own evaluation of possible soil deposition which might be associates with the emissions of the Hampton, Virginia incinerator facility. The Subcommittee concluded that simplistic environmental transport models, which did not include any allowance for the possible breakdown of emitted compounds, did indeed provide similar estimates to those cited above. Dispersion modeling of PCDD by Higgins, predicted maximum ground-level atmospheric concentrations on the order of 10^{-12} to 10^{-13} g/m^3 [21]. Average ground-level concentrations were predicted to be approximately 5 orders of magnitude lower than stack concentrations. However, until confirmed by measurements, the significance of these simplistic modeling exercises will remain very controversial.

2. The Terrestrial Environment

The Subcommittee has examined the terrestrial fate of PCDD and PCDF as examples of the terrestrial fate of MWC emissions because emissions of PCDD/PCDF have generally been studied more intensively than the emissions of other compounds, such as metals and acid gases. Unfortunately, knowledge of the fate and transport of PCDF/PCDD emissions is largely based upon the application of mathematical models. In this case, knowledge of the physical transport models is superior to our understanding of the fate of these chemicals during transport and subsequent deposition.

Despite a limited understanding of the terrestrial fate of dioxins and furans that have the potential to be deposited on ground and vegetation surfaces as a result of municipal waste combustion, there is some evidence that incinerators are the source of dioxins found in nearby surface soils [22]. Given this evidence, major questions arise concerning the fate and mobility of dioxins in the terrestrial environment due to the lack of definitive information concerning the physical nature of the stack emissions, atmospheric transformation, photodegradation,

volatilization, mobility in soil, and translocation in and retention by plants.

Whereas particulate dioxin emissions are characterized by condensation onto fly ash, virtually all research on the environmental fate of dioxins has focused on pure dioxin, dioxins in solvents and herbicides, dioxins in aqueous solution, and dioxins from the 1976 ICMESA accident in Seveso, Italy. Furthermore, most research on the fate of dioxins has been concerned with 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD) which is a solid at standard atmospheric temperature and pressure, has low solubility in water but high solubility in organic solvents and has a very low vapor pressure. Approximately half of all incinerator emissions are gaseous and dioxins may be emitted along with these gases, however, most relevant research has been conducted with TCDD, a solid. Therefore, the fate of gas-phase dioxin emissions is largely unknown. Except as noted, the following discussion refers to the environmental fate of 2,3,7,8 - TCDD.

In the atmosphere, 2,3,7,8-TCDD may be subject to photolysis and oxidation by the hydroxyl radical. A photolysis half-life on the order of 5 to 24 days is estimated for typical sunlight conditions. No quantitative estimates of oxidation rate are known to be available, presumably due in part to the lack of information on atmospheric abundance and distribution of the hydroxyl radical.

Photodegradation of dioxins appears to be the principal loss mechanism, although the findings are in some cases contradictory and poorly understood. Research indicates that TCDD is unstable when dissolved in solvents and exposed to ultraviolet light [23, 24], while thin films of pure TCDD applied to glass plates are reported to be stable in sunlight [24]. Later studies indicate that TCDD photodegrades when contained in a herbicide solution; the loss rate is greater when the solution is applied to plant leaves and less when applied to soil surfaces (presumably due to

shading) [25]. Subsequently, Plimmer confirmed that pure TCDD can decompose by UV photolysis when applied to glass in very thin layers, while soil appears to protect against UV degradation [26].

Studies of fate in soils indicate that TCDD can be persistent under certain conditions with an apparent half-life of approximately one year [24, 27]. TCDD is nearly immobile in the soils tested by Helling [28] and Matsumura and Benezet [29]. The latter also found microbial degradation of TCDD to be very slow as did Isensee and Jones [30]. On the other hand, Young et al. report biodegradation losses with apparent half-lives of 250 days. They also report that plant uptake and transport are very slow [31].

Perhaps highly relevant environmental studies regarding soil transport and fate are those of DiDomenico et. al., [32, 33], who made measurements following the ICMESA chemical plant accident and release of 2,3,7,8-TCDD. Surface soil samples (7 cm deep) were analyzed at 44 locations 1, 5 and 17 months after the accident. Overall, concentrations decreased significantly between the first and second surveys with an equivalent mean half-life of 10 or 14 months. Concentrations changed very little between the second and third surveys, and the apparent half-life was estimated to be greater than 10 years. These changes in apparent half-lives with time show that half-life, or first-order kinetics are inappropriate for describing the persistence of TCDD. Concentration profiles were also measured at about 32 sites to depths of 136 cm, up to 17 months after the accident. Significant soil penetration was observed, although concentrations decreased rapidly away from the soil surface. As a generalization, the concentration of TCDD more than 8 cm from the surface was ten fold lower than that in the upper 8 cm. Some of the soil profiles showed maximum concentrations in the 0.5 to 1.0 cm layer, rather than in the uppermost layer, suggesting degradation at the surface as well as migration away from the surface. Loss mechanisms at the surface were not identified, nor

were the specific transport phenomena, although it was suggested that "migration in the soil may have occurred along with soil colloids and particles to which TCDD may have been bound."

3. The Aquatic Environment

Even less information is available on the transport and fate of MWC emissions and residues in aquatic systems. Contaminants associated with particulates emitted from MWCs are subject to deposition on surfaces downwind from the facility. This fallout is subsequently subject to dissolution or suspension in rain or meltwater from precipitation events. Eroding soil and flowing water enter nearby water bodies, and suspended solids may settle out and become incorporated with the sediment in such water bodies. The dissolved portion may also infiltrate into the ground, recharging groundwater and may be re-evaporated into the atmosphere.

Again, PCDD and PCDF emissions, specifically TCDD, have been studied in more detail than other identified contaminants and, therefore, they are used as examples. The transport of dioxin - contaminated soil into lakes and streams by erosion is evidenced by the detection of 2,3,7,8-TCDD in water samples from a Florida pond adjacent to a highly contaminated land area [34]. Additionally, several laboratory studies have shown that lakes or rivers can become contaminated with minute quantities (ppt) of 2,3,7,8-TCDD and possibly other dioxins through leaching from contaminated sediments. In a study reported by Isensee and Jones 2,3,7,8-TCDD was adsorbed to soils, which were then placed in aquariums filled with water and various aquatic organisms [30]. Concentrations of the dioxin in the water ranged from 0.05 to 1330 ppt. These values resulted from initial soil concentrations of 2,3,7,8-TCDD ranging from 0.001 to 7.45 ppm. The investigators concluded that dioxin adsorbed to soil could lead to significant concentrations of 2,3,7,8-TCDD in water if the dioxin-laden soil was washed into a pond or other small body of water.

Other investigations have given similar results. Using radiolabeled 2,3,7,8-TCDD, Ward and Matsumura showed that, after dissolution from contaminated lake bottom sediment, dioxin concentrations in water ranged from 0.3 to 9 percent of the original dioxin concentration found in the sediment [35]. Results of another test indicated that a total of about 0.3 percent of the applied dioxin concentration passed through sand with leaching water [29]. In some cases, the observed concentration of TCDD in the water was greater than its water solubility (0.2 ppb). The dioxin present in the aqueous phase probably results from presence of 2,3,7,8-TCDD metabolites, and binding or adsorption of TCDD onto organic matter or sediment particles suspended in the water. In another study, application of 0.1 ppm TCDD to a silt loam soil led to TCDD concentrations in the water ranging from 2.4 to 4.2 ppt over a period of 32 days [32].

The findings of such investigations are consistent with recent reports that TCDD migrates to nearby water bodies from industrial chlorophenol wastes buried or stored in various landfills. At Niagara Falls, New York, for example, 1.5 ppb TCDD has been detected at an onsite lagoon at the Hyde Park dump where 3300 tons of 2,4,5-TCP wastes are buried. Sediment from a creek adjacent to the Hyde Park fill is contaminated with ppb levels of the dioxin. There is growing evidence that TCDD has migrated from process waste containers in the landfill of a former 2,4,5-T production site in Jacksonville, Arkansas. The dioxins have been found in a large pool of surface water on the site (at 500 ppb), downstream of the facility in the local sewage treatment plant, in bayou bottom sediments, and in the flesh of mussels and fish. TCDD is also apparently being leached into surface and groundwaters from an 880-acre dump site of the Hooker Chemical Company at Montague, Michigan. Dioxins were found on the site at a level approaching 800 ppt [37].

A recent study, [38], considers the fate of 1,3,6,8-tetrachlorodibenzo-p-dioxin in aquatic systems. This congener,

though less toxic and persistent than 2,3,7,8-TCDD, has been reported as a component of fly ash from municipal incinerators. A major portion of the total TCDD isomers entering the environment from both herbicide and combustion sources is 1,3,6,8-TCDD. Movement and accumulation of 1,3,6,8-TCDD were monitored in air, water, sediment and vegetation over a 426-day period. Sediments were shown to be the major reservoir for the compound, accounting for 5 to 14 percent of the added compound after 426 days. Five to eight percent of the applied compound could be accounted for in the water. The experimenters concluded that volatilization losses may represent a significant route of release following slow release from sediment and decayed plant material. TCDD isomers degrade only under conditions of high microbial activity, such as in the presence of decaying plant material, and in situations where the compound is bioavailable. Direct and indirect photolysis are major paths of chemical loss in shallow water; however, little of the compound is degraded in waters shielded from sunlight.

The above information on the fate and dispersal of TCDD in waters is relevant to assessments of MWC emissions and residues, but these compounds are not the only ones likely to be present in such emissions and residues, as previously pointed out. Metals and acidic gas components should also be assessed to adequately characterize the transport and fate of MWC by-products in aquatic environments. A considerable data base gives insight into the participation of metals in environmental processes. MWC emissions, however, have not been well characterized, and likely constituents have not been identified or verified. Without an understanding of the metal contaminants that are likely to result from MWC emissions, environmental transport and fate determinations cannot be scientifically supported. Similar problems with different complexity surround acid gas emissions and associated transport and fate determinations.

B. Conclusions and Recommendations

1. Conclusions

Atmospheric concentrations and surface depositions of MSW emissions result from a complex relationship among such factors as emission rates, plume rise, downwash, dispersion, chemical reactions, and wet and dry removal processes. Casual attempts to simulate or estimate ambient and surface pollutant levels can lead to large uncertainties in the results. Notable gaps in current knowledge include identification and quantification of the organic or other chemicals contained in stack emissions, and aquatic and terrestrial transport and fate processes. There are other cases where current information is inadequate to permit reliable predictions of concentrations and compounds that result from MSW emission.

2. Recommendations

o A comprehensive data base should be developed through atmospheric field studies at several representative MSW facilities. The data base should be used to estimate deposition (wet and dry) of particulate and gaseous emissions, and the organic compounds generated should be identified and quantified. Such field studies and the resultant data base should also be used to evaluate mathematical and fluid models of transport, diffusion and deposition in urban and suburban environments. The data base should include measurements of MSW emissions (stack and fugitive), plume rise, dispersion, and wet and dry deposition, and should incorporate the use of inert gaseous tracers and soluble particle tracers; both long-term and case-study (i.e. intensive) measurement programs should be conducted.

o Fluid modeling studies should be conducted for urban MSW incinerators and those likely to be affected by complex terrain. EPA should implement fluid modeling methods for GEP stack height determination in the design and siting of MSW facilities.

Fugitive particulate emissions also need to be considered. Estimation of their impact on areas downwind is complicated by the need to model the processes by which the particles become airborne. Major difficulties include description of the source term and specification of the accompanying local wind field.

o There have been significant advances in the design and performance of municipal waste incineration facilities. An environmental monitoring program should be instituted that will assess the occurrence of combustion products from diverse sources before a state-of-the-art municipal waste incinerator begins operation, and then assesses the incremental contribution of combustion products from the municipal waste incinerator after it begins to operate.

C. Transport and Fate of MWC Ash

1. Considerations

The solid waste or ash generated by municipal waste incinerators potentially contains any and/or all of the same chemical substances found in stack emissions. The masses of most individual components are likely to be greater in the solids since the chemicals preferentially partition to the solid particles. Unfortunately, in few data sets are the solids well characterized chemically.

The ashes remaining after combustion, and those collected by pollution control devices, can pose a threat to humans and the environment if not properly handled and disposed. For example, ash from particulate control devices at one incinerator visited by the Subcommittee was poorly contained and was observed to be partially dispersed into the ambient air through large, unsecured openings in the exterior walls of the incinerator building. Fugitive dust (ash) was also observed to be blowing off the top of uncovered dump trucks.

It is common practice to dispose of incinerator-generated solids in municipal landfills. Once landfilled, the solids and associated pollutants are mixed with other wastes, some of which may be liquid. These wastes vary considerably in their chemical and solvent characteristics. They are composed of mixtures of organic solvents, decomposing organic materials, and high or low pH liquids. Just how the pollutants will react and interact as they associate with added MWC ash under such conditions is unknown. Some of the organic pollutants may leach from the ash particles, especially if they are exposed to organic fluids. Some of the trace metals may be dissolved under normal conditions in ground water.

A Canadian study has been recently completed which focuses on the leachability of metals and trace organic compounds for different ashes from a dry scrubber/fabric filter system, and a wet/dry, scrubber/fabric filter system [3]. Batch leaching tests with distilled water on a laboratory scale indicate that there was no organic contaminant mobility from any of the ashes, except for chlorophenols. However, long-term leaching of organic compounds was not determined.

An extensive investigation of the disposal of bottom and fly ash in a separate ash landfill subjected to acid precipitation showed no significant mobility of metals [39]. Although the ash contained significant quantities of metals, most were not mobilized at the expected pH of the ash/leachate system. In contrast, some metals, such as copper, lead, zinc, and boron, were leached to varying degrees when subjected to waters of varying pH in a Canadian Study [3]. Significant quantities of cadmium, lead, zinc, and copper may be leached in the short-term, suggesting that further investigation and special handling of these ashes are needed for safe disposal.

Landfilling of fly and bottom ash, without some stabilization, may or may not pose hazards that surpass those presented by burying wastes that have not been incinerated. The

mass of municipal waste may be reduced considerably by incineration, but some of the constituents in the ash, especially heavy metals, may become correspondingly more concentrated. Also, the chemical form of many elements may change during the incineration process, affecting the subsequent transport and fate of the resulting compounds. Such changes may result in either increases or decreases in the leachability of the substances.

EPA has developed two leaching tests with potential applicability to assess transport and fate of pollutants in ash. These tests are the Extraction Procedure (EP) test, and the Toxicity Characteristic Leaching Procedure (TCLP). Such tests were designed for purposes other than assessing the pollution potential of MWC ash, and, therefore, the salient features of these tests should be evaluated to determine their applicability for assessing MWC ash.

2. Conclusions and Recommendations

a. Conclusion

Insufficient data exist on the identities and quantities of chemicals in ash residues, preventing a rigorous scientific evaluation of the transport and fate of contaminants discharged from municipal waste incinerators.

b. Recommendation

State-of-the-art analytical chemical techniques should be employed to characterize ash samples, and as many of the extracted compounds from selected installations should be identified as feasible, to provide a useful data base. The goals of this effort should include determination of the speciation and mobility of trace metals and trace organics released from municipal solid waste combustion facilities.

c. Conclusion

The practice of disposing of bottom ash and fly ash from municipal waste combustors by landfilling will be of increasing concern as more MWC employ state-of-the-art pollution control technologies. It is time to consider the disposal of ash as a discrete problem, independent of the combustor itself. A number of approaches already being applied to the disposal of hazardous residuals could be utilized. Generally these involve solidification or vitrification of the waste material. Grouting of disposal trenches, sometimes in combination with liners, is another technique that may be applicable. The Subcommittee recognizes that these techniques may need to be modified to meet the particular chemical characteristics of bottom ash and fly ash, although much work has been done on the utilization of coal-fired power plant fly ash.

d. Recommendation

The present handling and disposal practices of ash, especially fly ash, should be examined closely in light of data regarding the potential for movement of heavy metals, contained in MWC ash, into the environment. This examination should include identification and quantification of the inorganic and organic chemicals that may leach from both fly and bottom ash. Determination of the transport and fate of identified chemicals should follow, and should include determinations of bioavailability.

VII. POTENTIAL EXPOSURE AND EFFECTS

The ensuing discussion of potential exposures and effects associated with municipal waste combustion should not be construed as a risk assessment of this technology. Rather, it is a discussion of the data needed to further improve EPA's ability to conduct a risk assessment of municipal waste combustion emissions and discharges and to enhance the public's understanding of this technology. The Subcommittee's critique of EPA's risk assessment methodology (See Appendix I) indicates that the procedure that has been developed is a significant preliminary step that aids decision makers in evaluating the risks of municipal waste combustion.

It is clear that a certain fraction of the components of stack gases and particulates, fly and bottom ash, and scrub waters will reach the ambient environment. Their presence in the ambient environment may result in human and environmental exposures. The preceding chapters have identified research needs pertaining to the quality and quantity of emissions and discharges, and their potential transformations and delivery to sites where ecosystems and humans could be exposed. In this section, the Subcommittee examines the need for data that will improve the characterization and prediction of potential exposures and effects to both humans and ecosystems.

On the basis of current scientific information, the Subcommittee cannot state that no risk is posed from municipal waste combustion. From both a scientific and a policy perspective, the two most critical unsolved questions are as follows:

o What is the relative contribution of pollutants emitted by municipal waste combustors relative to other combustion sources?

o What is the probability that human or environmental receptors will be exposed to harmful amounts of incinerator emissions or discharges?

At best, obtaining answers to these questions can help resolve the issue of the risk associated with this technology. At a minimum, such answers can reduce the current uncertainties faced by scientists and decision makers as they seek to develop environmentally "safe" alternatives for municipal solid waste disposal.

A. Environmental Loadings

The by-products of municipal waste incineration (stack emissions and ash discharges, for example), contain constituents that are virtually all already present in the environment. They originate from a variety of combustion sources including vehicles, smelters, home wood burners, and fossil fuel power plants. The emissions generated by municipal waste incineration will add to emissions from other sources to yield the total environmental load. The relative proportion that MWC discharges will contribute to total ambient levels is open to question, and will vary from site to site.

The Subcommittee concludes that, with state-of-the-art combustor designs, controlled operating conditions, and effective emission control devices, the emissions from MWC alone are not likely to significantly increase total environmental loadings on a national basis over the next generation. This conclusion rests on the observation that the reported environmental levels of chemicals known to be emitted from MWCs do not appear to be significantly greater in Sweden or Japan, countries that practice a much greater degree of incineration than that projected for the United States. In addition, this conclusion assumes that, over time, existing facilities, both controlled and uncontrolled, will be replaced or retrofitted with advanced design features, controlled operating conditions, and emission control equipment.

This conclusion can, of course, vary with the total loadings generated from this and other sources in specific municipalities. It should not be expected that loadings from an incinerator in Philadelphia or Boston will be of the same proportion (relative to other combustion sources) as loadings from an incinerator in the rural southwest. The policy issues faced by decision makers in these two regions of the country may also be different. In the former case, a chief issue will be the incremental risk that is experienced by urban populations relative to other sources; in the later instance, a major issue will be the impacts of a new source, a risk in the absence of other major combustion sources. Members of this Subcommittee cannot answer the question of whether such risks under either scenario are acceptable. What scientists and engineers can do is inform citizens and decision makers of current risks and uncertainties, and develop recommendations for further reducing them.

B. EXPOSURES

1. Human Exposures

The ambient environment at any particular MWC site may present a hazardous exposure to either humans or ecosystems. Assessing exposure to MWC emissions is particularly difficult. The compounds present are generated from a variety of sources, and isolating the contribution of pollutants from MWC is a complex undertaking. The magnitude of exposure to MWC emissions depends upon 1) the density of respective populations, and 2) the extent to which the environment already receives discharges from other sources. Individual life styles also influence the body burdens of these chemicals. For instance, cigarette smokers may have higher levels of cadmium in their kidneys than individuals of the same age who do not smoke. Cadmium may also be a component contributed by MWC ash residues. The level of human exposure to municipal waste combustion discharges will be highly

site-specific, and its significance will be dependent on contributions relative to other combustion sources.

Based on present and proposed incinerator sitings, it is likely that municipal incinerator facilities will be sited in or near areas with dense human populations. Siting areas are likely to be industrial and urban, as opposed to agricultural and rural.

A significant amount of background information on the toxicity to and tolerance of humans to many of the components identified in MWC emissions has been collected. Much of this information exists in the general toxicological literature. The data also appear in secondary sources, where the information has been summarized and evaluated, such as in criteria documents and health advisory documents prepared by the U.S. EPA, in criteria documents prepared by the National Institute of Occupational Safety and Health, and in various publications of the National Research Council. When combined with existing data on precombustion exposure levels, adequate criteria can be developed to both protect human health and facilitate the permitting process for plant construction and operation.

2. Ecosystem Exposures

When compared to humans, much less is known about the exposures of plants and animals to MWC discharges and potential toxicants. Moreover, even less is known about how well (or poorly) ecosystems respond to, tolerate or recover from exposure to these substances.

EPA supports research on the tolerance of aquatic vertebrates and invertebrates to such substances dissolved in water. These efforts, along with work in structure/activity relationships among chemicals, toxic equivalency research, investigations into the tolerance relationships among species, and research into the community and ecosystem level responses to toxicants, serve to provide a basis for the kind of information

necessary for ecological risk assessment in general. However, little of this effort is directed specifically to municipal waste combustion emissions.

The ecosystem components most likely to encounter risk from municipal waste incineration emissions, in the short-term, will be aquatic and terrestrial life existing near the facilities. Ecosystems may experience longer-term or chronic risk depending upon the persistence and accumulation of emitted substances.

3. Approaches for Estimating Exposure

EPA's approach, to date, for estimating exposures of humans and ecosystems has been to develop models that make a number of assumptions, in the absence of data, as to how pollutants reach human and environmental receptors through direct and indirect pathways. The Subcommittee believes that modeling represents a first but only a preliminary step towards answering the two major questions of this chapter. Modeling in the absence of even limited data or validation is simply too uncertain a tool from which to present statements to the public on the presence or absence of risk from a technology. What is needed is for EPA, the private sector and the public to take the next step, that is to develop a strategy for: 1) measuring the emissions and discharges from major combustion sources and the proportion of such emissions and discharges attributable to municipal incinerators, 2) measuring selected human and environmental receptors in urban and rural areas to discern impacts, and 3) comparing the source-receptor relationships that emerge.

C. Effects

1. Human Health Effects

The impact on health from ingestion, inhalation and dermal absorption of individual chemicals or chemical mixtures emitted by municipal waste combustors depends on the dose humans receive

and the duration of the dose. The Agency has maintained an active program to develop health advisories, criteria documents, and risk assessments that characterize the toxicology data base and evaluate the dose-response relationships in humans for many of the chemicals identified as by-products of MWC. Understanding the impacts from MWC was not the primary motivation for such efforts. Nonetheless, pertinent information and analyses have resulted. Additional relevant information is available in the toxicological literature. Very little information is available on the effects of specific isomers or on effects of mixtures. Interactions between and/or among compounds may enhance or eliminate their toxicity or bioavailability.

Although a data base exists for many compounds, the effects caused by a significant number of substances are relatively unknown. There may also be chemical constituents in MWC emissions or residues that have not been identified.

2. Environmental Effects

The response of individual organisms to toxic substances is a function of concentration, toxicity and duration of exposure. Combinations of these functions may produce lethality or more subtle responses, such as behavioral changes or reproductive inhibition. These sublethal effects can take on a multitude of forms with varying effects. They are often difficult to detect under field or laboratory conditions.

Much of the bioassay research on environmental pollutants has been conducted using fish and aquatic invertebrates. Less research has been performed with plant, mammalian and avian species and with microbes. To a large extent, this research has yielded data on the levels of a toxicant to which species produce an acute response, while research on chronic and behavioral responses is now under way.

Beyond studies of individual organisms, the responses of populations, communities and ecosystems are important to assess. Because these environmental units are not easily subjected to experimentation, simulation models are often utilized. However, models are often limited in their capability to predict responses.

Unlike the human health effects data base, very little information is available on the environmental effects that result from compounds contributed by MWC technology. While EPA and other research organizations support work on the toxicity of atmospheric toxicants to terrestrial plants and animals, little of this effort is directed to specific evaluation of MWC emissions or residues.

D. Conclusions and Recommendations

1. Conclusions

o The Subcommittee concludes, based on currently available information, that emissions from state-of-the-art, well-controlled and operated municipal waste incinerators are not likely to significantly increase total pollutant loadings to the environment on a national basis. However, background levels will vary with the sites selected for the incinerator plants, and it is important to distinguish background levels from new emissions before adequate exposure and effects assessments can be developed.

o There are very limited data for evaluating both exposure and effects of MWC emissions or residues. It is clearly not feasible to conduct toxicity tests on representatives of all species, but effects on animals, terrestrial plants and microbes have not been well characterized when compared to fish and aquatic invertebrates.

o More data are available for assessing environmental effects on individuals and populations than on more complex communities and ecosystems. Very little is known about how ecosystems respond to toxicants from any particular source, including municipal waste incinerators.

o Exposure data for some selected compounds that are potentially emitted by MWC are available for evaluating human health effects; however, data on specific isomers and other compounds identified as by-products of MWC have not been collected. In addition, mixtures of compounds and associated interactions under environmental conditions have not been investigated or evaluated.

o Throughout its report, the Subcommittee has separated the evaluation of municipal waste combustion into various components including: feedstock, the incineration process, combustion system design, performance of pollution control technologies, operator capabilities, environmental transport and fate processes, and potential exposures and effects. Each of these can also be thought of as a critical component for assessing the risk of this technology.

2. Recommendations

o EPA, private industry and other interested organizations should initiate efforts to characterize emissions into the ambient environment or conduct baseline surveys through site-specific sampling and field monitoring techniques. EPA should consider whether to require such data collection as part of the permitting process. By accumulating and analyzing such background data, the foundation for an accurate comparison of post-combustion environmental effects can begin to emerge.

o The Subcommittee recommends that a higher priority be placed on evaluations of environmental exposure and effects. Individual or species level toxicity testing should be conducted

with compounds potentially emitted by MWCs. This testing should occur in species that are known to be of primary importance in community interactions, including terrestrial plants, animals and microbes for which data are scarce.

o The exposure and effects data base for human risk assessment should be expanded to include more of the compounds identified in MWC emissions and residues, as well as their transformation products. The use of toxic equivalency and structure/activity relationships should be expanded and refined through collection of such data. In addition, toxicity evaluations of mixtures and products that are predicted from interactions should improve the risk assessment process.

To improve the utility of such investigations for decision makers, data should be generated and evaluated from a range of incinerators (controlled and uncontrolled, as well as both new and old designs) in a variety of locations. From such efforts, scientists can obtain data that can be used to test the "ground truth" and the sensitivity of previous modeling efforts. In combination, modeling and measurements will provide decision makers with more powerful tools to assess the relative contribution of pollutants from MWCs relative to other sources, and the probability of exposures reaching human and environmental receptors.

VIII. CONCLUDING PERSPECTIVES

The Municipal Waste Combustion Subcommittee recognized a central fact throughout every phase of its deliberations on the incineration of municipal wastes - the existence of some degree of hazard, or risk, associated with the application of any technological alternative (landfilling, preprocessing and recycling, etc.) for managing the disposal of solid waste. Limitations in current scientific understanding make it difficult to make precise statements on the relative risk from the various alternatives on a large scale and over time. Since every recognized alternative practice has some associated risk, it is important to compare the risks posed by all waste management alternatives. Risk-based comparisons of the various options can provide a valuable perspective to aid local decision makers in choosing the most appropriate option for their community.

The previous chapters have pointed out some of the deficiencies in the data base for conducting a formal MWC risk assessment. Nevertheless, the Subcommittee finds that a significant amount of research has been carried out on the biological and human health effects of dioxins and, that considerable data are becoming available on levels of emissions and on the impact that control technologies have on emissions at incinerators currently in use. In addition, government agencies, industry and other researchers are currently characterizing potential human and environmental exposures from air emissions and from ash, and have begun to establish research plans.

Unfortunately, the other waste management options are also plagued by significant data gaps, preventing scientifically rigorous analyses that could lead to comparative risk assessments. On the basis of risk assessment alone, therefore, the Subcommittee believes that no single waste management alternative is universally applicable to the range of site-specific solid waste problems that municipalities encounter. At the same time, the Subcommittee concludes that well-designed,

well-operated and well-controlled incinerators represent one alternative that should be available for use by localities.

As stated at the beginning of this report, the Subcommittee did not evaluate the other waste management technologies in depth, but it is possible to illustrate certain commonalties and differences among these alternatives. In Table 6, the Subcommittee compares the relative advantages of landfilling (without prior treatment), municipal waste combustion and recycling. For the purposes of this illustration the reader should assume that incinerator ash is landfilled, that the portion of waste that can not be recycled is landfilled, and that recycling procedures include processing after collection. The relative importance of each issue can differ significantly, depending in part upon site-specific conditions. The relative advantage for each factor, as judged by the Subcommittee, is denoted as (a) for most advantageous, (b) moderately advantageous and (c) as least advantageous.

While Table 6 considers only a limited number of issues, it illustrates that when different management options are compared, they may exhibit advantages or disadvantages, depending upon which issues are highlighted. Comparisons among these options for a single issue are difficult. For instance, in the case of groundwater contamination, incineration may produce a major impact as metals leach out of ash. The same metals are present in raw, landfilled waste, but metals become more concentrated in ash. The form of metals also affects their leachability. In the case of recycling, the potential problems are intimately related to the exact recycling process used, and can range from negligible to very significant.

TABLE 6

COMPARATIVE ADVANTAGES OF SELECTED WASTE DISPOSAL OPTIONS

ISSUES	INCINERATION	LANDFILL	RECYCLING
Air Emissions	c	b	a
Methane Generation	a	c+	a
Land Volume Required	a	c	b
Transportation	depends on distance		
Energy Recovery	a	c	b
Leachable Metals	b-c	b-c	a
Leachable Organics	a	c	a
Reduction of Infectious Agents	a	c	?-c
Reduction of Rodents	a	c	b
Groundwater Contamination	b	b	a-c
Surface Water Contamination	a	a	a-c
Capital Cost	c	a	b-c

a = most advantageous

b = moderately advantageous

c = least advantageous

? = uncertain

+ = methane generation can be harnessed to advantage

- Conclusion

All waste management options entail some form of risk. Each option has environmental advantages and disadvantages. Although the assessment of municipal waste incineration *per se* generates useful information, the value of that information is very limited when one seeks to develop guidance for the selection of the preferred waste management options in specific communities. In order for decision makers and the public to make informed decisions on the most appropriate waste management options for their community, it is important to have comparative assessments of the options that are under consideration for specific sites.

- Recommendation

EPA can assist local decision makers and the public by developing ways to collect and analyze data that will allow more informed choices regarding the management of municipal solid waste. Such support can be provided by developing approaches for assessing exposure and by generating models for assessing risk. In addition, means should be provided or improved to facilitate the transfer of such tools and information to the parties responsible for making the decisions. The Agency should develop guidance for evaluating individual waste management options, as well as comparative exposure and risk assessments between available options.

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Appendix A

ASSESSING EPA'S RISK ASSESSMENT METHODOLOGY FOR MUNICIPAL INCINERATOR EMISSIONS: KEY FINDINGS AND CONCLUSIONS

ASSESSING EPA'S RISK ASSESSMENT METHODOLOGY FOR MUNICIPAL INCINERATOR EMISSIONS: Key Findings and Conclusions

Introduction

On November 10, 1986, the Municipal Waste Combustion Subcommittee of the Environmental Effects, Transport and Fate Committee of EPA's Science Advisory Board reviewed a draft document entitled "Methodology for the Assessment of Health Risks Associated with Multiple Pathway Exposure to Municipal Waste Combustor Emissions" prepared by the Office of Air Quality Planning and Standards (OAQPS) and the Environmental Criteria and Assessment Office (ECAO). This document will be referred to hereafter as the "methodology".

The purpose of the risk assessment and exposure methodology developed in the document under review is to examine the potential health and environmental effects exposed populations are likely to experience as a result of municipal waste combustion (MWC) technologies. This asessment allows comparison of variations in the efficiency of combustor design and operation, and is also intended to predict the effects resulting from multiple exposures to emissions from more than one source.

OAQPS and ECAO requested the Subcommittee to evaluate the scientific validity of the methodology for assessing health risks associated with multiple pathway exposures to municipal waste combustor emissions. Specifically, the Subcommittee was asked to determine whether the methodology provides a reasonable scientific approach to evaluating effects on public health given the available data, the validity of exposure assessments, and the appropriateness of transport and dispersion models. The Subcommittee's key findings are reported in the following pages; detailed comments and meeting transcripts have been provided to appropriate Agency authors.

General Comments and Methodology Overview

Overall, the Subcommittee considers the proposed methodology to be conceptually thorough, although it identifies a number of areas where specific technical improvements are needed. Since the methodology will be used as a technical support document for regulatory decision making, a thorough technical effort is necessary. The approach also makes reasonably effective use of existing scientific data and exhibits the degree of accuracy and understanding needed for using models. The Subcommittee consensus is that the methodology is a credible effort towards developing a tool for assessing multiple media exposures from this source category.

The Subcommittee commends the authors on both the tone and the detail used in documenting the assumptions that support the methodology. The uncertainties and possible consequences of

using the methodology are clearly presented in a number of instances, such as limitations created by focusing on stack pollutants rather than total pollutant loadings (e.g., ash residues, aqueous residues, and stack emissions). Another concern is the uncertainty in identifying specific pollutants in emissions from a municipal waste combustor, since characterizing emissions improves the ability to predict the physical and chemical properties and effects of emitted substances. The authors are clearly aware that the methodology they have developed is but a step in a development process to expand current risk assessment methodologies to include other pathways, in addition to atmospheric, exposures beyond inhalation and non-human effects.

The Subcommittee has several recommendations for placing the scientific issued raised by the use of this technology into better perspective. These recommendations include:

° The methodology should attempt to predict the risk posed from both combustion as a whole and from specific activities, such as automobile use, industrial practices (e.g., coal combustion for energy production), and both hazardous chemical and municipal incineration.

° While individual scenarios are modeled in this methodology, calculating dose from the source and dispersal through various pathways does not lead the reader to understand the entire risk perspective that incineration technologies present.

° In applying the models, the methodology utilizes two separate sites as examples: 1) Hampton, Virginia, and 2) a proposed, or hypothetical, state-of-the-art facility to be located in Florida. Although both sites are individually discussed and evaluated as to the risks they presumably pose, they are not compared. Since risk assessment is a comparative tool, the Subcommittee recommends that the chosen sites be evaluated in comparison to one another, and for reasons to be discussed later, recommends that facilities in addition to Hampton be used for this comparison.

° The subcommittee believes that the most appropriate data for monitoring MWCs may be derived from combining actual field measurements with predictions from mathematical models. For the field measurements, this presupposes that measurements have been made in appropriate locations, at appropriate times, and with appropriate methods. It also presupposes, for the mathematical models, that they have been validated at least to the extent that their limitations are understood and that the range of divergence between model predications and reality can be quantified. In this context it is important to consider both statistical variability and its propagation through the model, as well as conceptual biases which inherently result from making the

simplifying assumptions required for the construction of models. The Subcommittee recognizes that elements of this recommendation are best carried out through a longer-term research program.

The document should definitely state that, even when models are validated, actual data are preferable to results predicted by models. Also, the methodology should caution that the existence of a useful model should not substitute for or discourage the collection of site specific data. In addition, the methodology should encourage the use of field data and model application in concert.

The methodology appropriately states that much of the information needed to further support the methodology does not exist, and that some assumptions about non-existent data must be made to make initial predictions. However, the specific choices in such assumption raise several questions for the Subcommitte, which are addressed in the sections to follow.

The Subcommittee recommends that uncertainties be identified as to whether they are the result of limitations in the understanding of the MWC process itself, or a result of the predictive capability of the model.

Technology and Emissions

The document cover attempts to represent a broad perspective of exposure patterns. However, the Subcommittee is concerned that the drawing depicts a worst-case exposure scenario without illustrating the problem-solving aspects of the technology. This concern centers around the negative impression that may result from the depiction of a particulate emissions plume. It was also noted that the illustration represents a rural setting, and does not depict the urban environment, where most incinerators may be built.

The methodology reviews the state-of-the-art for existing and projected municipal waste combustors, and provides useful background information. However, various sections on existing and projected facility sites are inconsistent with regard to future locations. In addition, projections for California may be misrepresented. The Subcommittee believes that it is important to distinguish between the number of facilities and the number of incinerator furnaces, since most facilities consist of several incinerators that can be operated independently.

Using a combination of dry scrubber and fabric filter technology for pollution control is reported to reduce mercury emissions by 50 percent. Data actually demonstrate that at 140 degrees Celsius (C) or below, 95-97 percent collection is achieved, while at 209 degrees C, no collection is achieved. The average may be 50 percent, but averaging this type of data does not accurately represent the performance of the control system.

The methodology discusses many factors that may influence emissions. The apparent and ultimate conclusion is that the efficiency of the air pollution control system determines the emission level of particulate matter (PM) and associated pollutants from the stack. This conclusion should be clearly stated.

The Subcommittee disagrees with the use of the Hampton facility to represent existing incinerators and their emissions. Use of this inappropriate example will yield a gross overestimation of emissions from new incinerators. The Hampton data set may be extensive, but the technology used at the facility is hardly representative of typical mass burn technology. The design and operating practices used at Hampton should be explained, along with the fact that this design is not in common use. This facility provides a worst case scenario that is not representative of most recent installations. The results of modeling will be very different when best available control technology (BACT) is used. The Subcommittee recommends that EPA develop more scenarios, including one for BACT, that can be used to evaluate a more complete range of source and emission characteristics for existing and proposed MWC facilities.

The methodology cites three reasons to explain the presence of polychlorinated dibenzo-dioxins and furans (PCDDs and PCDFs, respectively) in MWC flue gases. A fourth reason should be added, since these organic compounds may be formed in the boiler during cooling, in the presence of fly ash (post-combustion formation). It should also be stated that little is known about reactions that occur between gaseous species within emission plumes.

The methodology recognizes that the available emissions data are limited in both quantity and quality. Few specific chemicals have been identified, although much of the total mass has been characterized as silicates and forms of carbon. There is reason to suspect that some of the chemical components of MWC emissions that remain to be identified may be toxic. However, these chemical components, such as polyaromatic hydrocarbons (PAHs), may be contributed by sources other than municipal incinerators, and background levels are not adequately established. Major data gaps exist with regard to chemical identity, toxic potential, and total environmental burden of MWC emissions, making the assessment of risk posed by the technology itself, and in comparison to other alternatives, difficult to predict.

Exposure Models

- Industrial Source Complex (ISC) Model

The introduction to the ISC model would be improved by a discussion of the likely uncertainties of the estimates for models of gaseous dispersion, particle dispersion, and wet and dry deposition of gases and particles. This discussion should

address uncertainties that arise both as a result of limitations in the understanding of the processes and those due to random variation in deposition and dispersal processes.

Although some of the assumptions made in parameterizing wet deposition may be rather crude (e.g., assumptions regarding the spatial distribution of precipitation), they are not likely to present a problem when annualized computations are made. However, the parameterization of dry deposition, particularly for emission of chemicals for which loss mechanisms are not understood, is not clear. The methodology seems to imply that gaseous components are not considered. This point needs to be clarified. The use of data concerning the size distribution of particles obtained from the Braintree MWC may not be representative, and the data on emission rates seem to be conservative.

The methodology for atmospheric dispersion and deposition of emissions should separately consider particulate and gaseous emissions and their fate. The contribution from chemicals in different physical and chemical states should be evaluated with respect to to direct and indirect routes of exposure. Variability in the size and solubility of particles should be considered. The biological availability of emitted materials is also affected by the degree of sorbtion to particles that occurs. The discussion should specify the assumptions made about emission characteristics.

The effects of buildings on lateral and vertical dispersion of emissions has been considered in the methodology. However, careful consideration of downwash is also necessary. The proximity of other structures in urban areas and the potential for downwash are not treated in the methodology. Since one of the strengths of the ISC model is the ability to consider multiple sources, the document should also address the issue of the proximity of other incinerator facilities.

The methodology does not consider the exposure of people who do not reside at ground level. This factor could be significant for urban residents, and is compounded by the likely concentration of incinerators in urban settings.

- Human Exposure Model (HEM)

The HEM is used to estimate the carcinogenic risk posed to populations by inhalation of predicted ambient air concentrations of MWC emissions. The model assumes equivalency of indoor and outdoor concentrations, an assumption that the Subcommittee finds suspect for two reasons: 1) the finite length of typical infiltration rates ($\geq$ 1 hour, typically), and 2) the significance of indoor sources of certain chemicals.

The HEM estimates do not consider the short or long-term mobility of the population. It also assumes a 70-year lifetime for MWCs. In other parts of the methodology, a more realistic 30-year estimate is utilized. The assumption of continuous operation of MWC facility is also an unrealistic assumption.

Specific aspects of the locality and siting of the MWC facility need to be considered because of their significant effect on concentration and dispersal of pollutants.

The document should refer to the discussion of quantitative risk assessment modeling found in EPA revised guidelines for cancer in order to provide the reader with a better understanding of the range of assumptions and models used in cancer risk assessment.

° Terrestrial Food Chain (TFC) Model

This model is used to predict the deposition of MWC emissions on soil and vegetation. Its pathways assess the exposure to humans, animals, soil biota and vegetation, and associated effects on the food chain. The TFC model has separate components for examining the potential for human exposure from ingesting contaminated soil and from consuming vegetation and animal tissues containing the contaminants. The potential for children to be exposed as a result of ingesting soil is also estimated. However, pathways of human exposure via consumption of herbivorous animals are not clearly explained. The assumption that herbivores are exposed only by ingesting soil or by consuming plants that have assimilated emitted materials deposited on soil neglects consideration of the component presenting the highest exposure potential. Herbivores are likely to receive the highest exposure from ingesting leaves of plants upon which particulate emissions have been deposited.

The Subcommittee questions the appropriateness of using sludge or pesticide amendment practices as surrogates for predicting fallout from MWC emissions. The burden of toxic compounds and metals that is created by applying sludges to soils should be compared to that presented by the assumption that rates of dioxin or furan emissions will equal or exceed 2.7 kg/ha over 50 km linear dimension as a result of MWC.

This model uses a hypothetical Florida MWC as an example for making predictions, but the input factors, such as rates of emissions, soil characteristics, and design and operation, are not documented. It is not clear whether the Florida MWC represents a best or worst case illustration. More exposition is needed with respect to both input and output parameters. These improvements would greatly enhance the reader's understanding of the methodology.

° Exposure Pathways

The assumptions required for determining the maximally exposed individual (MEI) need to be considered more carefully to prevent the overconservatism which may result from combining the basic MEI concept with those resulting from the multi-exposure models. The MEI concept estimates the effect on only one hypothetical human subject; population effects and effects over generations are not determined. The MEI concept also does not consider acute exposure or exposures to other biota. These oversimplifications result in conservative estimates of human exposure. A new concept should also be developed which includes the cumulative probability of MEI exposure.

Another flaw in the methodology is the assumption of flat terrain. Urban or hilly settings may, in actuality, result in greater levels of human exposure.

The methodology does give appropriate consideration to soil type. Soils differ greatly, making the selection of a specific standard soil density and penetration depth tenuous. Compounds from MWC emissions will be deposited at different concentrations and will be found at varying depths in the soil, depending on soil type. Assumptions that toxicants will be concentrated in the upper centimeter of soil may be incorrect for some locations because of differences in soil density, moisture and composition. Some toxicants will be concentrated near the soil surface, while others may move down from the surface and be dispersed.

Degradation of chemicals in soil is often assumed to be a first-order reaction, even when data for specific chemicals indicate that the degradation rate is not first order. The best available kinetics should be used, since first order kinetics may often be inappropriate.

In the methodology, trace metal contaminants are assumed to persist indefinitely unless loss constants are available. A reasonable loss constant, which can be derived from soil pH values, should be used instead of making a blanket assumption that contaminants will persist.

Assuming that no degradation and no retardation takes place for chemicals in the plow depth layer is of concern when there is a lack of data to support this assumption. The fate of chemicals is known to be altered in plow depth layers composed of organic clays as a result of biologic activity.

° Surface/Ground Water Models

Tier one of the surface/ground water methodology assumes that all material deposited during a single year is incorporated into the water in the same year. This model does not take into account the potential for build-up over periods of more than one year, or the potential for this large amount of material to be released by a single storm event at some future time. In drier

climates (i.e., the Intermountain West and the Southwest deserts) major storms or "gully washers" can occur as seldom as once in 10 years, rendering doubtful the assumption that all toxicants adhering to particulates are flushed out in a one year period. Furthermore, in wet climates the opposite may be true, as some toxicants may not build up appreciably.

° Other Exposures Not Considered

As the authors point out, no consideration is given to exposures from landfilling ash. Similarly, consideration is not given to the potential for change in emission characteristics that may result from incinerator upsets. These data gaps are significant, but consistent with the inadequate knowledge regarding MWCs. The Subsommittee recommends that the methodology address these issues.

Estimation of Risk to Humans

The equation used to calculate the adjusted reference intake (RIA) is logical for application, since the use of the acceptable daily intake (ADI) is well established. Also, the use of excess concentration over background in the equation is an established measure of the potential for human health effects. However, the definition of total background intake (TBI) of pollutants from all existing sources needs some clarification.

Examples presented in the methodology use national averages to define the TBI, although these values may not be representative of the particular sites where risk is to be evaluated. The approach taken for risk assessment is based on the location with the minimum RIA, although people at this location may not be those with the maximum exposure to the pollutant. The Subcommittee believes that the values selected may not be valid for the particular sites being evaluated.

Defining the TBI as the sum of contributions from individual sources assumes that no interactions, such as synergism or antagonism, occur when sources are combined and individuals are exposed by multiple routes. There are many instances where this concept is not supported by the available data.

There is inconsistency in the methodology's treatment of exposure to background concentrations of different chemical substances. For some chemicals, such as cadmium, contributions from MWC emissions are added to contributions from all background sources to give total exposure. For other substances, such as benzo(a)pyrene, exposures to background concentrations are ignored and assessment is conducted in terms of additional risk posed by MWC contributions alone. The methodology should assess exposure to chemical substances in a consistent manner.

The prediction of inhalation exposure, which assumes that individuals are exposed to emissions only in gaseous form, neglects the potential for particulate absorption and particle

deposition. Pathways other than inhalation, such as dry depositon of particulate emissions and related dermal absorption, need to be considered.

The methodology postulates that some noncarcinogenic effects that exhibit thresholds occur only after nearly an entire lifetime of exposure. This assumption does not reflect the actual situation. For example, fibrotic lung diseases occur after less than a full life span of exposure, and their onset is very gradual. For many chemicals, the reported latency periods tend to be measured in terms of weeks or months, rather than years.

Relative effectiveness (RE) is used in the methodology to standardize effects of exposure by one route to the effects of exposure by another. There may not be scientific justification for this conversion factor. However, the concept is useful as long as users realize that the effect of an exposure does not relate solely to absorption efficiency, but is also related to differences in the sensitivity of absorption sites to damage, and to differences in toxicokinetics between exposure routes. The methodology should acknowledge the assumptions required for using this approach.

Consumption of fish by the general population is discussed, but the discussion does not take into account the fact that fish may come from a variety of sources with varying degrees of contamination. A similar situation exists for drinking water. Drinking water obtained from any one tap may consist of water from a local source, may contain water that originates outside of the localized delivery area, or may be a mixture of both. Alternatively, drinking water may be obtained from individual wells drawing on ground water from a large source or deep aquifer. Local contamination is not always represented in the localized supply of drinking water.

With regard to water consumption, the amount of fluid intake documented is low. It is not clear whether this amount represents total fluid intake or the intake of water alone. It is usually assumed that fluid intake for adults averages 2 liters per day. It is questionable, therefore, that females between the ages of 14 and 16 would only take in 586 ml water per day, as reported in the document.

Ecological Effects

The treatment of plant uptake as a linear function is erroneous unless no other information is available. Many toxicants, especially metal salts, are actively transported across membranes or cell walls and, therefore, cannot be described by a linear function.

The Subcommittee disagrees with the assumption that plants are exposed to contaminants mainly through uptake from soil. Greater exposure is likely to occur from foliar deposition. Estimates of deposition can be obtained from acid deposition

studies and also from studies of the nuclear energy industry, e.g., deposition of radioiodine (I^{131}).

The Subcommittee also questions the method used to average bioconcentration data for aquatic species. Even when means are calculated separately for bivalves and fin fishes, misleading interpretations can result. The bioconcentration data should be correlated with human dietary factors. For example, humans consume more oysters than mussels, and oysters may accumulate significantly more contaminants than mussels. Averaging bioconcentration factors together for oysters and mussels may create a significant source of error in calculating exposure to bioaccumulated chemicals.

The document summary mentions measurement of adverse effects on natural ecosystem vitality. The definition of ecosystem vitality is unclear, as are the endpoints to be used in measurement. Uptake from water is modeled, but few other environmental endpoints are considered. One important component not treated is the highest trophic level, predators. Predators play an important role in community regulation. There is also a need to consider the potential for concentration of materials in sediment, since sediments may serve as a source of contamination for overlying waters, and materials concentrated in sediment may be biologically available to benthic organisms and organisms dwelling in the water column. Assessments of exposure cannot be derived from water quality concentrations for benthic dwellers, since they are exposed in a totally different way.

In closing, the Subcommittee agrees that the methodology represents an appropriate step towards modeling and predicting exposure from MWC emissions. Some conceptual assumptions can be strengthened by closer examination of the complexities associated with pollutant emission to and interaction with the environment, while others must await collection of actual field data to fill in knowledge voids and elucidate environmental interactions. Finally, the methodology, over time, must be validated with actual data to evaluate and demonstrate its utility, and to guide its further development and refinement.

Appendix B

DIOXIN TOXIC EQUIVALENCY METHODOLOGY SUBCOMMITTEE REPORT: EXECUTIVE SUMMARY

A. Major Subcommittee Conclusions

EPA has proposed interim procedures for estimating health risks for CDDs and CDFs based on the premises that: (a) toxicity equivalence factors can be assigned to untested (or incompletely tested) compounds on the basis of structure/activity relationships; and (b) the toxicity of mixtures of these compounds can be approximated for policy purposes by the sums of their TEF times concentrations. Empirically, the present proposal falls generally between the positions adopted by certain European countries, which rank 2,3,7,8 TCDD far above any other congener in toxicity, and that initially proposed by the state of California, which equates all the dioxin congeners. All have used similar scientific assumptions in developing policy.

The Subcommittee agrees that the congeners of CDDs and CDFs constitute a class of chemical substances that share similar structural relationships and qualitatively similar toxic effects and, therefore, can reasonably be considered together. From the limited toxicologic data available it seems reasonable, too, to consider those tetra-to hexa-chlorinated compounds with chlorine substitutions at the lateral 2,3,7,8 positions as a closely related subclass in terms of biological activity and environmental fate.

The Subcommittee also concurs that the problems in assessing the health risks of dibenzo-p-dioxins and dibenzofurans are two-fold. They include: limited information from human or experimental studies about the hazards from exposure to these compounds (few of the 75 CDDs and 135 CDFs have been tested at all) and even more limited information about their possible interactions in mixtures. Indications of interactions, mostly additive, are found in certain experimental model systems (e.g. binary combinations). Not addressed in the draft document, however, is the possibility of chemical and toxicologic

interactions with other types of compounds in complex environmental mixtures, especially solvents that might affect uptake and retention by the body. EPA should address the latter subject in the TEF document, perhaps with more specific reference to its recently published Risk Assessment Guidelines and to three National Academy of Sciences' reviews on toxicological interactior the last of which is currently being prepared for EPA and the National Institute of Environmental Health Sciences. The Subcommittee also questions the basis for including or excluding other chemicals with effects similar to CDDs and CDFs, such as chlorinated biphenylenes.

Based upon its review of the draft document, the Subcommittee concludes that the method proposed by EPA is a reasonable interim approach to assessing the health risks associated with exposure to mixtures of CDDs and CDFs for risk management purposes. It is necessary, however, as lessons are learned from toxicologic research and from application, the approach should be re-evaluated systematically by EPA. Moreover, attempts should be made to validate the method by selected experimental testing of hypotheses. For example, more data are needed on in vivo potencies of additional PCDDs and PCDFs to compare with in vitro test results. The assumption of additivity can be evaluated by comparing observed activities with predicted activities in selected tests.

The Subcommittee recommends that EPA place more emphasis on the interim nature of the method in the document. The Subcommittee anticipates that, over time, the method will be modified and eventually superseded as more precise data become available. Meanwhile, the general method proposed appears to have utility for this and for other classes of closely related compounds where toxicologic data are incomplete. Application of structure activity relationships is an old and established practice of demonstrated usefulness in pharmacology and toxicology.

However, EPA should not abandon its exploration of other approaches to estimating risks for substances in mixtures. For example, where variability in the composition of environmental samples is not wide, a reference standard approach might be used (similar to those used in toxicology for selecting a reference cigarette or a representative blend of gasolines). As another example, the incorporation of a small amount of radiolabeled test compound into a representative and defined mixture might be one useful way of determining *in vivo* whether the uptake and metabolism of one congener is greatly modified by the presence of other substances in a mixture.

Some additional technical comments that the Subcommittee wishes to draw to the Agency's attention include: 1) perceptions by many Subcommittee members of an over-reliance upon the postulated mechanisms of the Ah receptor/AHH enzyme induction upon which to gauge relative and absolute toxicity; 2) the need to discuss the work of Matsumura, Rozman, Greenlee, Poellinger and others on additional toxicologically significant effects of the dioxins other than those associated with receptor binding or with cytochrome P-450 induction; 3) observations of a disassociation between AHH induction and cytotoxicity in studies on the gonado toxicity of TCDD; and 4) examination of the extent to which the longer biological half-life of higher chlorinated dioxin isomers, as compared to 2,3,7,8-TCDD, counter-balances their lesser *in vivo* potency.

B. Major Subcommittee Recommendations

The Subcommittee has several recommendations for improving the report. First, the draft report narrative is relatively brief and may not be readily understood by those not familiar with dioxins. For example, four

possible approaches are introduced and one (TEF) selected, but the document does not clarify what the other three aproaches are and the reasons for their rejection. The first approach, long-term animal testing, might be appropriate for municipal incinerator fly ash, where analytic data suggest there is a characteristic pattern of composition. The second approach (short-term assays) is not clearly described (not even whether they are in vivo or in vitro). The third approach, additivity of the toxicity of components, is at first rejected in the narrative but then forms the basis for handling the equivalents to 2,3,7,8-TCDD in mixtures.

Because the draft document presents a procedure, it is essential that the decision steps be clearly articulated, the assumptions made explicit, and the mechanics of calculating be illustrated in a stepwise fashion. To approach the subject from the viewpoint of studying the whole class of pollutants and to avoid bias by selecting data, the Subcommittee recommends that the tabular data be enlarged to include all compounds with zero to eight substituted chlorines. Biological activity has been reported for di- and tri-CDDs, and carcinogenicity studies exist for DD and 2,7 DCDD, as examples. Moreover, the activity of brominated and other substituted compounds should also be indicated and a specific effort encouraged to collect data on non-chlorine substituted compounds.

In contrast with the document's first priority on carcinogenic and then on teratologic effects in animals, the Subcommittee recommends that the TEF methodology assign first priority to human data when it exists. In evaluating experimental data, EPA should continue to follow the current

toxicologic practice of evaluating all endpoints, and selecting the ones most reliable, sensitive, and important for risk assessment. Thus, columns should be added to the tables in the document for other important toxic endpoints including immunotoxicity, thymic atrophy, body weight, and enzyme induction in vivo. The limited data points from which TEFs are currently derived (e.g. carcinogenicity of 2,3,7,8-TCDD, 2,3,7,8-Hx CDDs and reproductive effects of those compounds plus 2,3,7,8-TCDF) should be critically re-examined and the range of experimental data and estimated potencies from all studies tabulated. The Subcommittee also recommends that EPA consider assigning higher relative TEFs to CDFs in general, and 2,3,4,7,8-PeCDF in particular.

The Subcommittee strongly believes that EPA should assign greater priority to obtaining and using data on toxicokinetics, including metabolism. The rates of uptake and distribution of compounds alone and in mixtures are important measures of bioavailability and dosimetry. The kinetics of metabolism and excretion, along with those of receptor kinetics and affinities, should be especially useful for interspecies comparisons and for estimating risks for this particular class of compounds.

The Subcommittee wishes to emphasize that the method proposed may lack scientific validity. The associated errors have not been quantified. It is important, therefore, that the Agency make every effort to validate the method. The Subcommittee recommends periodic review and analysis as better data are obtained, and that EPA make systematic efforts to obtain critically important data, including that from in vivo tests on compounds

with representative positional substitutions. Efforts should continue to develop methods for assaying the biologic activity of important mixtures (e.g. fly ash) in in vitro systems, using other cells in addition to hepatocytes and other endpoints in addition to AHH activity. Until the uncertainties are reduced, the interim TEF method should be largely reserved for specific situations where the components of the mixture are known, where the composition of the mixture is not expected to vary much with time, and where the extrapolations are consistent with existing animal data.

Appendix C

REVIEW OF THE MUNICIPAL WASTE COMBUSTION RESEARCH PLAN

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

April 11, 1988

OFFICE OF
THE ADMINISTRATOR

The Honorable Lee M. Thomas
Administrator
U.S. Environmental Protection Agency
401 M. Street, S.W.
Washington, D.C. 20460

Dear Mr. Thomas:

The Municipal Waste Combustion Subcommittee of the Science Advisory Board's Environmental Effects, Transport and Fate Committee has completed its review of the Office of Research and Development's (ORD's) "Municipal Waste Combustion Research Plan". The review was initiated at your request, along with two other charges related to municipal waste combustion, and was reviewed concurrently with other issues on March 10, 1987.

The Subcommittee concludes that the research plan is well defined and reflects considerable thought, however, the proposed level of funding for the research appears grossly inadequate in view of the large number of scientific uncertainties associated with this technology, and EPA's responsibility to develop scientifically credible regulatory decisions. Important areas, such as ecological effects, are entirely left out or are addressed in a cursory fashion, which is understandable since allocated funds are inadequate for the areas that are addressed. Prioritization of research emphasizes avenues with short-term goals which may be necessary to meet the needs for technical guidance in permitting the many MWCs that are being planned or are already in operation.

The Subcommittee believes that emissions should be characterized as a first priority through analytical chemistry projects, methods development, and field testing. Risk assessment, health effects prediction and emission control cannot be adequately conducted without a thorough knowledge of the quality and quantity of the emissions, both gaseous and residual.

Following such characterization, environmental transport, fate and bioavailability should be determined, since they are key to assessing both risk and exposure to humans and the environment.

Monitoring is also considered by the Subcommittee to be an important research priority, and research directed towards monitoring goals will insure the development of tools to ensure compliance with guidelines or standards that may be set. In addition, monitoring is important for the validation of predictive models which have been developed for air transport of stack emissions.

The Subcommittee agrees that major areas of promising research have been proposed and developed to investigate important areas of uncertainty with respect to municipal waste combustion technology. However, budgetary constraints shed doubt, in the Subcommittee's opinion, on EPA's ability to reach the objectives defined in the program. Considerations of priority might be revisited to allow identification of research areas with high priority and attainable objectives.

The Subcommittee appreciates the opportunity to conduct this scientific review. We request that the Agency formally respond to the scientific advice transmitted in the attached report.

Sincerely,

Norton Nelson, Chairman
Executive Committee
Science Advisory Board

Rolf Hartung, Chairman
Municipal Waste
Combustion Subcommittee

Enclosure

cc: A. James Barnes
Vaun Newill
Alfred Lindsey
Larry Fradkin
Terry Yosie

Appendix D

DESCRIPTION OF REFUSE DERIVED FUEL (RDF) CATEGORIES

Appendix D

ASTM CLASSIFICATION OF RDFs

CLASS	FORM	DESCRIPTION
RDF-1	Raw	Municipal solid waste with minimal processing to remove oversize bulky waste.
RDF-2	Coarse	MSW processed to coarse particle size with or without ferrous metal separation such that 95% by weight passes through a 6-inch-square mesh screen.
RDF-3	Fluff	Shredded fuel derived from MSW processed for the removal of metal, glass, and other entrained inorganics; particle size of this material is such that 95% by weight passes through a 2-inch-square mesh screen.
RDF-4	Powder	Combustible waste fraction processed into powdered form such that 95% by weight passes through a 10-mesh screen.
RDF-5	Densified	Combustible waste fraction densified (compressed) into pellets, slugs, cubettes, briquettes, or similar forms.
RDF-6	Liquid	Combustible waste fraction processed into a liquid fuel.
RDF-7	Gas	Combustible waste fraction processed into a gaseous fuel.

Source: Hickman, H.L., "Thermal Systems for Conversion of Municipal Solid Waste: Overview," Argonne National Laboratory/CNSV-Tm-120, Volume 1, May 1983.

A measured RDF particle size distributions indicated that 95 percent by weight of the RDF is smaller than 2 inches, and that over 99 percent by weight of the RDF is smaller than 2.5 inches.

Appendix E

GLOSSARY OF TERMS AND UNITS

GLOSSARY OF TERMS AND UNITS

Acid gases	-	Compounds, such as hydrochloric acid (HCl), sulfur dioxide (SO_2), nitrogen oxides (NO_x) and hydrofluoric acid (HF) that are in the gaseous state.
As	-	Arsenic
Back-pass convective heat recovery boiler, convective back-pass	-	the heat recovery boiler at the furnace outlet generating steam by convective heat transfer.
BACT	-	Best Available control technology
Bed agitation	-	Agitation of the burning fuel bed by mechanical movement of the furnace grate
Bottom ash	-	Residual ash resulting from the burning of garbage, as discharged from the bottom of the incinerator
BTU	-	British Thermal Units
Burning refuse bed	-	MSW bed burning on the furnace grate
CB	-	Chlorobenzenes
Cd	-	Cadmium
CO	-	Carbon Monoxide
Congeners	-	A group of closely related chemical compounds such as the 75 chlorinated dibenzodioxins or chlorinated dibenzofurans
CP	-	Chlorophenols
DC	-	Direct Current
Dioxins	-	See PCDD below
Downwash	-	Downward air movement in lee of buildings and structures due to aerodynamic forces
Dry Deposition	-	Turbulent exchange of gases and small particles from the atmosphere to the ground surface

EPA	-	Environmental Protection Agency
ESP	-	Electrostatic precipitator
Efflux velocity	-	Flue gas velocity leaving the furnace grate passing up through the combustion chamber
Electrostatic precipitator (ESP)	-	An air pollution control device designed to remove particulate matter from a gas stream using electrostatic forces.
Elutriate	-	Particulate ash carried up from a furnace fuel bed by the gas velocity through the grate
Excursion	-	Deliberation from normal operating conditions resulting in incinerator upset conditions
Fabric filter, or fabric filter baghouse	-	An air pollution control device used to remove particulate matter from a gas using filtration principles
Feed pit	-	Receptor pit used for MSW storage from which the fuel is introduced into the MWC
Fly ash	-	General term for all ash carried up from the grate and out from the incinerator/boiler by the flue gas
Front, rear arch geometry	-	furnace wall design configuration
Gasification of MSW	-	Heating of the MSW at the entry point of the furnace grate - which drives off MSW Moisture and Volatile hydrocarbon constituents of fuel
Gravitational settling	-	Settling of particulate matter by force of gravity
HCl	-	Hydrochloric acid
HF	-	Hydrofluoric acid
Hg	-	Mercury

Homologue groups	-	Group of chemicals which vary in structure but have the same composition, such as degree of chlorination
Hydrometeors	-	Solid and liquid water particles and droplets
Isomer	-	2 particular members of a homologue group
KV	-	Kilovolts
mg/Nm^3	-	Milligrams per normal cubic meter
MSW	-	Municipal Solid Waste
MWC	-	Municipal Waste Combustion (or Combustors)
Mass-burn units	-	Incinerators that burn unprocessed MSW, typically in refractory or waterwall furnaces
Modular incinerator	-	Factory preassembled mass burn units usually employing controlled air combustion technology to incinerate considerably lower volumes of waste than those employed by mass burn or RDF units
Na	-	Sodium
ng/g	-	Nanograms per gram
ng/Nm^3	-	Nanograms per normal cubic meter at normal temperature and pressure conditions
NO_X	-	Oxides of Nitrogen, such as NO_2, or nitrogen dioxide
PAH	-	Polycyclic aromatic hydrocarbons
Pb	-	Lead
PCB	-	Polychlorinated biphenyls
PCDD	-	Total of all isomers and/or all homologue groups of polychlorinated dibenzo dioxins

PCDF	-	Total of all isomers and/or all homologue groups of polychlorinated dibenzo furans
Plume rise	-	A term used to describe the rise of a steady stream of flue gas due to buoyant effects after it leaves a stack
Pneumatic injection	-	Air injection of MSW or processed refuse into the furnace
ppb	-	Parts per billion
ppm	-	Parts per million
Proximate Analysis	-	The gravimetric composition of moisture, Ash, volatile matter and fixed carbon in a MSW fuel
Pyrolysis of MSW	-	The heating of MSW in the absence of oxygen, which drives off moisture and volatile matter in municipal waste
RCRA	-	Resource Conservation and Recovery Act
RDF	-	Refuse-derived fuel (unprocessed or processed municipal solid waste)
RDF processes	-	Refuse derived fuel processes that subject MSW to varying degrees of processing to improve fuel quality for better combustion efficiency and to achieve some material recycling or recovery.
Rotary combustors	-	MSW combustion occurring in a rotating drum (or kiln)
Scavenging coefficient	-	the coefficient describing the exponential decrease with time of atmospheric contaminants due to capture by rain and cloud droplets; usually applied to single precipitation events
Scrubber/baghouse	-	An air pollution control system consisting of a scrubbing device (lime injector) followed by a fabric filter dust collection
Se	-	Selenium

SO_2	-	Sulfur dioxide
Spreader stoker	-	Coal or RDF injection over a forward moving traveling grate
Stack	-	Chimney through which gases and particulate residues are emitted
Starved air incinerators	-	MSW combustion occurring in primary combustion chambers supplied with sub-stoichometric air
Sub-stoichometric air	-	Combustion air supplied that is less than that theoretically required to burn the fuel completely
TCDD	-	Any tetra isomers or the tetra homologue group of dioxins
TCDF	-	Any tetra isomers or the tetra homologue groups of furans
Tetrahomologues	-	As applied to PCDD and PCDF - those isomers and homologues which are chlorinated at 4 positions
THC	-	Total hydrocarbons
TiO	-	Titanium oxide
TPD	-	Tons per day
Ultimate analysis	-	A gravimetric fuel analysis giving mass composition of fuel elements necessary to do combustion calculations
Underfire air	-	Combustion air introduced under the grates of an incinerator or furnace
Washout ratio (Wr)	-	The effluent concentration in precipitation normalized by the effluent concentration in air used to describe average conditions over many precipitation events
Waterwall incinerator	-	The furnace of a MWC that is lined with tubes recovering heat for steam generation
Wet deposition	-	Removal of atmospheric contaminants as a result of capture by cloud droplets as well as precipitation

Windboxes - multiple air compartments	-	The use of multiple compartments under a furnace grate to allow for better undergrate combustion air distribution
Zn	-	Zinc
2,3,7,8 TCDD	-	2,3,7,8 tetrachlorodibenzo-p-dioxin

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