



**CEMENT KILNS
FOR HAZARDOUS WASTE DISPOSAL**
Opportunities and Constraints

by

**Krish Ravishankar
Research Intern**

and

**Wayne Mitter
Consultant**

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1777 East-West Road
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PRINCIPAL ABBREVIATIONS

DRE	Destruction and Removal Efficiency
ESP	Electrostatic Precipitator
PAH	Polyaromatic Hydrocarbons
PIC	Products of Incomplete Combustion
POHC	Principal Organic Hazardous Constituents
VOST	Volatile Organic Sampling Train
THCs	Total Hydrocarbons
VOC	Volatile Organic Carbon
SDF	Solvent-Derived Fuels

ABSTRACT

This study was initiated by the Pacific Basin Consortium for Hazardous Waste Research (PBCHWR) to document current knowledge and operating experience in the United States, Canada, and elsewhere concerning the use of cement kilns for the destruction of hazardous waste. The report summarizes results of tests in the United States by the Environmental Protection Agency (EPA) and State agencies, and in Canada, Norway, and Sweden. The predominant types of wastes tested included chlorinated organic compounds and metal-contaminated waste oil. Kiln types included dry, wet, and preheat processes.

Parameters investigated in this study include destruction and removal efficiency (DRE) of principal organic hazardous constituents (POHCs), particulate and HCl emissions, metals, and the effect of burning hazardous waste on sulfur dioxide (SO_2), nitrogen oxide (NO_x), total hydrocarbons (THCs) and carbon monoxide (CO) emissions. Sampling and analytical procedures required to monitor and dispose of wastes safely are discussed. Technical and economic factors, and risks associated with the use of cement kilns to destroy waste materials are reviewed.

Potential applications of cement kilns for economic and environmentally sound disposal of some hazardous wastes in developing countries are examined. Many existing cement kilns in the Asia-Pacific region, when properly operated, have the potential to economically dispose of a substantial share of the organic chemical wastes generated in that region with acceptable risk of adverse effects on human health and the environment. More than twenty cement kilns in the United States are currently being used for hazardous waste disposal.

Site-specific feasibility studies, risk assessments, and trial burns are recommended in order to determine limiting conditions that may be applicable. Risk assessment can help determine whether potential benefits can be achieved at acceptable levels of risk.

This study constitutes the Consortium's initial phase of research on this topic.



1. INTRODUCTION

1.1 Background

High-temperature industrial processes have often been used for the disposal of organic wastes. Process heaters and boilers are among the most common industrial processes; however, since the equipment for these cannot tolerate more than trace quantities of organic chlorine, they cannot be used for many wastes currently generated. Consequently, a number of other processes (e.g., cement kilns, lime kilns, aggregate kilns, and blast furnaces) that can destroy chlorinated wastes have been proposed. Cement kilns are of particular interest because of their potential for reducing the environmental impact of disposal in a cost-effective manner. The promising characteristics of cement kiln disposal include:

- Existing high-temperature combustion processes at 2,500° to 3,000° F (1,350° to 1,650° C), long gas residence times of up to 10 seconds or more, and strong turbulence in the kiln virtually assure the complete destruction of even the most stable organic compounds (Hazelwood et al. 1982).
- Rapid temperature drops are unlikely because of the huge thermal inertia.
- The alkaline environment in a kiln absorbs and neutralizes HCl from chlorinated waste combustion products.
- Kilns are operated under draft (slight vacuum); therefore, there is little outward leakage of fumes.
- Burning of liquid organic hazardous wastes as a replacement for primary fuels (oil, coal, or gas) allows for the recovery of substantial amounts of energy from these wastes. Liquid waste fuels typically being burned in U.S. cement plants have a heat value of 10,000 to 12,000 Btu/lb, a heat content comparable to coal (Peters et al. 1986).
- There is a potential for earning disposal fees from waste generators by treating wastes in a kiln.

- Cement kilns have the potential to dispose of large volumes of liquid organic wastes. A typical cement plant in the United States can burn 25,000 gallons (about 100 tons) of hazardous liquid waste per day (Beers 1987).
- Cement quality is relatively insensitive to the addition of most of the impurities found in hazardous wastes and waste oils (Mournighan et al. 1985).
- Bottom ash is incorporated into the clinker product, eliminating bottom-ash disposal problems. Any metals contained in the bottom ash are incorporated into the cement product in an inert form (Branscome 1985).
- Modification of existing cement kilns to accept hazardous waste fuels requires relatively small capital investment (Beers 1987).

The scope of this paper is limited to cement kilns. However, much of the discussion on opportunities and constraints is also applicable to lime kilns.

The combustion of hazardous waste in cement kilns has been investigated in Canada (Berry et al. 1975; MacDonald et al. 1977), Sweden (Ahling 1979; Piasecki and Davis 1987), Norway (Calonius 1984; Viken and Waage 1983), and New Zealand (Holden et al. 1983), as well as in the United States (Weitzman 1983; Lauber 1982; Hazelwood et al. 1982; Branscome et al. 1985; Mournighan and Branscome 1988; Argonne 1981). Some researchers report that disposal in cement kilns is often preferable to other hazardous waste disposal options, particularly for chlorinated organics (Black and Swanson 1983; Lauber 1982; USDOE 1983; Beers 1987; Holden et al. 1983).

Papers have also been published indicating actual and potential risks associated with hazardous waste combustion (Mix and Murphy 1984; Bouse and Kamas 1987). A number of kilns using different waste fuels have been tested under varied operating conditions (Day et al. 1985; Jenkins et al. 1982; Duckett and Weiss 1980; Peters et al. 1984; Branscome et al. 1984; Swanson Environmental 1976; Carter and Benson 1984; Stohrer 1986). Some of these tests have been very comprehensive. Purposes of tests have included determination of

effects of various wastes on stack emissions and on cement quality, determination of the fate of metals and chlorine, and identification of products of incomplete combustion and mechanisms of their formation (Branscome et al. 1985; Mournighan and Branscome 1988; Viken and Waage 1983; Higgins and Helmstetter 1982; Oppelt 1987; Peters et al. 1984).

Over the past decade, there has been a gradual increase in use of this technology in the United States. Bouse and Kamas (1987) have addressed opportunities and constraints, have documented the use of cement kilns for disposal of solvent-derived fuels (SDF) at seventeen U.S. sites, and have cited at least three additional plants that were scheduled to begin such disposal in 1987. Relatively slow acceptance of the process has been partly due to public perception of risks associated with the siting of any facility dealing with "hazardous" wastes.

1.2 Purpose

This investigation was initiated by the Pacific Basin Consortium for Hazardous Waste Research (PBCHWR), a group of research institutions. The purpose is three-fold: first, to assemble and analyze reports on current and past use of cement kilns for the destruction of hazardous wastes; second, to discuss some of the major issues associated with burning hazardous wastes in cement kilns; and third, to investigate the potential application of cement kilns for safe disposal of hazardous wastes generated in the Asia-Pacific region. This study constitutes the Consortium's initial phase of research on this topic.

1.3 Methods of Study and Analysis

To accomplish the stated purpose, it was first necessary to obtain technical reports of laboratory tests and demonstration projects. These reports included detailed descriptions of cement production processes, waste fuel handling systems, and technical capabilities and

limitations. Operational data, where available, were obtained to assess performance of kilns while burning wastes. Information was also sought on energy savings from substitution of waste fuel for primary fuel. Information was sought from the USEPA on regulatory measures, license and permit requirements, and state-of-the-art technology. A thorough search of the literature available in this field was made. Discussions were held with cement manufacturers, EPA personnel, and researchers at Argonne National Laboratory and the Portland Cement Association. Information was also sought from selected PBCHWR members about research or operating experiences in their countries.

Specific critical issues addressed in this study are (1) operating experience, waste types and characteristics, and test results--destruction and removal efficiencies (DREs), emissions, products of incomplete combustion (PIC); (2) sampling and analytical procedures; and (3) economics of waste fuel use.

1.4 Organization of the Report

First, a brief overview of the cement industry, the technology of cement production, and waste fuel handling systems are presented. Second, the operating history of burning hazardous waste in cement kilns and a summary of test results are discussed collectively under various emission categories of interest. Third, the economics of waste fuel burning is discussed. Fourth, risks associated with the burning of hazardous wastes in cement kilns are evaluated. Last, an overview of cement plants in selected Asia-Pacific countries is presented from which one can infer potential for hazardous waste disposal. Findings and recommendations follow.

2. CEMENT PRODUCTION

This section provides a brief overview of the cement industry in the United States and describes the technology of cement production.

2.1 Overview of the Industry

Portland cement is one of the largest scale mineral commodities produced in the United States with an annual production in 1985 of 74 million tons. About 200 cement plants with more than 325 kilns are located throughout thirty-eight states.

The cement industry is capital-intensive and is dependent on the construction industry. Energy costs normally amount to 33 to 40 percent of the total cost of cement manufacture, but in some cases may even be as high as 65 percent. Energy efficiency improvements have been made since 1950 when about 7.8 million Btus were required per ton of product. The estimate for 1979 was 6.5 million Btus per ton for the wet process cement kiln. This figure has probably continued to decline based on historical trends (USDOE 1980). Preheater modifications on dry process plants have reduced energy consumption to as low as 3 million Btu per ton in some instances (Branscome et al. 1985). In 1972, only 39 percent of the industry's energy was supplied by coal, but conversion to coal started in the 1970s. In 1978, pulverized coal accounted for 63 percent of the fuels used in cement production (USDOE 1980). Currently, more than 90 percent of the installed capacity uses coal as the primary fuel (Mournighan and Branscome 1988).

2.2 Process Description

Portland cement is produced by controlled high-temperature (2,500° to 2,800° F; 1,400° to 1,500° C) processing of a carefully

proportioned mixture of finely ground limestone, silica, alumina, and iron oxide-bearing raw materials in a rotary kiln.

For a typical U.S. cement plant, the raw materials--limestone, silica, and iron ore--are proportionately mixed together in approximately 4:1:.07. The crushing and mixing may be either performed dry or wet (i.e., as slurry with 30 to 40 percent water). For several years, the wet process was preferred by the U.S. cement manufacturers because of its advantages in control of blending and ease of grinding (USDOE 1980). Recently, however, there has been increased conversion to improved forms of dry processing primarily because of lower energy requirements for the dry process (5.5 million Btu/ton for the dry process, as compared to 6.5 million Btu/ton for the wet process).

Thermal processing of the mixed raw materials may be viewed in three stages: drying, calcining, and clinkering. The first stage (drying) applies primarily to the wet process and requires temperatures in the neighborhood of 212° F (100° C). The second and third stages (calcining and clinkering) apply to both the wet and dry process. Calcining is the controlled heating of the mixture in order to dehydrate the materials and to drive off carbon dioxide from the limestone. Calcining temperatures are in the range of 1,000° to 1,800° F (550° to 1,000° C). Clinkering (sometimes called "burning") is the term for the chemical reactions that convert the raw materials into hardened granular masses of calcium aluminates and calcium ferrites. The clinker reactions take place at temperatures in the range of 1,800° to 2,500° F (1,400° to 1,500° C). The resulting clinker is then air-cooled and ground to a fine powder (90 percent <200 mesh) for use as portland cement. The solid's residence time varies from kiln to kiln and is controlled by the kiln's revolution. Typical solids residence times are on the order of 2 (range of 1 to 4) hours. Often, gypsum (i.e., calcium sulfate, CaSO_4) is added to the clinker during grinding in order to retard the setting time of the cement. Portland cement often contains 5 to 6 percent gypsum.

For most (about 80 percent) of the cement production in the United States, all three stages of thermal processing take place in a rotary kiln. Figure 1 is a schematic of a typical cement plant. The

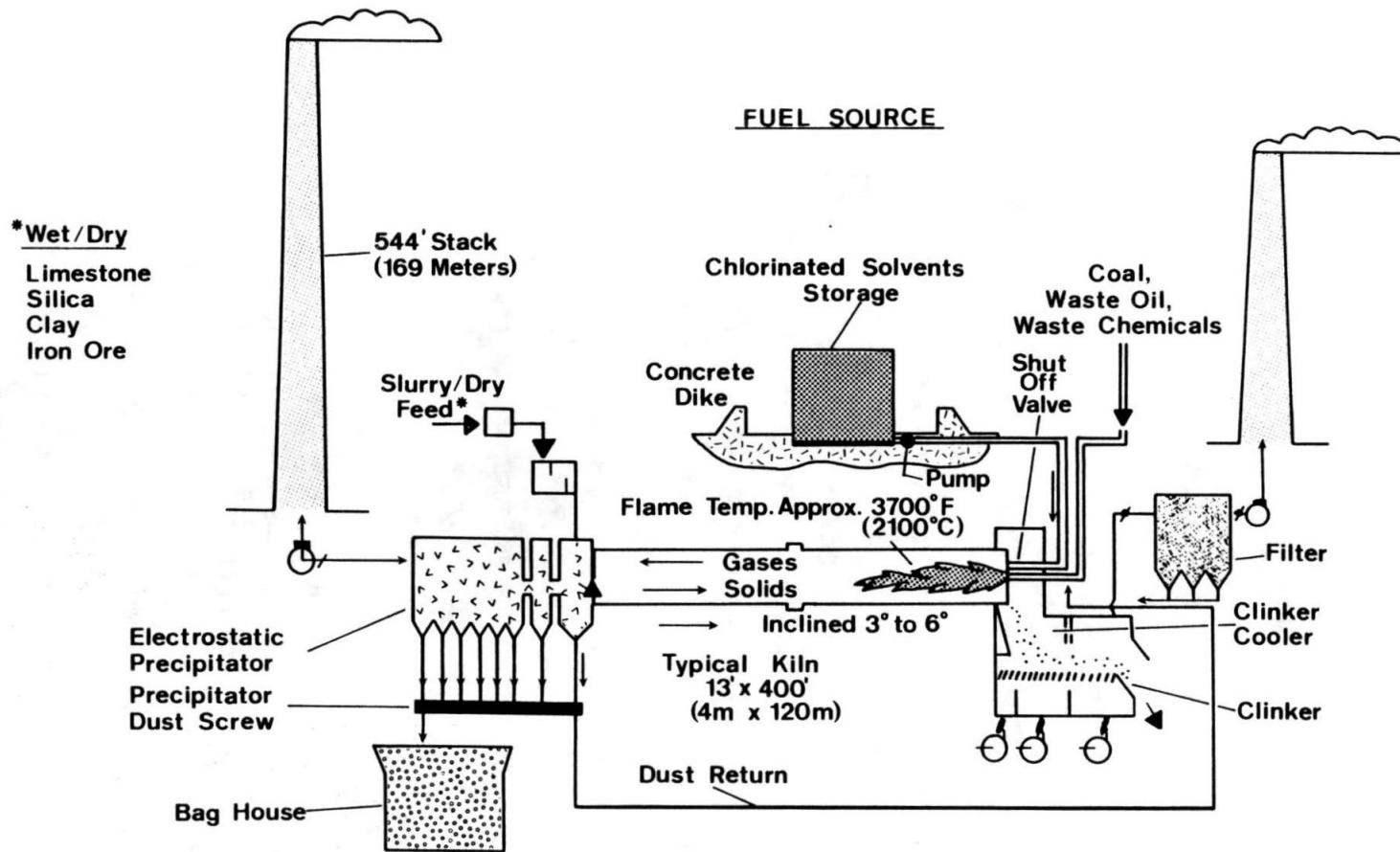


Figure 1. Schematic drawing of a typical cement kiln (Source: Lauber 1982. Reprinted by permission of the publisher.)

wet or dry mixture of raw materials enters the rotating cylinder at the upper (or back) end of the kiln and proceeds through zones of drying (only for the wet process), calcining, and clinkering until it reaches the lower (front) end of the kiln where it exits as clinker. Heat for the operation of the kiln is supplied by suspension firing of fuels through burners located at the lower end of the kiln. As indicated in the figure, the flow of the heated gases in the kiln is countercurrent to the flow of the solid raw materials. Gas residence times range from 3 to 8 seconds. Rotary kilns for cement-making range in size from 8 to 25 feet (2.4 to 7.6 m) in diameter and from 200 to 600 feet (60 to 183 m) in length, and are inclined at approximately 3 to 6 degrees.

Two features of the cement-making process are of special interest when coal and easily combustible solid wastes are used for fuel. First is the fact that much of the ash from combustion of these fuels becomes incorporated into the clinker. It is a standard practice in the cement industry to adjust the raw materials feed to account for incorporation of ash into the clinker (USDOE 1980). Second is the fact that the kiln itself acts somewhat as a scrubber for sulfur oxides, thus removing some potential pollutants from exhaust gases. This scrubbing effect is partially present in the calcining zone of the kiln where calcium carbonate is converted to calcium oxide (lime), which can react with the sulfur oxides to form calcium sulfite and sulfate. This scrubbing effect permits the kilns to use relatively high sulfur fuels (reportedly up to 4 percent) without exceeding air pollution codes (Ahling 1979).

The exhaust stream leaving the upper end of the kiln must undergo cleaning before discharge to the atmosphere. The most common types of air pollution control devices that are used to clean the exhaust are electrostatic precipitators (ESP), or baghouses, often preceded by a centrifugal separator. As much as 125 tons of particulates may be collected during the production of 1,000 tons of cement clinker. Most of these particulates (90 percent or more) are fine particles of cement or raw materials rather than particles of fly ash from the fuel. In some cases, the collected dusts are recycled through the kiln, but in other instances--for environmental and safety

reasons--the dusts are considered detrimental to the process and are therefore discarded as wastes.

Several U.S. and European cement manufacturers have begun modifying their plants to accommodate lower priced fuels and to incorporate energy-conserving process changes. In addition to shifting toward the use of the dry process, most of these modifications involve some separation of the three thermal processing phases carried out in a conventional rotary kiln. Such modifications include the use of preheaters (either suspension or grate type) and the use of so-called "precalciners" to carry out drying and calcination of the raw materials before the mixture enters the rotary kiln. The rationale for performing the three thermal processing stages in separate furnaces is that each furnace can be designed to optimize a specific function, and the rotary kiln can then be used for clinkering alone.

3. USE OF WASTES AS FUELS

3.1 Waste Fuel Systems

Many liquid hazardous wastes have heating values of 10,000 Btu/lb or more. Bouse and Kamas (1987) state "The annual estimated generation of all types of hazardous waste in the United States is 265 million short tons. Fifty-five percent of that total is estimated to be combustible. EPA data suggest that 26 million tons of hazardous waste fuel with a heating value 8500 Btu/ lb is available and that only 7 percent is presently committed to energy use."

Liquid organic wastes that are presently burned in cement kilns include:

- Spent halogenated and nonhalogenated solvents generated by a wide variety of manufacturing processes, including metalworking, degreasing, painting, and printing;
- Still bottoms from solvent recovery;
- Petroleum industry wastes;
- A number of used and off-specification organic chemicals; and
- Waste oils, consisting primarily of engine crankcase oils, but also including transmission fluids, hydraulic and compressor fluids and coolants.

Although cement kilns have the potential to incinerate all types of organic wastes, cement manufacturers have been interested to date only in burning high-Btu wastes. Due to a desire to avoid public opposition, these facilities have not burned "high-profile" hazardous wastes, such as polychlorinated biphenyls (PCBs), on an ongoing basis, despite the fact that test burns have demonstrated the ability of cement kilns to destroy these substances (Lauber 1987).

In order to properly burn complex chemical wastes in cement kilns, it is important to have technical data such as shown in Table 1. Instruments required to analyze waste fuel in an on-site laboratory include an atomic absorption spectrometer or emission

Table 1. Data pertinent to incineration of chemical wastes

Critical waste incineration parameters	Physical and chemical properties
Ultimate analysis	C, H, O, N, S, ash, and moisture
Metals	Ca, Na, K, Cu, V, Ni, Fe, Pb, Hg, Cr, Cd, As, etc.
Halogens	Chlorides, bromides, fluorides
Heating value	Btu/lb or cal/gram
Solids	Size, form, and quantity to be received
Liquids	Viscosity, specific gravity and impurities, H ₂ O
Gases	Density and impurities
Organic portion	Percent total organic carbon
Special characteristics	Corrosiveness, reactivity, flammability
Toxicity	TLV (Toxic Limit Value), carcinogenicity, aquatic toxicity, etc.

Sources: Lauber (1982).
Branscome et al. (1985).

spectroscope, a bomb calorimeter (for heat value measurement), a hydrometer (for density measurement), a viscosimeter (for viscosity measurement), Karl Fisher apparatus (for water-content analysis), a gas chromatograph/mass spectrometer with flame ionization (for organic specification/quantification) and an electron capture detector, and a combustion bomb with combustion product analyzer (for ultimate analysis of gas and ash content) (Branscome et al. 1985; Bouse and Kamas 1987).

Tank truck shipments of waste fuel are analyzed for the parameters described in Table 1 before unloading. Approved shipments are unloaded into storage tanks. Each shipment is filtered as the truck is emptied. The storage tank contents are kept well mixed by agitators and a bottom-to-top recirculation line. The waste fuel is filtered again before being pumped to the kiln's burner line.

The waste fuel pumped to the burner floor enters the waste fuel line inside the burner pipe. Fuel supply pressure varies from 30 to about 50 pounds per square inch gauge (psig) depending on burner capacity and size of kiln. Air is also introduced into the waste fuel through a whirling vane near the burner nozzle to aid in atomization. Air pressure supply ranges from 40 to 70 psig (Viken and Waage 1983; Ahling 1979; Branscome et al. 1985).

3.2 Plant Modifications Required to Burn Hazardous Wastes

Cement plant modifications required to burn liquid hazardous wastes as a supplemental fuel include:

- Installation of relatively sophisticated laboratory equipment to characterize wastes on site;
- Construction of waste receiving, storage, blending, and piping equipment; and
- Modification of the kiln's fuel injection system.

In 1986, capital costs for construction of plant modifications at a U.S. cement plant planning to burn 16 million gallons of waste fuels

annually were estimated at a little more than \$1 million (Henz 1986). Costs of permitting insurance, safety equipment, and public relations were additional.

On an experimental basis, selected solid wastes can be fed into a kiln together with primary fuel. For some solid wastes, a prekiln must be installed. The prekiln is set or programmed to suit the type of waste that is being destroyed. In some cases, combustion of the solid waste takes place in the prekiln, and in other cases only low-boiling substances from the solid waste are driven off in that kiln. There are two kinds of prekilns available, namely, rotary kilns and pyrolysis gasifiers (Ahling 1979; Weitzman 1983).

Despite the potential for burning solid hazardous wastes in cement kilns, any ongoing commercial burning of hazardous wastes in cement kilns has been limited, insofar as is known, to pumpable liquids containing minimal amounts of water. To accommodate solid wastes, major plant modifications would be required (USEPA 1986).

4. OPERATING EXPERIENCE AND TEST RESULTS

4.1 Introduction

A number of test burns have been conducted at cement facilities to determine the impact of burning organic hazardous wastes on emissions of many air pollutants, including organic constituents and products of incomplete combustion, lead and other metals, hydrogen chloride, particulates, and sulfur and nitrogen oxides.

Trial burns conducted at more than a dozen cement plants over the past 9 years in the United States, Canada, and Europe have demonstrated that these facilities have the capability to destroy greater than 99.99 percent of even the most difficult-to-incinerate organic substances (Beers 1987). Although exceptions to the 99.99 percent destruction and removal efficiency (DRE) were noted during some of the trial burns at two of these facilities, the majority of these tests demonstrated DREs approaching 99.999 percent. Those tests at which the 99.99 percent DRE were not obtained appear to have resulted from a failure to properly atomize wastes or other operating errors.

Small amounts of hazardous waste burned in an incinerator achieving a DRE of 99.99 percent may escape complete destruction and be emitted to the atmosphere. The resulting concentration of unburned waste in exhaust gases can range from 5 to 50 parts per billion (Fennelly 1986). These emission levels of unburned waste are below the New York State Department of Environmental Conservation's regulatory air emission standards for the classes of solvents and organic chemicals that cement facilities incinerate.

4.2 Operating History, With Highlights of Test Burns

Pyroprocessing of hazardous wastes in the cement kilns began in the 1970s in Canada, Europe, and the United States. An outline of this early experience is included in Table 2. Before 1980, waste fuel

Table 2. Operating history of cement kilns

Plant	Year	Process	APCD	Primary Fuel	Test Prog. Parameters					Fuel types tested
					PAH	POHCs	PICs	Cl	Metals	
St. Lawrence Cement Mississauga, Ontario	1974	Dry-Preheat	ESP	Fuel oil	x	-	-	-	-	Lubricating oil contaminated with metals
	1975-76	Wet	ESP	Fuel oil	x	x	-	x	x	Chlorinated aliphatics (ety. dichloride); chlorinated aromatics; PCBs
Peerless Cement Detroit, MI	1976	Wet	ESP	Coal	-	x	-	x	-	PCBs
Stora Vika Cement Sweden	1978	Wet	ESP	Coal	x	x	x	x	-	Chlorinated aliphatics; chlorinated aromatics; Chlorophenols and phenoxy acids; Freon 113
Norcem Cement Slemmestad, Norway	1980-82	Wet	ESP	Fuel oil	x	x	-	x	x	Tar (alkanes, alkabenzenes, poly aromatics, hydrocarbons - PAH) PCBs (48% Cl)
Marquette Cement Oglesby, IL	1981	Dry	ESP	Coal	x	x	-	x	x	Chlorinated aliphatics, MEK, toluene
San Juan Cement Puerto Rico	1981-82	Wet	Baghouse	Fuel oil	x	x	x	x	x	Chlorinated aliphatics
Alpha Cement Cementon, NY	1982	Wet	ESP	Coal	x	-	-	x	x	Waste solvents (halogens = 590 ppm)
General Portland Los Robles, CA	1982	Dry	Baghouse	Coal	-	x	-	x	x	Aromatics and chlorinated aliphatics
General Portland Paulding, OH	1983	Wet	ESP	Coal	x	x	x	x	x	Chlorinated aliphatics, MEK, toluene
Lone Star Oglesby, IL	1983	Dry	ESP	Coal/Coke	x	x	x	x	x	Chlorinated aliphatics, MEK, toluene

Sources: Mournighan and Branscome (1988).
Branscome et al. (1985).
Viken and Waage (1983).

APCD: air pollution control device
ESP: electrostatic precipitator

was used at St. Lawrence Cement, Peerless Cement, and Stora Vika. The waste burned at all three locations included PCBs and other organics. Test data generally indicated acceptable performance in terms of kiln operations and emissions; however, since there was adverse public reaction to burning PCBs at St. Lawrence Cement and Peerless Cement, hazardous waste burning was discontinued at both locations (Berry et al. 1975; Bouse and Kamas 1987).

The 1980s have seen continued testing of waste fuels in cement kilns at several cement plants. Table 2 continues with the experience of the early 1980s. This section presents highlights of tests at each specific site, with pertinent comments on operating history and test results.

4.2.1 St. Lawrence Cement Company

From 1974-76 the St. Lawrence Cement Company, Mississauga, Ontario, burned waste chemicals in two separate kilns. The test in 1974 burned waste lubricating oils contaminated with lead and zinc in the company's dry process kiln with a 4-stage preheater. Test results indicated that these metals became incorporated into the clinker. Waste chlorinated hydrocarbons, consisting of approximately 45 percent PCBs, 12 percent aliphatics, and 33 percent chlorinated aromatics, were burned in 1975 in a wet process kiln.

Extensive tests were conducted during these trial burns of chlorinated organics. Stack tests performed during the trial burns indicated a destruction efficiency of at least 99.986 percent for the chlorinated hydrocarbons. PCBs were not found in the clinker. About 50 ppb of volatile low molecular weight compounds (carbon tetrachloride, chloroform, dichloromethane) were found in the emission samples. A mass balance carried out for chlorine indicated that essentially all the chlorine had reacted with the process solids. This demonstrated that acid gases such as HCl, which are generated by the pyrolysis and oxidation of chlorinated hydrocarbons, are effectively neutralized by process lime in the cement kiln (Mournighan and Branscome 1988; Hazelwood et al. 1982). This provides an

additional benefit. Some cement plants have a need to produce low alkali cement products. In such cases, the burning of chlorinated hydrocarbons directly results in the lowering of the alkalinity of the cement products.

During test burning of chlorinated wastes, the average replacement of primary fuel with waste fuel was about 12 percent, whereas the heating value of these wastes averaged about 10,000 Btu/lb. Fuel requirements for the kiln were reduced by about 65 percent of the actual energy content of the wastes burned (Hazelwood et al. 1982). It was demonstrated that chlorine can be added to a typical wet process kiln at rates of about 0.4 to 0.7 percent of clinker weight without disrupting kiln operations.

The burning of PCB waste at St. Lawrence was a technical success in that the wastes were destroyed to below analytical detection limits. For about 2 years, wastes with up to 10,000 ppm of PCBs, a most difficult compound to destroy, were burned completely without accident. Public opposition, including resentment, developed because they had not been informed. PCB operations were subsequently suspended after extensive public hearings.

4.2.2 Peerless Cement Company

In December 1976, a test burn of PCB wastes (a mixture of 40 percent archlor 1260 PCB with primary fuel) was conducted at the Peerless Cement Plant, Detroit, Michigan. The waste was pumped at a rate of up to 0.75 gal/min directly into the main coal flame of the kiln using an auxiliary burner. The burning zone of the kiln was at 2,650° F with a residence time of 10 seconds.

Stack emissions during PCB tests showed a DRE of 99.99 percent. However, when background stack tests were performed with no PCBs being injected into the kiln, some low-level PCB emissions were detected in the kiln emission stack. The paradox was that PCBs were detected in the plant's feed water used in the raw materials feed slurry.

Following these PCB waste destruction tests, considerable public opposition developed and hearings were held.

4.2.3 Stora Vika Cement Plant

Between February and July 1978, various chlorinated chemical wastes were burned at the Stora Vika Cement Plant, about 70 kilometers south of Stockholm, Sweden. Chlorinated aliphatics, PCBs, chlorophenols, and phenoxyacids were burned during these tests. Average chlorine content was 17 percent of waste fuel weight. Chlorine content in the wastes averaged 0.35 percent of clinker weight. There were no kiln operational problems so long as chlorine input was kept below 0.6 percent of clinker weight; at higher rates, alkali halogen rings began forming in the kiln. These problems disappeared when chlorine feed rates were reduced (Hazelwood et al. 1982). Destruction and removal of PCBs was 99.9999 percent.

Analyses were also conducted for dioxins and furans, but no detectable quantities were found. Dust emissions from the plant increased during the trial burns due primarily to an increase in potassium chloride concentrations in the kiln dust. Water was used to extract these chlorides from the dust before recycling.

4.2.4 Norcem Cement Plant

At the Norcem Cement Plant in Slemmestad, Norway, an energy-saving program using hazardous waste fuel was initiated in the early 1980s. By introducing 30 percent combustible hazardous waste, energy consumption of primary fuels was reduced from 1,000 to 700 kcal/kg of clinker (Viken and Waage 1983). A high temperature (above 1,400° C) in the combustion chamber was maintained for decomposition of stable materials such as PCBs and other polyaromatic hydrocarbons (PAH). DRE for PCBs was 99.9999 percent. Special efforts were made to detect dioxins and furans, but none were found. No organics were detected in the dust from the electro-filter or in the clinker. During the burning of these PAHs, instrumentation allowed detection of heavy organics in the stack emission at extremely low levels (e.g., PAH, ketones, alkanes at 14, 23, and 150 $\mu\text{g}/\text{Nm}^3$, respectively). The detected levels of these decomposition products did not vary greatly

from emissions under baseline conditions (i.e., without hazardous waste fuels).

4.2.5 Marquette Cement Company

During 1981, the Marquette Cement Plant, Oglesby, Illinois, burned chlorinated aliphatics, methyl ethyl ketone (MEK), and toluene as waste fuel in their dry process cement kiln. Test programs included POHC analysis, metal analysis, and THC analysis. DREs for various organics ranged from 99.94 to 99.999 percent. When lead contaminated waste oil was burned, reduction in lead emissions down to a level comparable with lead emissions from burning primary fuel (coal) only was reported (Mournighan et al. 1985). Quantitative data was not included in the report available. The Marquette Cement Company is currently owned by Lone Star Industries.

4.2.6 San Juan Cement Company

During fall and winter of 1981 and 1982, the USEPA conducted several worst-case trial burns of highly chlorinated chemical wastes at the San Juan Cement Company in Puerto Rico.

The San Juan tests were conducted in a wet process cement kiln fired with bunker fuel (no. 6 oil) as the primary fuel. Eight test burns were conducted. Process temperature was 2,400° F. Gas residence time was 4 seconds. Chlorine content of some waste fuels was as high as 38 percent. The fuel mixture with the "most difficult to destroy" constituents included 1.4 percent methylene chloride, 4 percent chloroform, and 8 percent carbon tetrachloride.

One of the objectives of the program was to determine if polychlorinated dibenzodioxins (PCDD) and polychlorinated dibenzofurans (PCDF) were emitted as products of incomplete combustion while hazardous waste was being fired to the kiln.

The report of the San Juan tests states (Peters et al. 1984):

"CONCLUSIONS

Some of the results observed in this demonstration program were contradictory to results from other cement kiln incineration tests; e.g., lower DREs, no change in particulate emissions, and significant changes in SO_2 and NO_x emissions. The conclusions presented below apply only to this particular kiln and the results from this demonstration program.

1. The inability of this kiln to consistently achieve 99.99% DRE (a value which hazardous waste incinerators must demonstrate) of the POHCs is attributed to unatomized waste introduction to the kiln flame and the difficult incinerability of the POHCs. These compounds (CH_2Cl_2 , $CHCl_3$, and CCl_4) are occasionally employed as fire retardants because of their ability to remove hydrogen atoms from the free-radical branching combustion reactions to form HCl. Combustion of chlorinated species containing less chlorine may have resulted in higher DREs.
2. Chlorinated dioxins and chlorinated dibenzofurans are not produced at detectable levels (1.6 ng/m^3) when a cement kiln firing chlorinated wastes is operating normally.
3. Cement kilns will absorb over 99% (about 99.7%) of the HCl formed during the combustion of chlorinated hazardous wastes. This absorption is partitioned between the clinker and baghouse dust.
4. At San Juan Cement Company, approximately 82% of the chlorine fed to the cement kiln appears in the clinker. This limits the chlorine content of the total fuel to less than 1%. This may vary at different cement plants because quarry alkalinity (ability to absorb chlorine) varies at each cement plant.

5. Achievable fuel savings are a function of the chlorine content of the waste and each plant's ability to absorb chlorine. At San Juan Cement Company, a hazardous waste containing less than 5% will result in at least a 20% savings in fuel costs. Higher fuel savings may be possible for higher chlorine contents at other plants.
6. Production of salable cement product is possible when burning chlorinated hazardous wastes provided the plant's chlorine absorbability limit is not exceeded.
7. Atomization of the waste fuel would be desirable, if a flame configuration can be obtained which does not alter the primary fuel flame configuration.
8. High feed line pressure [1,380 to 2,070 kPa (200 to 300 psig)] is not required for waste injection to the kiln. This pressure requirement may change depending on the type of atomizing nozzle used.
9. There is no significant change in particulate emissions due to burning chlorinated hazardous wastes. This result was observed on a cement kiln equipped with a fabric filter air pollution control system. A cement kiln with an electrostatic precipitator may not achieve similar results due to a change in dust resistivity.
10. Emissions of sulfur dioxide, total hydrocarbons, and hydrogen chloride increased significantly when waste was burned. A cement kiln with a higher alkalinity feed than that at the San Juan Cement Company may not have an increase in SO₂ emissions.
11. Emissions of nitrogen oxides decreased significantly when waste was burned.
12. There is no change in particulate ambient air quality due to hazardous waste combustion in cement kilns.
13. The solid waste (baghouse dust) generated by hazardous waste burning and its RCRA extract (leachate) are suitable for landfilling."

4.2.7 Alpha Cement Company

During summer 1981, the burning of waste solvents was begun in the wet process cement kilns at Alpha Cement Company, Cementon, New York. During tests, up to 15 gal/min of waste solvents containing up to 2 percent chlorinated organics were burned at this demonstration project. These waste fuels were fired at up to 25 percent replacement of primary fuels. Front-end kiln temperatures were 2,200° F and above. Gas residence time was 5 seconds. In the tests, DREs of 99.99 percent were achieved for the POHCs. The demonstration project indicated about 58 percent lower SO₂ emissions than when the primary fuel (coal) was burned alone.

The firm planned to conduct additional worst-case trial burns involving various higher halogenated principal organic hazardous compounds in the near future.

4.2.8 General Portland Cement Company

The cement kiln at General Portland Cement Company, Paulding, Ohio, uses the wet process with coal as the primary fuel. Beginning in 1983, normal operation of this kiln included co-firing of waste solvents as supplemental fuel.

An EPA demonstration test at this plant in 1983 included 4 days of baseline testing and 5 days of testing during the waste burn. The POHCs in the waste fuel included methylene chloride, MEK, toluene, and Freon 113. The waste fuel was fired through a separate burner pipe inside the coal burner with air atomization of the solvents. Process temperature was in the range of 2,500° F to 2,600° F with a gas residence time of 4 seconds.

Test results indicated DREs of 99.99 percent for Freon 113 and >99.99 percent for trichloroethane. There was no statistically significant difference between average POHC emission rates for the baseline and waste fuel burn. This was also true for PICs.

Most of the chloride (about 95 percent) was removed with the dust. Less than 5 percent left with the clinker and stack gas. There

were emissions of Cd, Cu, Hg, Pb, and Se when waste fuel was burned.

Dibenzofurans and dibenzodioxins found in the stack gas were at a concentration level of less than 0.17 ppb.

4.2.9 Lone Star Industries

The first trial burn in this plant at Oglesby, Illinois, was conducted in 1981 when it was formerly owned by Marquette Cement Company. In 1983 there was a second demonstration project at this plant, now owned by Lone Star Industries. The test used paint solvents composed of chlorinated aliphatics, MEK, and toluene. The waste was spiked with Freon 113 and fired through a separate pipe under the coal burner with pressure atomization. DREs were in the range of 99.999 percent.

4.3 Test Results

Test results have shown that use of waste fuels does not affect cement quality. Other specific test results for each of the demonstration projects are discussed here collectively under various categories of emissions interest.

4.3.1 DREs for POHCs

Destruction and removal efficiency (DRE) is a simple efficiency calculation based on the amount of a compound emitted from the stack after thermal destruction and gas treatment in the control device compared to the quantity of that compound entering the kiln with the waste. Demonstration projects for study of hazardous waste disposal in incinerators and cement kilns use the EPA-developed VOST (volatile organic sample train) and Modified Method 5 (MM5) techniques to determine the concentration of principal organic hazardous constituents (POHCs) in stack gases.

The DRE results for some of the demonstration projects are summarized in Table 3. The reported DREs are >99.99 percent for wastes with mostly chlorinated organics, >99.989 percent for chlorinated aromatics, and >99.986 percent for PCB mixtures.

4.3.2 POHC Emission Rates

POHC emission rates are summarized in Table 4. The tests at Paulding, Lone Star, and Los Robles showed that the difference in POHC emissions between baseline burns and waste burns was not statistically significant. During the trial tests at Stora Vika, the only compounds detected in the stack gas were chloroform and Freon. In burns at Peerless Cement, there were low-level PCB emissions during both the baseline and PCB burn. PCB was detected in the plant's feed water used in the raw materials feed slurry, which accounts for PCBs in baseline emissions. At San Juan, lower DREs were attributable to unatomized waste introduction to the kiln. Also, the most difficult-to-burn compounds were chosen as POHCs (i.e., CH_2Cl_2 , CHCl_3 , CCl_4).

4.3.3 PICs (Products of Incomplete Combustion)

The burning of complex mixtures of organic compounds yields emissions of compounds other than POHCs. Several tests at kilns have attempted to quantify concentrations of both volatile (boiling point $<100^\circ\text{C}$) and semivolatile organic compounds that are emitted under baseline and waste fuel conditions.

Table 5 lists the types of compounds that appeared as PICs in the tests. The results show that when hazardous wastes were burned, there generally were minor increases in PICs compared to baseline conditions. The results for baseline burns (i.e., no hazardous waste) indicate that many of the POHCs are by-products of coal combustion. Trace quantities of PICs were found at San Juan during kiln upset.

Table 3. Summary of DREs

Plant	Waste Compound	Destruction and Removal Efficiency (DRE)
St. Lawrence Cement Mississauga, Ontario	Chlorinated aliphatics Chlorinated aromatics PCBs	> 99.99 > 99.989 > 99.986
Peerless Cement Detroit, MI	PCBs	99.9981-99.9986
Stora Vika Sweden	Methylene chloride Trichloroethylene All chlorinated hydrocarbons PCBs Chlorinated phenols Phenoxy acids Freon 113	> 99.995 > 99.9998 > 99.988 > 99.99998 > 99.99999 > 99.99998 > 99.99986
San Juan Cement Puerto Rico	Methylene chloride Trichloromethane Carbon tetrachloride	93.292-99.997 92.171-99.96 91.043-99.996
General Portland Los Robles, CA	Methylene Chloride 1,1,1-Trichloroethene 1,3,5-Trimethylbenzene Xylene	> 99.99 > 99.99 > 99.95 > 99.99
General Portland Paulding, OH	Methylene chloride Freon 113 Methyl ethyl ketone 1,1,1-Trichloroethene Toluene	99.956-99.998 > 99.999 99.978-99.997 99.991-99.999 99.940-99.988
Marquette Cement Oglesby, IL	Methylene chloride Freon 113 Methyl ethyl ketone 1,1,1-Trichloroethene Toluene	99.94-99.99 99.999 99.997-99.999 > 99.999 99.986-99.998
Lone Star Oglesby, IL	Styrene Ethylbenzene O-Xylene Benzaldehyde	> 99.999 > 99.999 > 99.999 > 99.998
Norcem Cement Norway	PCBs	> 99.9999

Sources: Branscome et al. (1985).

Mournighan and Branscome (1988).

Table 4. Summary of POHC emission rates

Test Location	POHCs	Baseline emissions (mg/s)	Waste burn emission (mg/s)
San Juan	Methylene chloride	1.4	94
	Chloroform	11.0	94
	Carbon tetrachloride	71.0	191
Paulding	Methylene chloride	0.6	1.1
	Freon 113	<0.02	<0.025
	1,1,1-Trichloroethane	0.04	0.149
	Methyl ethyl ketone	0.77	0.54
	Toluene	4.7	4.70
Stora Vika	Methylene chloride	*	<7.3
	Trichloroethylene	*	<0.3
	Chloroform	*	10.0
	PCBs	*	<0.04
	Chlorophenols	*	<0.025
	Phenoxy acids	*	<0.05
	Freon 113	*	0.03
Peerless	PCBs	0.1-0.75	0.13 - 0.55
Los Robles	Methylene chloride	<0.1 - 0.43	<0.003
	1,1,1-Trichloroethane	0.13- 0.34	0.005
	1,3,5-Trimethyl benzene	<0.1 - <7.5	<0.42
	Xylene	<0.1 - <3.1	<0.21
	Benzene	35 - 54	75.00
Lone Star	Methylene chloride	4.8	0.9
	Freon 113	0.43	0.075
	1,1,1-Trichloroethane	<0.025	<0.014
	Methyl ethyl ketone	0.17	0.14
	Toluene	1.5	0.98

* None of the target compounds except chloroform was found during the baseline test.

Sources: Branscome et al. (1985).

Mournighan and Branscome (1988).

Table 5. Products of incomplete combustion (PIC)

Tests	Baseline combustion	Waste combustion
San Juan, Puerto Rico	--	Benzaldehyde Phenol Alkylbenzene Benzoic acid Naphthene isomers Anthracene Polychlorinated dibenzofurans (Cl: 5,6,7 isomers)*
Los Robles, CA	Benzene Toluene Methylene chloride Trichlorethene	--
General Portland, Paulding, OH **	Methyl ethyl ketone Toluene Benzene Biphenyl Naphthalene	Methyl ethyl ketone Toluene Benzene Biphenyl Naphthalene
Lone Star, Oglesby, IL	Toluene Benzene Biphenyl * Naphthalene	Biphenyl Naphthalene
Stora Vika, Sweden	---	Chloroform*

Sources: Branscome et al. (1985).
Viken and Waage (1983).

*Trace quantities

**No increase due to waste fuel combustion

conditions, and trace quantities may have been present when chlorophenols and phenoxy-acids were burned at Stora Vika. However, tests at two other kilns (Oglesby and Paulding) and most of the analyses at San Juan and Stora Vika revealed no detectable quantities of PICs as determined by MM5 and VOST (Branscome et al. 1985; Mournighan and Branscome 1988).

4.3.4 Particulate Emissions

Emissions of particulates from cement and lightweight aggregate kilns may increase slightly when waste fuels are burned. This occurs because the presence of chlorine in the waste feed changes the resistivity of dust particles, which in turn reduces the effectiveness of electrostatic precipitators in capturing particles in exhaust gases. However, by making certain operating adjustments, facilities utilizing electrostatic precipitators have demonstrated the ability to meet regulatory standards for particulate emissions (Mournighan et al. 1985).

The effect of waste combustion on particulate emissions has been of interest because the earlier cement kiln tests (St. Lawrence and Stora Vika) indicated that burning chlorinated wastes increased emissions of particulates. Subsequent tests indicate that the burning of hazardous wastes does not affect the emission of particulates from facilities that utilize a baghouse filter or scrubber system to trap dust particles. A summary of particulate emissions in some of the tests is presented in Table 6. Average particulate emissions during waste burns, about 0.65 lb/ton of product in most of the later tests, were lower than during baseline burns (0.87 lb/ton of product).

4.3.5 Fate of Chlorine

Emissions of hydrogen chloride (HCl), a highly acidic compound, often present problems for commercial incinerators burning chlorinated organic wastes. However, HCl emissions from cement kilns are minimal.

Table 6. Emissions of particulate matter

Site	Test condition	Particulate matter			Cl (kg/mg clinker) into kiln
		gr/SCF	lb/h	lb/t	
St. Lawrence	Chlorinated aliphatics	0.21	123 ^a	3 ^a	4.0
	Chlorinated aromatics	0.086	45	1.1	5.5
	PCBs	0.078	44	1.1	2.5
	Baseline	0.038	21	0.5	-
	Lubricating oil	0.064	83	0.7	-
	Baseline	0.107	139	1.1	-
Marquette	Waste solvents	0.104	58	<1	1.1
	Baseline	0.093	50	<0.8	-
Alpha Cement	Solvents	0.041	44	0.8	-
	Baseline	0.050	53	1.1	-
San Juan	Wastes	0.043	22.4	0.66	5.5
	Baseline	0.041	21.7	0.64	-
Paulding	Wastes	0.030	18.9	0.65	2.2
	Baseline	0.030	19.6	0.64	0.2
Lone Star	Wastes	b	b	b	1.2
	Baseline	0.17	116	2.0	0.2
Stora Vika	Aliphatics	0.039	21	0.88	4.4
	Baseline	0.009	4.7	0.21	0
	PCBs	0.024	12.7	0.53	3.6
	Baseline	0.011	5.9	0.25	0
	Chlorophenols and phenoxyacids	0.058	30.9	1.36	0.95
	Baseline	0.014	7.7	0.34	0
	Freon 113	0.062	33.3	1.39	1.7
	Baseline	0.022	11.7	0.49	0

Sources: Mournighan and Branscome (1988).
Branscome et al. (1985).

^a Ring formation and ESP difficulties

^b ESP malfunctioned

Because conditions within the cement kiln are highly caustic, virtually all of the chlorine entering the kiln is neutralized by alkalis to form calcium chloride, sodium chloride, and potassium chloride, substances which are not acidic. The Paulding test report indicated that most of the chloride was removed with the waste dust. Less than 5 percent was emitted with the clinker and stack gas.

Data in Table 7 show that during some waste burns there were increases in chloride emissions compared to baseline conditions, and in other cases there were decreases.

4.3.6 NO_x and SO₂ Emissions

Unlike coal, which typically contains significant amounts of sulfur, hazardous wastes usually contain little or no sulfur. Therefore, the use of hazardous waste as a supplemental fuel in cement manufacture provides the indirect benefit of reducing emissions of sulfur dioxide from the kiln (Branscome et al. 1985). Nitrogen oxide emissions generally are not affected by the burning of waste fuels.

NO_x and SO₂ emission results are summarized in Tables 8 and 9, respectively. Tests at Lone Star and Paulding showed higher NO_x concentrations during the waste burns. This was probably due to the higher O₂ input (Branscome et al. 1985).

SO₂ test emission results show that substitution of the sulfur-containing primary fuel with a low sulfur waste fuel decreased SO₂ emission in the tests at Alpha Cement, Marquette Cement, and General Portland at Paulding. The San Juan test showed an increase in SO₂ emissions when waste fuel was burned. The increase was attributed to a lower O₂ input (as evidenced by low NO_x emissions) and competitive acid gas scrubbing from HCl in a relatively low alkaline kiln when burning the highly chlorinated wastes (Mournighan and Branscome 1988).

Table 7. HCl emissions

Site	Test condition ^a	HCl		Notes
		(lb/h)	(lb/t)	
Alpha Cement	W	5.8	0.11	Organic halogens in fuel = 590 ppm
	B	2.4	0.05	
Marquette	W	115	1.9	Avg. 1.1 kgCl/mg clinker for waste burn; waste avg. = 4.5% Cl
	B	190	3.2	
San Juan	W	0.79	0.02	Avg. 5.5 kgCl/mg clinker for waste burn; waste avg. = 6.5 - 35.1% Cl
	B	<0.19	<0.06	
Los Robles	W	1.03	0.015	Waste = 2% Cl; avg. 1.1 kgCl/mg clinker
	B	0.55	0.007	
Paulding	W	4.62	0.16	Avg. 2.2 kgCl/mg clinker; waste avg. = 2% Cl
	B	1.25	0.04	
Lone Star	W	25.3	0.46	Avg. 1.2 kgCl/mg clinker; waste avg. = 1.9% Cl
	B	2.9	0.054	
St. Lawrence	W	<1	<0.02	6.8 kgCl/mg clinker, max. 0.7 kgCl/mg clinker for baseline
	B	<1	<0.02	

Source: Mournighan and Branscome (1988).

^aW = waste burn
B = baseline

Table 8. Summary of NO_x emissions

Site	Test condition ^a	NO _x		
		(lb/h)	(lb/t)	(ppm)
Marquette	W	275	4.6	544
	B	404	6.7	920
San Juan	W	31.3	0.9	68
	B	60.4	1.8	136
Los Robles	W	304	5.3	486
	B	444	8.2	680
Paulding	W	174	6.0	478
	B	140	4.6	371
Lone Star	W	472	8.6	814
	B	371	6.9	620

Source: Branscome et al. (1985).

^aW = waste burn

B = baseline

Table 9. Summary of SO₂ emissions

Site	Test condition ^a	SO ₂			
		(lb/h)	(lb/t)	(ppm)	
Alpha Cement	W	58.5	1.1	33	S in coal = 2.6%; S in waste = 0.2% S during waste burn = 2.0%
	B	138	2.7	78	
Marquette	W	11.5	0.19	18	S in waste = 0.08% S in coal = ?
	B	57.1	0.95	93	
San Juan	W	264	8	450	S in fuel oil = 2.15%
	B	170	5	279	
Los Robles	W	21.7	0.36	27	S in coal = 0.43%
	B	23.7	0.38	27	
Paulding	W	207	6.8	265	S in coal = 4.3%
	B	526	17.2	636	
Lone Star	W	14.7	.12	19	S in coal/coke = 2.7%
	B	5.6	.10	7	

Sources: Mournighan and Branscome (1988).
Branscome et al. (1985).

^aW = wasteburn
B = baseline

4.3.7 THCs and CO Emissions

Test results for THCs and CO are summarized in Table 10. THCs increased during waste fuel combustion at three test locations (San Juan, Paulding, and Lone Star), decreased at one test location (Marquette), and remained the same at another (Stora Vika).

The results of CO emissions indicate that combustion of waste fuels does not significantly affect CO concentrations.

4.3.8 Metals

Because waste oils and many hazardous wastes typically contain metallic constituents, most notably lead, concerns have been raised over emission of metals in cement kiln exhaust gases. The data on metal emissions from hazardous waste incinerators are less well developed than the data characterizing destruction and removal efficiencies for organic substances (Oppelt 1987). However, evidence published to date indicates that the burning of waste fuel in cement and lightweight aggregate kilns results either in no increase or in only a slight increase in air emissions of lead and other metals (Higgins and Helmstetter 1982). Studies have shown that greater than 99 percent of the lead contained in waste fuels is either incorporated in an inert form in the clinker product or is adsorbed onto kiln dust particles that are removed by air pollution control devices (Branscome et al. 1984). For comparison, a recent survey of trial burns in which wastes containing lead incinerated in cement kilns concluded that lead emissions from six of the seven facilities tested were less than lead emissions from several automobiles burning leaded gasoline (Mournighan et al. 1985).

4.3.9 Dioxins and Furans

Two types of highly toxic PICs, dioxins (TCDDs) and furans (TCDFs), have received special attention because they have been

Table 10. Summary of THC and CO concentrations

Site	Test condition	THC (ppm) ^a	CO (ppm)
Marquette	Waste burn	470 ^b	-
	Baseline	1,250 ^b	
San Juan	Waste burn	12.7	24-738 ^c
	Baseline	8.3	25-349 ^c
Los Robles	Waste burn	d	25-100
	Baseline	4	10-618
Paulding	Waste burn	21	190
	Baseline	10	212
Lone Star	Waste burn	5	24-49 ^c
	Baseline	2.5	35-40 ^c
Stora Vika	Chlorinated aliphatics	<10	300-1500
	Baseline	<10	1500
	PCBs	<10	100-1500
	Baseline	<10	100
	Chlorophenols/ phenoxyacids	10	50-500
Baseline		10	50
	Freon	<10	100-500
Baseline	<10	100	

Source: Branscome et al. (1985).

^aExpressed as ppm methane unless otherwise noted

^bTotal nonmethane hydrocarbons

^cRange of test averages

^dNot measured

identified in air emissions from a number of solid waste incinerators. However, a survey of test results from trial burns conducted at cement kilns and other industrial hazardous waste incinerators indicates that emissions of dioxins and furans from these facilities are not significant (Oppelt 1987). The dioxin isomer of greatest concern (2,3,7,8-TCDD) has not been detected in emissions from any of seventeen hazardous waste incinerators where tests for these substances have been conducted. Although other isomers of dioxins and furans have been identified in stack gases at several of these facilities (including during a trial burn conducted in 1985 at the Lehigh Cement facility in Cementon, New York), emissions from hazardous waste incinerators appear to be approximately 3 orders of magnitude less than those reported for municipal incinerators (Oppelt 1987).



5. ECONOMICS OF WASTE FUEL USE

This section examines the economic feasibility of burning hazardous wastes in cement kilns. From the viewpoint of a cement plant manager, there must be a reasonable assurance of increased profit or reduced cost to the plant before expenses for burning wastes can be incurred. One U.S. cement plant with 1.5 million ton/yr cement capacity anticipates an annual net savings of \$3 million by providing 35 percent of its energy requirements with liquid chemical wastes (Beers 1987).

A report by Hazelwood et al. (1982) indicates that burning hazardous liquid wastes in cement kilns generally can be economically attractive (i.e., for the waste generator, cement kiln disposal costs less than commercial incinerator disposal; and for the cement plant manager, net energy costs are reduced substantially). Bouse and Kamas (1987), Mournighan and Branscome (1988), Ahling (1979), Viken and Waage (1983), and Henz (1986) have confirmed this economic attractiveness.

5.1 General Economic Factors

Energy costs in the cement industry normally amount to 33 to 40 percent of total cement production costs, and in some cases may be as high as 65 percent (Bouse and Kamas 1987). Organic wastes burned in cement kilns can reduce fuel cost substantially and thus affect the economics of waste disposal. The amount of waste fuel that may be used at a particular plant depends primarily on the characteristics of the waste and the ability of the plant to store and pump wastes in the required quantities.

Fees charged for waste disposal at cement kilns vary with heating value, toxicity, water content, chloride content, sediment content, metals and solids content, and waste sampling and analysis required. Fees vary widely from region to region depending on the availability and continuity of waste supply.

Capital costs for plant modifications (i.e., for storage, handling, fuel injection, and laboratory equipment) are required to burn waste fuels, but no additional capital costs for control of particulate emissions are necessary at a cement plant. Electrostatic precipitators and fabric filters are already an essential part of the engineering design in modern cement plants. However, some increased operating and maintenance costs may be necessary in order to accommodate waste fuels. Compliance testing will also increase costs.

Waste characteristics are necessary concerns in the design and construction of waste transport and handling system. For example, if sludge accompanying a waste to be burned must be disposed of separately, some added capital and operating cost must be anticipated.

Additional insurance coverage in the form of environmental impairment liability is a cost factor in assessing the economics of cement kilns for waste disposal.

One set of factors that influences costs and fees has to do with the responsibility for laboratory analyses of primary fuels and waste fuels. In the case of primary fuel, the fuel supplier is responsible for laboratory analysis of the product that he sells to the cement kiln, and the fuel costs include necessary analytical costs. In the case of hazardous waste fuel, the burden of laboratory costs may fall on the cement kiln unless by some contractual arrangements these costs are to be assumed by the waste generator. Whoever is responsible for the quality of the waste (user or generator) must assume the analytical cost, which for most complex wastes is considerable. In addition, the cost of flue gas sampling and analysis for complex POHCs and PICs would be the responsibility of the cement kiln. These analyses are far beyond the scope and cost for normal environmental regulations of cement kilns. In some cases, proper sampling equipment may well cost \$100,000 or more. Continuous emission monitors might also be required, depending on applicable regulations. At about \$20,000 to \$50,000 for each parameter measured, users of supplemental waste fuels might not wish to accept the risk of assuming constant waste quality either from the standpoint of their own cement quality or from an environmental regulatory position. The cost of establishing a field laboratory for burning of some waste might be in

the range of \$500,000 to \$700,000 with annual operating costs in the range of \$100,000 to \$150,000 (pers. com. Malcolm Wilson, November 1988).

The continuity of waste fuel supply in the future may be affected by the impact of gradual reduction in the quantities of certain hazardous wastes (e.g., PCBs) whose manufacture, at least in the United States, has been terminated.

5.2 Economic Data for Model Plant A

Hazelwood et al. (1982) and Branscome et al. (1985) have developed a cost model for hazardous waste disposal in a hypothetical cement plant. This model demonstrates the relationship between costs, disposal fees, and return on investment. The features of the model are as follows:

- The small wet process kiln has an annual capacity of 230,000 tons;
- Waste fuels are delivered by truck;
- Coal is the primary fuel;
- Air and water pollution control systems--ESP, exhaust air, and waste-water treatment are available with excess capacity;
- Adequate space for siting of any needed facilities is available.

Table 11 presents cost estimates for the additional installed equipment and operating expenses necessary for hazardous waste disposal in the kiln.

Annualized cost is composed of fixed cost, including loan repayment over 5 years, interest, labor, utility, maintenance, and insurance costs related to waste burning. As shown in the table, annualized capital and operating costs are estimated to total approximately \$43,200. On a production basis, this would be equivalent to 19 cents/ton of clinker produced (for the one 230,000 tons/yr kiln utilized). Considering production cost of cement (about

Table 11. Cost estimates for waste disposal in a model cement kiln

Cost Elements	Estimated Cost
Capital Cost (Cost of Installed & Operating Equipment) *	
Area preparation (cleaning, leveling, trenching, tamping, etc.)	\$ 2,000
Concrete slabs (2)	3,200
Fuel tank	750
Steel industrial waste tank (25,000 gallons capacity)	12,000
Tank diking	1,600
Truck unloading connections	500
Waste tank float level (with high and low alarm)	3,000
Piping and small fuel oil transfer pump	900
Piping and waste feed pump	3,000
Grounding	500
Flame arrestors	200
Carbon dioxide fire protection system	2,200
Electrical equipment for	2,500
Normal fuel flow interruption	
Normal make-up air interruption sense	
Transducers	
Pump starter-shut off control	
Waste flow meter and instrumentation	1,200
Miscellaneous, hardware (coding, painting, etc.)	2,500
Nozzle assembly	450
Engineering and Installation	8,000
Portable fire extinguishers (large)	1,200
Personal protective equipment	2,100
Self-contained breathing apparatus (2)	
Goggles	
Gloves	
Boots	
Organic respirators	
Dust respirators	
Portable hydrocarbon detector/direct reading detector tubes	1,500
Total cost of installed and operating equipment	49,300
Annual Operating Cost *	
Labor : 330 days/yr. at 4 hrs/day at \$ 8.00/hr	\$ 10,600
Utilities: Electricity	3,000
Maintenance costs (5% of investment)	2,200
Total annual operating cost	15,800
Annualized capital cost with 5 years payback (\$ 49,300) @ 13%	\$ 12,400
Insurance cost	15,000
Total annual cost *	\$ 43,200
Cost per ton of cement produced: \$ 43,200 per year/230,500 tons per year	\$ 0.188/ton

Sources: Hazelwood et al. (1982).
Branscome et al. (1985).

*All cost estimates are at 1982 constant prices.

\$45/ton), this is an insignificant outlay. Nevertheless, to obtain a 15 percent return on this additional investment for construction and operation of the waste-handling system would require a total income from the operation of at least \$49,700 a year. Two cost scenarios are presented here to illustrate the positive net savings due to substitution of waste fuel for primary fuel.

The following data are common to both the cost scenarios:

- Kiln production--230,000 tons/yr;
- Unit fuel cost for primary fuel--\$2.46/million Btu;
- Chlorine limit--0.6 percent of kiln production, or 1,440 tons/yr;
- Heat value of waste--10,000 Btu/lb;
- Existing kiln monitoring systems and on-site laboratory facilities are adequate, so no additional investment is required for this purpose;
- Annual return of capital + 15 percent profit = about \$50,000/yr.

EPA has used these data in calculating revenues resulting from two levels of waste fuel use (two scenarios) and three levels of waste fuel cost (Hazelwood et al. 1982). The net savings estimated for the two scenarios are presented here.

5.2.1 Cost Scenario I

In the first cost scenario, it is assumed that a waste containing 20 percent by weight of chlorinated hydrocarbons is available and that 80 percent of the waste's heating value can be recovered.

The maximum amount of chlorinated waste that can be used, assuming a chlorine limit of 0.6 percent of clinker weight, is 1,440 tons/yr, divided by 20 percent, the % of each mixed fuel which is chlorinated hydrocarbons (i.e., 7,200 tons of waste per year). The recovered heating value of the waste fuel used will total 1.15×10^{11} Btu. This is equivalent to 7.9 percent fuel substitution.

If the waste is delivered at no cost to the cement plant (i.e., disposal fee = 0), total savings will be \$283,000 per year. Net savings, subtracting investment costs plus a 15 percent return on investment, would be \$233,000 per year or 97 cents per ton of cement produced.

If the cement plant purchased the waste for \$1 per million Btu of waste, net savings would be 49 cents per ton of cement produced.

If the cement plant charged a disposal fee equivalent to \$1 per million Btu of waste fuel heating value (\$32/ton of waste), net savings would be equivalent to \$1.45 per ton of cement produced.

5.2.2 Cost Scenario II

In the second cost scenario, it is assumed that a waste containing 10 percent by weight of chlorinated hydrocarbons is available and that 90 percent of the waste's heating value can be recovered.

The maximum amount of waste that can be used is 14,400 tons/yr. The recovered heating value of this quantity of waste is about 2.59×10^{11} Btu or 17.8 percent of the kiln's fuel requirement.

Net savings per ton of cement produced will be:

- \$2.45 if the waste is delivered to the cement plant at no cost;
- \$1.37 if \$1 is paid per million Btu of waste fuel by the cement plant; and
- \$3.53 if \$1 is charged per million Btu of waste fuel by the cement plant.

5.3 Economic Data for Model Plant B

The economic data in these models are rough estimates with only partial information and should only be taken as guidelines for

economic analysis. The costs of equipment and facilities at any specific plant may vary considerably.

In the model, costs for sampling and analysis of wastes and emissions were not included. In a routine ongoing waste disposal operation, these sampling and analysis costs are relatively small. However, during a trial burn to establish satisfactory plant operating conditions for hazardous waste disposal, these sampling and analysis costs could be significant.

USEPA (1985b) has developed a cost model for another plant about double the size of Plant A, with higher required investment costs to burn hazardous wastes and with higher waste fuel substitution rates. The features of this model are:

- The medium-size wet process kiln has an annual capacity of 500,000 tons;
- 50 percent fuel substitution is assumed;
- Waste fuel feed rate is 1,900 gal/hr with a heat value of 10,000 Btu/lb;
- Waste fuel costs \$4 per MBtu; plant uses 2,500,000 MBtu/yr so waste fuel costs \$10 million/yr.

A. Capital costs for plant modification (1985 dollars)

Four 25,000-gal storage and blending tanks	\$ 240,000
One 150,000-gal working tank	150,000
Pumps, motor, and auxiliary equipment and instrumentation	180,000
Containment system, sumps, and paved areas	70,000
Laboratory building	100,000
Laboratory equipment and safety equipment	120,000
Fuel delivery system	50,000
Contingencies, 20%	<u>180,000</u>
	\$1,090,000

B. Annualized costs for plant modification
plus operations and maintenance

Materials and supplies	\$ 30,000
Maintenance	20,000
Operating labor and overhead	160,000
Capital recovery (@ 15% interest, 10-year life)	<u>220,000</u>
	\$ 430,000

In Model B, significant additional costs have been estimated as follows:

	<u>Annual cost first year</u>	<u>Annual cost in subsequent years</u>
Permits	\$ 250,000	\$ 40,000
Public education	100,000	10,000
Extraordinary measures (not defined)	350,000	100,000
	<u>\$ 700,000</u>	<u>\$ 150,000</u>

First year total costs = \$430,000 + \$700,000 = \$1,130,000

Subsequent year annual costs = \$150,000 + \$430,000 = \$580,000

A \$2.5 million/yr net fuel savings is reported for the 50 percent fuel substitution case. These savings in relation to costs clearly indicate attractive economies.

It is, however, important to establish the economics of waste disposal on a case-by-case basis for each individual cement kiln since many economic factors differ substantially from kiln to kiln.

6. RISK ASSESSMENT

There are risks in any method of hazardous waste disposal. This section attempts to put the risks of cement kiln disposal in perspective.

The USEPA has conducted a risk assessment of the potential health effects of toxic organic and metals emissions based on trial burns conducted at nine hazardous waste incineration facilities. This risk assessment conservatively estimated that the increased cancer risk for an individual exposed to incinerator emissions over a 70-year period ranges from 1 in 100,000 to 1 in 1 million. Because this is a worst-case estimate, it likely overstates the actual risk of cancer resulting from emissions from hazardous waste incinerators. Although EPA's risk estimate was based on data from a relatively small number of facilities, other available risk assessments corroborate EPA's assertion that emissions from properly operated hazardous waste incinerators do not pose a significant threat to public health or the environment (Oppelt 1987).

Interestingly, the 99.99 percent destruction and removal requirement, which has generally been used for permitting hazardous waste disposal in cement kilns and incinerators, is not based on any risk assessment of the environmental hazards associated with emissions from a facility meeting this standard. Rather, the 99.99 percent DRE target was developed by EPA as an achievable standard based on the results of approximately 50 trial burns conducted during the 1970s. Some authors have argued that the 99.99 percent DRE standard is a highly conservative requirement, as existing air emission standards for many organic chemicals from industrial process sources are 10 to 100 times less stringent than this requirement (Beers 1987).

The remainder of this section provides details on risks of transportation, storage, handling, kiln emissions, and other risks.

6.1 Transportation Risks

Any waste that must be disposed of at a site other than its point of generation will require transport to the disposal site and will, during its transport, create a risk of spillage and/or fire. Such risks are not unique to a given method of off-site disposal and will be incurred whether the waste is to be disposed of by incineration, landfilling, or destruction in a cement kiln.

Wastes supplied to cement plants for disposal are likely to be transported by tank trucks over public highways or by rail. In the United States, compliance with federal or state environmental regulations serves to mitigate risks involved in transporting hazardous wastes. In addition, plants utilizing waste fuels should exercise managerial procedures that further reduce risks to the public. These procedures include selection of a reputable licensed waste hauler, identification of most favorable transport routing, and insistence on, and drill in, emergency contingency plans (Bouse and Kamas 1987).

In some cases, transporting of waste fuels from the source to the cement plant is the responsibility of the waste supplier; in other cases, it is the responsibility of the cement plant. In either situation, both parties are likely to share the responsibility for safe transport. Therefore, the cement manufacturer must be actively involved in selection of the fuel transporter and fuel transport methods. It is also likely that cement plants, when contracting for delivery of waste fuels, will assign the responsibility for safe transport to the waste supplier. Transportation risks will normally be the responsibility primarily of the waste hauler and secondarily of the waste generator. In the United States, the "cradle to grave" manifest system inherently formalizes this responsibility.

In planning for delivery of wastes, care should be taken to route shipment to minimize potential public exposure to hazards from transportation accidents. This will involve identification of alternative routes, assessment of roadway conditions, and analysis of population exposures along alternative routes. A principal concern in evaluating transport routes is likely to be the population along

proposed routes. Environmental impact assessment of transportation should incorporate risk factors involved in accidental spills.

Assuming an average waste fuel heating value of 10,000 Btu/lb or 90,000 Btu/gal, and a typical tank truck capacity of about 45,000 pounds or 5,000 gallons, it is possible to calculate the number of shipments required for various levels of waste fuel utilization at a cement plant. The number of shipments can be used to estimate total ton-miles of transport required. Probability of accidental spills in any given year can be estimated by the means of the Poisson distribution, which governs infrequent random occurrences as follows:

$$P_n = \frac{e^{-x} x^n}{n!}$$

where x = no. of accidents/yr of this type country-wide from trucking industry records or insurance company statistics;

n = no. of truckspill accidents expected over lifetime of the specific cement facility;

P_n = probability of an accidental spill during transport for that cement facility in any one year.

Based on historical accident rates, probability of a transportation accident resulting in a spill exceeding a certain level of damage can be estimated (Menzie 1979).

Risk is a function of probability and consequences of an unfavorable event. Consequences of the event must be calculated for specific types and locations of such events after functional analysis of a proposed operation.

6.2 Storage and Handling Risks

Storage and handling of waste fuels at cement plants entail risks similar to those encountered by many industries that use or generate flammable or toxic materials. Techniques commonly employed to

mitigate such risks are well developed and can be applied with minimal modification. Storage and handling requirements will differ according to characteristics of the waste being used. Variables to be considered in selecting appropriate equipment and handling methods include the waste's toxicity, flammability, corrosivity, reactivity, vapor pressure, viscosity, and solids content.

Principal concerns in storage and handling of fuels are the risks posed by spills and fires. A spill of waste fuel can result in the contamination of soil, groundwater or surface water, and release of hazardous vapors. Additional risks associated with waste fuel fires are those of property damage, personal injury, and gross contamination of air with combustion products.

Off-loading of tank trucks must be conducted in a way that minimizes vapor releases into the air. Closed transfer lines should be used between tank vents.

Through use of well-designed systems and procedures, probability and severity of accidental spills during storage and handling can be limited.

6.3 Other Risks

It is conceivable that there might be some potential contamination of the cement product with the hazardous waste fuel. In the review of plant histories, there is evidence that such a risk is insignificant (Mournighan and Branscome 1988; Berry et al. 1975; Lauber 1982).

The consensus among studies investigating cement dust disposal by on-site landfilling has been that although certain precautions may be necessary to prevent wind dispersal or direct runoff to surface water, the disposal of kiln dust from cement kilns burning hazardous waste does not appear to present a significant environmental risk (Hazelwood et al. 1982).

6.4 Kiln Emission Risks

Risk posed by stack emissions from cement kilns utilizing waste fuels will vary with characteristics of the waste used, rate of waste injection into the kiln, existing kiln chemistry, and efficiency of the particulate control devices employed for cleaning stack gases. Attention must also be effectively directed to fugitive emissions of kiln dust.

Toxic organic emissions could pose some risk to the community during upset operation due to a rapid movement of clinker down the kiln and into the clinker cooler. Also, substantial nonuniformities in waste fuel composition from batch to batch may increase the difficulty of maintaining stable operations. During such an upset, emissions of incompletely combusted toxic organic compounds are usually evident from the smoke and dust cloud accompanying their release. Continuous emission monitoring may be necessary. Prompt termination of waste feed flow to the kiln when an upset is detected can prevent waste fuel from further contributing to those products of incomplete combustion that might pose some risk. A number of investigators have studied the chemical reactions that occur under conditions of upset kiln operation (Mix and Murphy 1984; Branscome et al. 1985). These investigations serve as a guide to minimizing upsets and dealing with the impacts.

Incineration of chlorophenols and other chlorinated aromatics can result in the emission of dioxins or furans. Reports of trial burns reviewed during this study indicate that emissions from cement plants burning chlorinated waste fuels have shown no evidence of major health concerns (Mix and Murphy 1984).

Trial burns at the General Cement Plant, Paulding, Ohio, introduced waste fuels containing phosphorus and zinc. However, phosphorus and zinc emissions were relatively insignificant in relation to their concentrations in the raw materials used to produce cement clinker (Branscome et al. 1985). Therefore, their low amounts in waste fuels are expected to present no significant health risks.

Waste lubricating oils burned at the St. Lawrence and Stora Vika kilns were contaminated with lead and zinc. Lead emissions in the

kiln exhaust gases did not increase as a result of burning that waste oil. In all the trial burns using waste oil, most of the lead was encapsulated in the cement clinker. Some of the lead from the waste oils was found in the kiln dust. Kiln dust disposal problems may increase when hazardous waste fuels are used. However, kiln dust can be effectively managed, principally by recycling through the kiln or through landfilling. Because cement dust is a highly buffered alkaline material, the leachability of metal oxides from kiln dust is low (Peters et al. 1986).

6.4.1 Dispersion of Kiln Emissions and Health Risk Assessment

The magnitude and nature of health risks posed by air emissions of a cement kiln burning hazardous waste can be estimated by use of mathematical models. Many diverse air-dispersion models and exposure assessment methodologies are available to determine the dispersion concentrations of pollutants in the atmosphere (Kelly 1986; Dobbins 1979). These models feature a high degree of uncertainty in the absence of more definitive data. However, they are also generally recognized as the only tool currently available for procedures such as estimating the magnitude of environmental pollutant concentrations associated with exposure to air pollutants.

Using the Gaussian Plume Model to account for pollutant dispersion downwind of the source, off-site downwind emissions concentrations have been estimated for four principal organic hazardous compounds that are likely decomposition products from burning chlorinated organic hazardous wastes. These compounds (methylene chloride, chloroform, carbon tetrachloride, and benzene) are of principal concern because of their known or suspected carcinogenicity and their relatively high emission levels in most of the observed trial burns (Table 4). Hexachlorobenzene and pentachlorophenol have also been suggested as compounds of concern whose dispersion might well be investigated.

The Gaussian Plume formula provides only rough estimates of downwind concentrations. Unsteady emission rates, varying

meteorological conditions, chemical reactions, scavenging, washout, and uncertainty of plume trajectories are not accounted for.

Axial mean concentration of the plume (C) at one kilometer distance from the source is computed using the Gaussian Plume formula.

$$C = \frac{Q}{\pi u \sigma_y \sigma_z} \cdot \exp\left(\frac{-H^2}{2\sigma_z^2}\right)$$

Where C = Axial mean concentration ($\mu\text{g}/\text{m}^3$)

Q = Pollutant source emission rate (g/s)

u = Mean wind speed (m/s)

y = Lateral Gaussian Plume dispersion coefficient

z = Vertical Gaussian Plume dispersion coefficient

H = Stack height (m)

In the absence of more definitive location data, we have estimated axial mean concentration (C) for a windy location (Case 1) and for a worst-case location (Case 2) under night inversion conditions. Most actual cases are likely to fall within these extremes.

Hypothetical Case 1:

Cement plant location = Windy island

Average wind speed = 6 m/s

Mean stack height, H = 20 m

Dispersion classes (Dobbins 1979:223-226)

Day time class is C (Varying amounts of incoming solar and sky radiation with slight convective activity)

Night time class is D (Neutral stratification when net radiation flux is 0)

Dispersion coefficients (Dobbins 1979:226)

Day time: $\sigma_y = 106.96$; $\sigma_z = 73.10$

Night time: $\sigma_y = 75.47$; $\sigma_z = 27.33$

Hypothetical Case 2:

Cement plant location = Inland with night inversion

Average wind speed = 1 m/s

Dispersion classes^{*}:

Day time = D (Neutral stratification)

Night time = E (Radiation inversion may form and will give rise to poor dispersion)

Dispersion coefficients^{**}:

Day time: $\sigma_y = 75.47$; $\sigma_z = 27.33$

Night time: $\sigma_y = 53.56$; $\sigma_z = 25.61$

Mean Stack Height (H) = 20 m

Axial mean concentration (C) values computed for two hypothetical cases are presented in Table 12. Using the values from Table 12, health risk for an individual can be estimated as follows:

$$\text{Health risk } R = Q^* \times D \quad \text{where } Q^* = \text{Unit risk factor (USEPA 1985a)} (\mu\text{g}/\text{m}^3)^{-1}$$

$$D = \text{Dose } (\mu\text{g}/\text{m}^3)$$

$$\text{But } D = C \times A \times F \quad \text{where } C = \text{Axial mean concentration } (\mu\text{g}/\text{m}^3)$$

$$A = \text{Absorption efficiency of lungs}$$

$$\approx 0.75 \text{ (approximately)}$$

$$F = \text{Fraction of time spent outdoors (assume 0.15)}$$

$$\text{Therefore, Risk } R = Q^* \times C \times A \times F$$

$$\approx Q^* \times C \times 0.11$$

Table 13 presents the potential individual health risks from exposure to the four POHCs.

The risk value "R" calculated for carcinogens, at a given dose "D," indicates the number of additional cases of cancer to be expected within a population due to a lifetime (70 years) exposure to dose "D." A risk of 1×10^{-6} , for example, indicates that in a population of

Table 12. Axial mean concentration of the plume (C) 1 km downwind from source

POHCs	Hypothetical Case 1				Hypothetical Case 2			
	Day		Night		Day		Night	
	$\mu\text{g}/\text{m}^3$	ppb	$\mu\text{g}/\text{m}^3$	ppb	$\mu\text{g}/\text{m}^3$	ppb	$\mu\text{g}/\text{m}^3$	ppb
Methylene Chloride	0.6	0.2	1.8	0.5	11.0	3.2	15.9	4.6
Chloroform	0.5	0.1	1.6	0.4	9.9	2.0	14.3	2.9
Carbon Tetrachloride	0.8	0.1	2.4	0.4	14.3	2.3	20.6	3.3
Benzene	0.3	0.1	0.8	0.3	4.8	1.5	6.9	2.2

Note: These ppb concentration levels are all below regulatory air emissions standards in the State of New York.

Table 13. Health risks from kiln emissions of four POHCs (Estimated upper limit of maximum individual health risks of kiln emissions--R values) *

POHCs	Hypothetical Case 1		Hypothetical Case 2	
	Day	Night	Day	Night
Methylene Chloride	1.2 E -08	3.6 E-08	2.2 E-07	3.1 E-07
Chloroform	5.9 E -07	1.8 E-06	1.1 E-05	1.6 E-05
Carbon Tetrachloride	1.3 E -06	3.9 E-06	2.4 E-05	3.4 E-05
Benzene	1.9 E -07	6.0 E-07	3.6 E-06	5.2 E-06

* In using Table 13 for judging risks from cement kiln emissions, it is pertinent to note that these R values assume 70-year lifetime exposures at the assumed periodic concentrations for 15% of each day (or night). Offsite exposures to emissions from hazardous wastes in cement kilns are normally periodic and of short duration, compared to a 70-year lifetime.

1 million, one additional cancer may occur as a result of this exposure. Off-site pollutant concentrations calculated from the Gaussian Plume formula represent a maximum individual dose expected. The unit risk value or Q^* is the estimated probability of contracting cancer as the result of continuous exposure to a concentration of 1 microgram per cubic meter ($1 \mu\text{g}/\text{m}^3$) over a 70-year lifetime. It is derived from the potency for a specific chemical as calculated by the USEPA through use of conservative linear models that extrapolate bioassay data from animal studies to estimate response at low doses. This response is further extrapolated to estimate human health effects based on differences in body weight and inhalation rates. The unit risk is multiplied times the dose to give the health risk "R." Resulting risk estimates represent the upper limit of expected health effects from this exposure and are subject to uncertainties of several orders of magnitude. A risk of 1×10^{-6} or less is generally acceptable. Risks in the range 10^{-6} to 10^{-4} or less are currently considered acceptable for many situations (USEPA 1985a).

Table 13 shows that carbon tetrachloride and chloroform risks are calculated to be 1×10^{-5} (i.e., within an acceptable risk range). Given the multiple uncertainties in the assumptions for the calculation, the calculated maximum expected health risk is highly uncertain. We can compare predicted concentrations shown in Table 12 with those measured in typical polluted urban air in U.S. cities shown in Table 14. For conditions typical of a windy island, all concentrations are for short exposures less than that found in the polluted U.S. cities. Under inversion conditions, the concentrations of methylene chloride, chloroform, and carbon tetrachloride are much higher than found in U.S. cities under polluted conditions. Table 14 also shows the International Agency for Research on Cancer (IARC) classifications of carcinogenicity for these substances. Before burning chlorinated organic wastes in a specific cement kiln, trial burns are suggested to determine emission rates and downwind concentrations for specific candidate hazardous wastes, and to make calculations of health risks under different conditions. For example, in some locations of specific cement kilns, it may be desirable to

Table 14. POHC concentrations in typical polluted U.S. cities
(classification of carcinogenicity and POHC concentrations)

POHCs	IARC Classification (1979-82)	Weight of Evidence for Carcinogenicity	Typical Concentration in polluted U.S. Cities* (ppb)
Methylene Chloride	3	Inadequate human and animal	0.5 - 4.0
Chloroform	2B	Sufficient animal; inadequate human	0.1 - 0.2
Carbon Tetrachloride	2B	Sufficient animal; inadequate human	0.1 - 0.3
Benzene	1A	Sufficient human	1.0 - 6.0

*Source: Shah and Heyerdahl (1988).

avoid burns of some hazardous wastes during some conditions such as atmospheric inversions. In some cases, it may be desirable to change stack heights.

7. CEMENT KILNS IN SELECTED ASIA-PACIFIC COUNTRIES

In June 1988, at the outset of the study of this topic, Consortium members were requested to provide information on cement kilns in their country. Specifically, they were requested to provide an inventory of cement kilns listing plant capacity, type of process, approximate age of plant, current ownership, location, population density, and type of surrounding land use, together with any notes on operating experience for those plants that might be pertinent in considering these plants as candidates for hazardous waste disposal.

Table 15 presents 1988 data provided by Consortium members in Malaysia, Korea, and New Zealand. These data give some insight into the potential for using cement kilns for disposal of hazardous waste in those countries. Hopefully, in subsequent phases of this study, similar data will be available from Consortium members in other Asia-Pacific countries. Even though recent experience in the United States indicates hazardous wastes can best be introduced as only a small percentage of input feedstock, a review of Table 15 indicates that cement plants in those three countries have a substantial potential for disposing of large quantities of hazardous wastes. If site-specific studies confirm the potential for safe and economical disposal, it will be possible to avoid major capital expenditures for new hazardous waste disposal facilities to the extent that certain cement kilns can be used for that disposal function.

It is of some interest to review the 1988 data in Table 15 in the light of some 1984 data in Table 16 from global statistics. As of 1984, the Asian region alone accounted for about 38 percent of world cement production; China accounted for about 35 percent of Asia's production, followed by Japan (22 percent), India (8 percent), and the Republic of Korea (6 percent).

The 1988 data compared with the 1984 data gives some measure of significant growth trends in the cement industry in New Zealand, Malaysia, and Korea. This growth probably also represents increasing opportunities for prudent and economical hazardous waste disposal through use of cement kilns in those countries.

Table 15. Profile of cement plants in selected Asia-Pacific countries (as of 1988)

Country	Name and location of cement plant	Production capacity (tonne/yr)	Type of process	Age of plant (yrs)	Pattern of ownership	Type of surrounding land-use
Malaysia	Associated Pan Malaysian Cement, Rawang, Selangor	1,000,000	Wet	35	Private limited	Residential-cum-urban area
	Perak-Hanjong Simen, Pedang, Pedang Perak	1,000,000	Dry	2	Private limited	Residential areas, fruit orchards, paddy fields, and rubber estates
	Cement Industries of Malaysia Berhad, Perlis	1,000,000	Dry	13	Public limited	Residential areas and rubber estates
	Tasek Cement Berhad, Joph Perak	1,000,000	Semi-dry and dry	26	Public limited	Industrial
	Kedah Cement Bdn, Lanekawi, Kedeh	600,000	Dry	4	Government-owned	Rubber and coconut estates, paddy fields, fruit orchards, and residential areas
	Associated Pan Malaysian Cement, Chernor, Perak	403,700	Wet	24	Private limited	Rubber estates and residential areas
	Malaysia Industrial Mining Corporation, Batu Cava, Belangor	60,000	Dry	29	Public limited	Residential areas and limestone hills
	Rock Chemical Industries, Lahat, Perak	12,000	Dry	13	Private limited	Rubber estates
Korea	Dongyang Cement, Samchuck	5,164,750	Dry with suspension preheat	46	NA	Urban; population density of 905/sq km
	Seangyong Vanghon Cement, Dornghan	10,385,710	Dry with suspension preheat	20	NA	Urban; population density of 509/sq km
	Seangyong Vanghon Cement, Yeonghul	2,346,950	Dry with suspension preheat	14	NA	Rural; population density of 74/sq km
	Seangyong Vanghon, Munkyung	317,550	Wet	31	NA	Urban; population density of 1209/sq km

Country	Name and location of cement plant	Production capacity (tonne/yr)	Type of process	Age of plant (yrs)	Pattern of ownership	Type of surrounding land-use
	Hanil Cement, Danyang	3,222,950	Dry with suspension preheat	24	NA	Rural; population 80/sq km
	Hyundai Cement, Danyang	3,212,000	Dry with suspension preheat	24	NA	Rural; population 80/sq km
	Asea Cement, Jeochun	2,387,100	Semi-dry and dry	22	NA	Rural; population 62/sq km
	Sungshin Yanghoe Cement, Danyang	3,639,050	Dry with suspension preheat	19	NA	Rural; population 80/sq km
	Goryu Cement, Jangsung	730,000	Dry with suspension preheat	15	NA	Rural; population 159/sq km
	Halla Cement, Okgyeu	1,314,000	Dry with suspension preheat	3	NA	Rural; population 89/sq km
	Union Ltd, Chungjoo	109,500	Dry with suspension preheat	7	NA	Rural; population 169/sq km
New Zealand	Golden Bay Cement Co., Portland near Whangarei	500,000	Dry with suspension preheat	6	NA	Rural; nearest village has 80 houses and 2 km distance
	Milburn New Zealand, Ltd., Cape Foulwind near Westport	420,000	Wet	32	NA	Rural
	Milburn New Zealand, Ltd., Burnside, Green Island	125,000	Wet	62	NA	Rural; nearest house is about 0.5 to 1 km away

Table 16. Cement production in selected countries

	Million metric tonnes (1984)
World	918.87
Africa	37.53
N. America	106.59
USA	70.54
S. America	39.54
Europe	246.55
Asia	353.16
China	123.02
Hong Kong	1.85
India	29.43
Indonesia	6.61
Japan	78.86
Korea, Republic	20.41
Malaysia	3.47
Philippines	3.66
Singapore	2.51
Thailand	8.27
USSR	129.87
Oceania	5.64
Australia	4.65
Fiji	0.10
New Caledonia	0.06
New Zealand	0.82

Source: United Nations (1987).

8. FINDINGS

1. Disposal of selected hazardous wastes is currently being safely conducted at more than 20 cement plants in the United States, with specific and significant economies being achieved. Other plants are in various stages of planning to use combustible hazardous waste as fuel.
2. Although data on cement-kiln disposal for a complete spectrum of hazardous waste types were not available during this initial phase of study, there is substantial information on cement-kiln disposal of solvent-derived fuels (SDFs). SDF constitutes a large fraction of hazardous wastes in many regions. Since many SDFs have high heat value and can be used as a partial substitute energy source for cement kilns, there is substantial economic motivation for developing countries to concentrate on SDFs in their initial trial programs for disposal of hazardous wastes in cement kilns. Bouse and Kamas (1987) provide information concerning disposal of SDF in cement kilns.
3. The Introduction listed many promising characteristics of the cement manufacturing process that can lead to opportunities for environmentally sound and economically attractive disposal of hazardous wastes. However, evaluation of this technology to date indicates that the following constraints must be recognized:
 - Waste type characteristics: Cement kilns are limited in the types of waste they can accept. Solid hazardous wastes, for example, do not appear to be economically attractive at present. Wastes with low heating value (e.g., under 8,000 Btu/lb) may be marginally attractive. Chlorine content of waste fuels must generally be kept under 0.6 percent of clinker weight. Water content of the waste fuel must not be excessive.

- Permits and regulations: To date, at least in the United States, the permitting process (including test burns) is usually time-consuming, complex, and expensive. This discourages some plant owners/managers from adopting this technology. Moreover, regulatory requirements for continuing monitoring and recordkeeping increase costs.
- Liability and insurance: Processing hazardous wastes often introduces additional liability and insurance costs.
- Waste fuel supply: There must be a reliable and continuing supply of waste fuel available within a reasonable distance at a reasonable price (or fee) to justify the investment necessary for burning the waste fuel.
- Public and employee acceptance: Due to a desire to avoid public opposition, some cement plants have not burned well-known hazardous wastes such as PCBs on a continuing basis, despite the fact that test burns have demonstrated the ability of cement kilns to destroy these substances (Lauber 1987).

Some cement plants, particularly those near residential neighborhoods because of inadequate attention to fugitive dust problems, have in past decades been considered as undesirable neighbors, regardless of what fuels the cement plants were using, or might use in the future. As a consequence, the public may often view new proposals concerning any changes whatsoever in cement operations with suspicion.

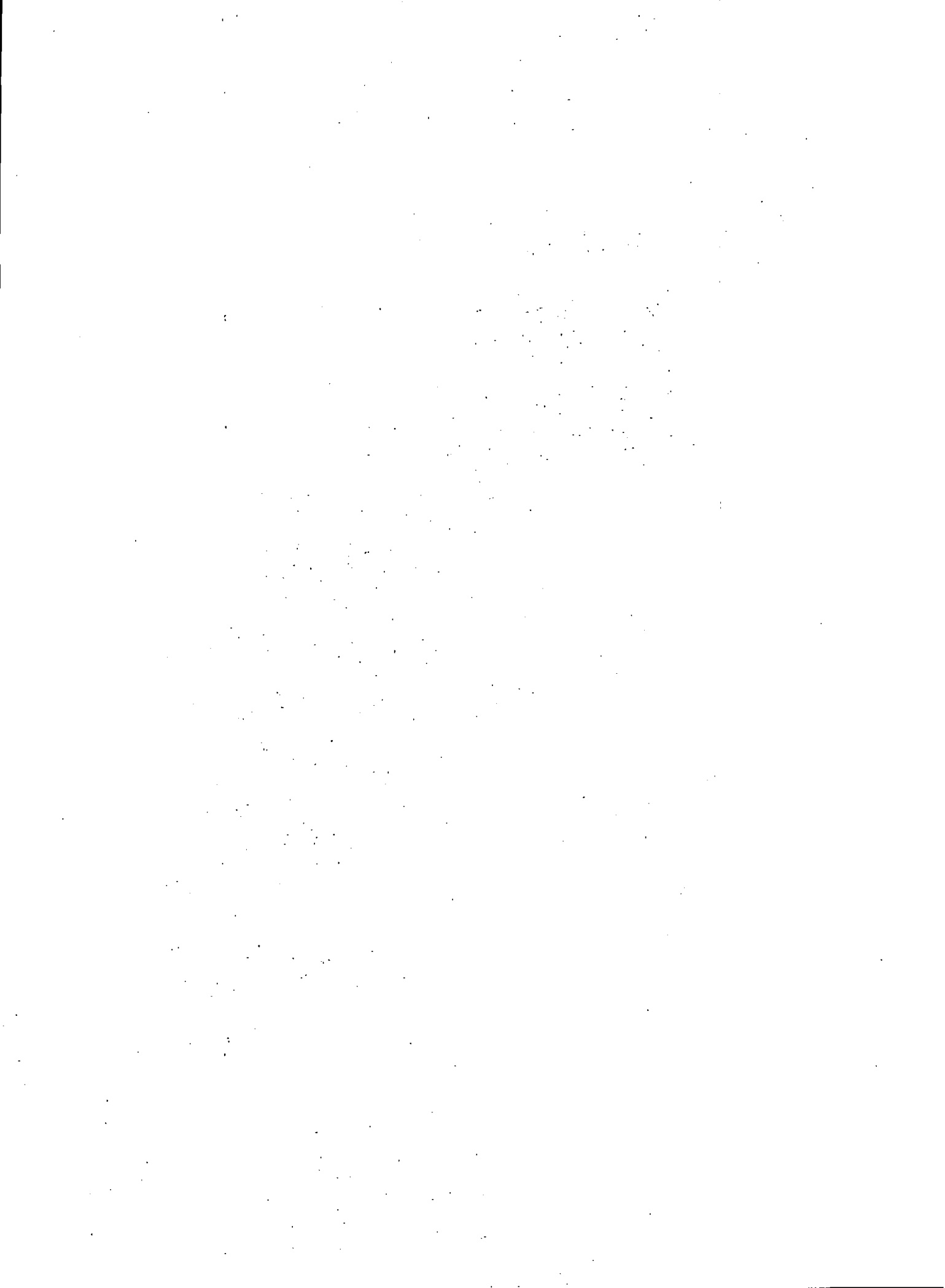
4. Despite the preceding constraints, it is considered that this technology in many instances can provide mutual benefits to both industry, which generates such wastes, and to society and governments that want to dispose of hazardous wastes properly. A thoughtful, well-designed community education program and appropriate risk assessment are necessary.

5. The applicability of this disposal technology at specific cement plants may be dependent on:

- Land use and population factors near the plant;
- Chemical and economic characteristics of a specific waste proposed for disposal;
- Unique operating characteristics of a plant;
- Local topography and meteorology at a plant site (which, for example, might be related to stack height); and
- Unique regulatory and permitting requirements.

Accordingly, some form of risk assessment for each specific waste at each specific site appears to be a prudent step to take before making any commitment to this technology. Section 6 presents the concepts of such risk assessment. If an initial risk assessment indicates a potentially unacceptable risk to human health or ecosystems, an adjustment of stack height, or added scrubbers, or reduction in firing rate (reduction in percentage of hazardous waste in feedstock) may be adequate mitigating actions to reduce risk to an acceptable level. Other risk management measures such as avoiding hazardous waste burns during atmospheric inversions may be available.

Even in a case where costs of dealing with concerns about health and the environment exceed energy savings, the cement-kiln disposal option might be the most prudent if other disposal options are still more expensive.



9. RECOMMENDATIONS

1. Consortium members interested in application of this disposal technology should first survey the types and quantities of combustibile hazardous wastes and the cement kilns and lime kilns in their geographic area.
2. For those who wish to pursue the cement kiln option further in their own country, it is suggested that brief preliminary risk assessments (including consideration of risk perception) be prepared for any candidate cement plant site.
3. For the most likely sites, it is recommended that trial burns be carried out. Appendix B of this study gives some guidelines for trial burns. These trial burns can help prepare a more quantitative risk assessment and establish operating conditions/limitations to assure that risks can be maintained at an acceptable level.
4. This study contains information on test burns and permitting procedures primarily in the context of environmental regulations in the United States. It is important that Consortium members in other countries make their evaluations of potential application of this technology using existing and planned environmental regulations in their own country.



APPENDICES



APPENDIX A

SAMPLING AND ANALYTICAL PROCEDURES

Introduction

The primary goal of the sampling and analysis effort is to determine the destruction and removal efficiency (DRE) of hazardous constituents in the waste fuel. However, environmental assessment of this destruction technology requires considerable knowledge of related factors (e.g., mass loading, combustion products, trace metals emissions, effects on other pollutants). Therefore, a comprehensive sampling program is usually designed before the trial burning stage to evaluate all significant pollutants leaving through the stack and to track the source and fate of specific elements entering the kiln.

Sampling and analytical activities for a demonstration project may include (1) the sampling and analysis of stack gas for principal organic hazardous constituents (POHCs), products of incomplete combustion (PIC), particulate matter, hydrogen chloride (HCl), sulfur dioxide (SO₂), nitrogen oxide (NO_x), carbon monoxide (CO), total hydrocarbons (THCs), and metals; (2) the sampling of process streams such as slurry, coal, waste fuel, cement clinker, and the electrostatic precipitator dust for quantitative analysis of a variety of compounds; and (3) obtaining detailed process data and observations for the sample.

Several different process conditions are evaluated: (1) baseline (no waste fuel burned), and (2) waste fuel supplementation (primary and waste fuel burned together). Fuel replacement rates and waste fuel characteristics are varied to provide comprehensive data for analysis.

The analytical methods that are used include (1) a volatile organic sampling train (VOST) for quantitative analysis of POHCs to determine the DREs of a compound entering the kiln; (2) a Modified Method 5 (MM5) train developed by the USEPA to collect and analyze PICs, as well as to estimate particulate matter emissions; (3) a

midget impinger train used to collect HCl samples; (4) continuous gas analyzers to measure O_2 , CO_2 , CO, SO_2 , THC's, and NO_x ; and (5) an atomic absorption (AA) and inductively coupled argon plasma (ICAP) technique for metals analysis of process samples (Branscome et al. 1985; Mournighan and Branscome 1988).

A brief description of these analytical methods is discussed here.

VOST Method for POHC Analysis

POHCs are the principal organic hazardous constituents in the waste as defined by the USEPA and are selected on a case-by-case basis before sampling and analysis. The concentration of a compound in the waste is an important consideration because this concentration, the waste and airflow rate, and the detection limit of the test determine the DRE. Because very low (ppb) levels must be measured in the gas, EPA has developed a VOST to collect volatile organics (normal boiling point less than $100^\circ C$) for analysis.

Figure A.1 depicts the VOST and its components. From a 20-liter sample, roughly 1 gram-mol of stack gas is sampled (22.4 l/g-mol at standard conditions). For a total sample of 100 ng of a POHC with a molecular weight of 100, the VOST should be able to detect levels of 1 ppb by volume.

Upon receipt of the VOST cartridge in the laboratory, it is spiked with an internal standard (bromochloromethane) and thermally desorbed at 180° to $200^\circ C$ with organic-free nitrogen in a thermal desorption unit. From the desorption unit, the gas is bubbled through organic-free water and trapped in an analytical absorbent trap. After the 10-minute desorption, the analytical absorbent trap is rapidly heated with the carrier gas flow reversed so that the effluent flow from the analytical trap is directed into the gas chromatograph (GC) and mass spectrometer (MS). The volatile POHCs are separated by temperature-programmed gas chromatography and detected by low-resolution mass spectrometry. The concentrations of volatile POHCs are calculated using the internal standard technique. Details

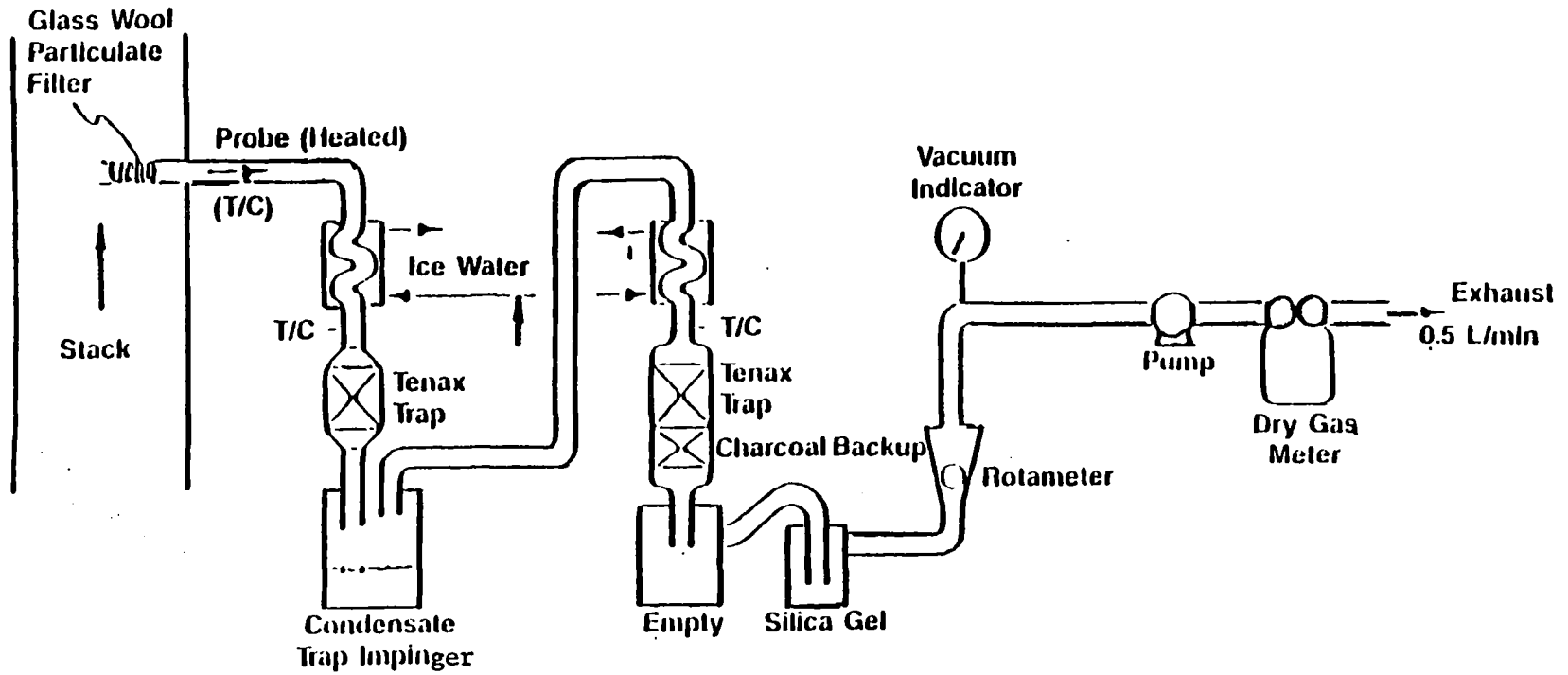


Figure A.1. VOST schematic (Source: Mournighan et al. 1985)

of the VOST method and calculation of specific amount of POHCs and DREs are described in Mournighan and Branscome (1988), and Branscome et al. (1985).

Modified Method 5 (MM5)

This sampling train is used to collect POHCs and PICs, as well as to estimate particulate emission rates.

In the EPA Method 5, emission samples are collected between the electrostatic precipitator and the ID fan. The sampling extracts a certain amount of a specific stack gas each time. In the MM5, the emission samples are collected from the breaching between the ID fans and the stack since the gas flow is expected to be more uniformly distributed in the duct, and because this location permits velocity traversing for various sample trains at the same time.

Extracts, rinses, and related materials from the probe/train system are analyzed to determine the presence of semivolatile POHCs. They are also gravimetrically analyzed for other particulate matter.

The gas stream sampled by the probe is directed to a modified EPA MM5 train, depicted in Figure A.2. This system consists of the following components in series: nozzle, probe, heated particle filter, one solvent module, impingers, and a meter box.

Organic constituents of the gas are removed by 20/40 mesh XAD-2 resin contained in an all-glass trap. High collection efficiencies (90 to 100 percent) are typical for vapor phase organic species with boiling points greater than 100° C. The XAD-2 sorbent is extracted with methylene chloride. The particulate matter from the filter and probe is also extracted with methylene chloride and concentrated to 10 ml. Serial concentrations are performed on the condensate. The extracts from the XAD-2 and condensate are then combined and spiked with an internal standard (fluoro-biphenyl) for a survey analysis by gas chromatography and mass spectrometry (GC and MS). From the survey analysis, the major compounds of interest are identified (Branscome et al. 1985).

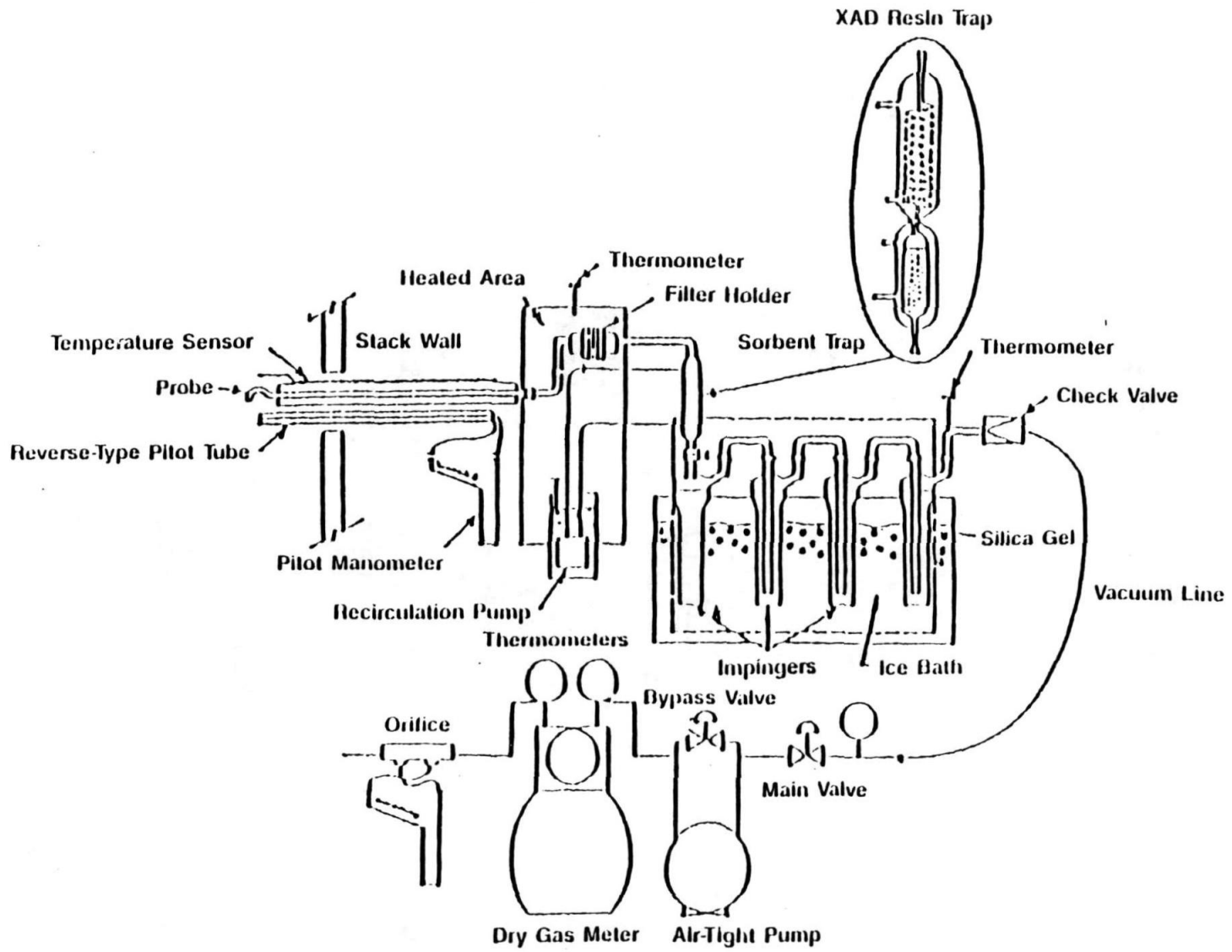


Figure A.2. Modified Method 5 schematic (Source: Mournighan et al. 1985)

The foregoing description of the MM5 perhaps understates the complexity of the process. Semivolatiles collected are separated into four to six classes by extensive column chromatographic clean-up procedures. PCB, chlorobenzenes, PAHs, dioxins and furans, chlorophenols, and others are concentrated into separate fractions first. All this requires a high degree of analytical skill.

Midget Impinger Train

The sampling train that is used to obtain gas samples for chloride analysis is essentially the EPA Method 6 midget impinger train, as shown in Figure A.3. The first two impingers are charged with 15 ml of distilled deionized water as absorbing solution. A glass wool plug for particle filtration is placed in the stack end of a heated glass probe, and stack gas is extracted.

After sample collection, contents of the impingers are transferred to a 250 ml polyethylene bottle. Chloride analysis is conducted with specific ion electrode (SIE) procedure. All samples are diluted to a fixed volume of 2 ml of ISA (ionic strength adjuster). Chloride ion concentration in the medium produces a DC potential against a standard solution that is measured with a Fisher Model 620 pH/mV meter. A series of calibration standards of known Cl⁻ concentration are analyzed to generate a calibration curve, and sample concentration is determined from the curve.

Continuous Gas Analyzers

The stack gas is analyzed for six gases (CO, CO₂, NO_x, O₂, SO₂, and THC) with continuous emission monitors (CEM). Gas samples for the CEMs are extracted through a single sample probe in the duct just upstream from the VOST sample location. The probe is equipped with a particle filter followed by a three-way valve out of the stack. Following the valve is an air-cooled condenser/moisture trap and a moisture removal system. A flow diagram of the CEM sample system is shown in Figure A.4.

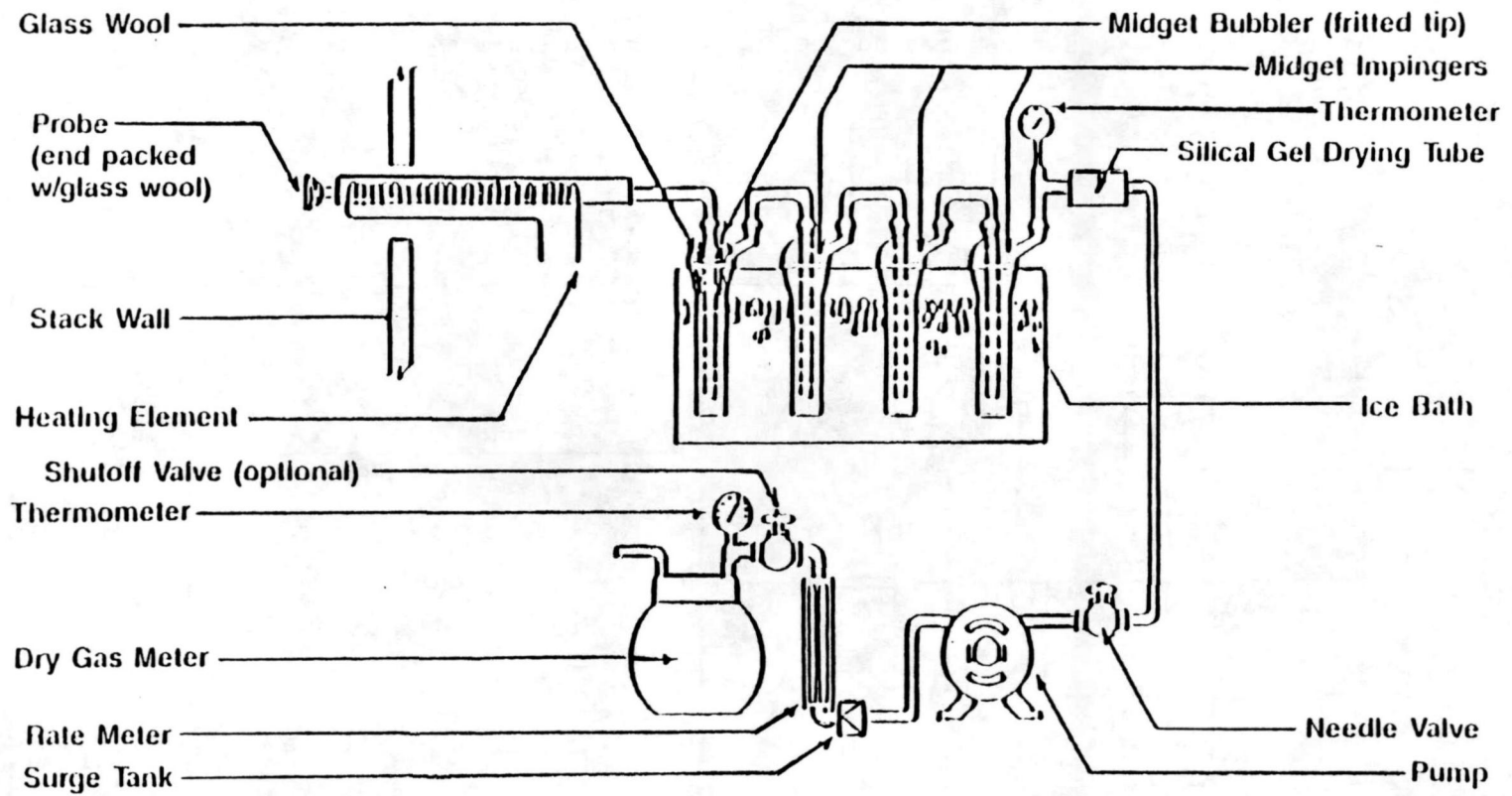


Figure A.3. HCl sampling train (Source: Mournighan et al. 1985)

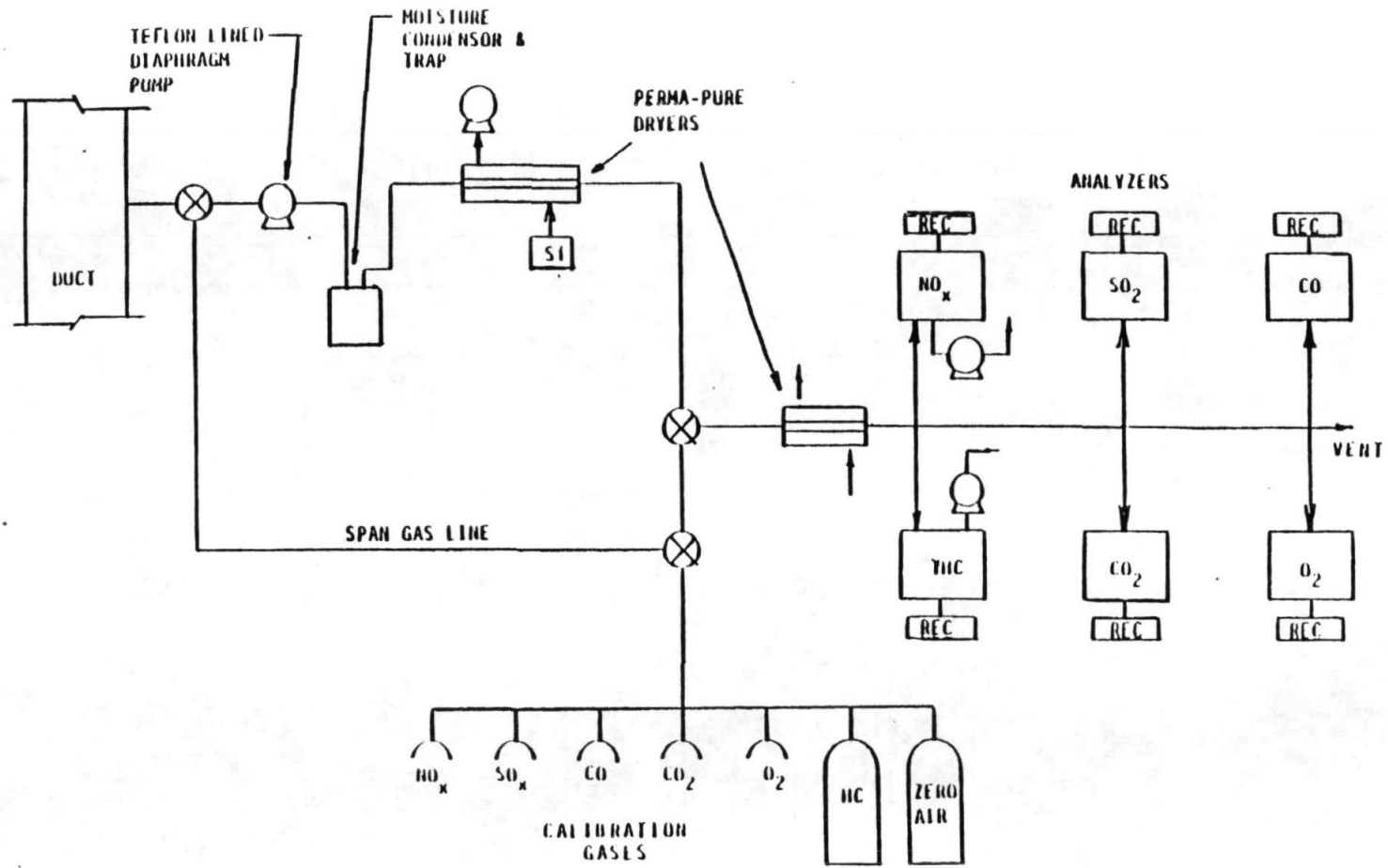


Figure A.4. Continuous monitor sample system (Source: Mournighan et al. 1985)

Nondispersive infrared absorption spectroscopy is used for SO₂, CO, and CO₂. Each of these gases absorbs infrared radiation of a characteristic wavelength, and the absorption is proportional to the concentration of the pollutant. Oxides of nitrogen are measured by chemiluminescence where the characteristic light emitted by the gas phase reaction of NO with ozone and the resulting decay of excited NO₂ is measured. Total hydrocarbons (THCs) are measured using a flame ionization detector burning sample gas in a hydrogen flame and measuring the electron flow resulting from the ionization from oxidizing C to CO₂ in the flame (Branscome et al. 1985; USDOE 1980).

Metals Analysis

The slurry, coal, clinker, waste dust, waste fuel, and particulate catch are analyzed for metals using atomic absorption (AA) and inductively coupled argon plasma (ICAP) techniques.

Atomic absorption methods include flame (FAA), graphite furnace (GFAA), and cold vapor (CVAA) atomization. Sodium, aluminum, magnesium, and lead are analyzed by FAA. Aluminum requires a nitrous oxide/acetylene flame instead of the more common acetylene flame used for the other elements. Arsenic and selenium are analyzed by GFAA, and mercury is determined by CVAA. All other elements are analyzed by ICAP. Procedural details are outlined in the EPA procedures manual (USEPA 1978).

Chlorine and Sulfur Analysis

The slurry feed, coal, clinker, waste fuel, and waste dust are analyzed for chlorine content. In addition, the coal and waste fuel are analyzed for sulfur content. For both analyses, the samples are oxidized by combustion under oxygen pressure. The chlorine and sulfur compounds that are liberated are absorbed in a sodium carbonate solution and are determined as chloride and sulfate by ion chromatography.

Waste Fuel and Water Analysis for Organics

The analysis of organic compounds in the waste fuel is conducted on a gas chromatography/mass spectrometer/computer system, with a 30-m fused silica DB-5 capillary column operated in the split injection mode. The samples are injected neat (undiluted), and each identified component is quantified relative to a standard of known concentration of that compound injected into the GC/MS.

Again, this procedure requires a high degree of analytical skill that should not be underestimated if one is to achieve the desired results.

APPENDIX B

PROTOCOL FOR A TRIAL BURN

Introduction

The most important question to ask with respect to a trial burn is "What is the objective of the trial burn?" The cement kiln manager's primary interest is in cement production. If burning waste as a supplemental fuel reduces cost and does not adversely affect the primary objective of cement production, net economic gain is possible. The cement plant and the hazardous waste generator may both benefit. The ultimate objective of a trial burn should be to establish that cement production is unaffected, costs are reduced, and no adverse environmental impact results. The trial burn can help establish limits on operations that may be necessary in order to meet objectives.

The risk assessment section of this paper correlates some current U.S. regulatory policies being used as trial-burn objectives with the underlying fundamental question, "What constitutes adverse environmental impact?"

Appendix B is intended to assist any Pacific Basin Consortium member who may wish to initiate a trial burn of hazardous wastes in a cement kiln in his country. Such trial burn can accelerate introduction of this technology into that country. This protocol addresses sequential phases of the trial-burn process, including planning and preparation, sampling and analysis, process monitoring during the trial burn, and data reporting. The discussion focuses on those aspects of a trial burn as conducted in the United States that are considered the most important and those that are potentially troublesome.

This study contains information on test burns and permitting procedures primarily in the context of environmental regulations in the United States. It is important that Consortium members in other countries make their evaluations of potential application of this

technology within the context of existing and planned environmental regulations in their own country.

Planning and Preparation for a Trial Burn

The trial-burn director's primary objective of a trial burn is to select those operating conditions under which the cement kiln may perform in a manner acceptable to regulatory agencies. The trial burn provides regulatory agencies with data that may allow them to issue an operating permit. Consequently, a trial burn is directed to demonstrating that kiln performance can achieve the environmental standards set by regulatory agencies.

When a cement plant is faced with the need to perform a trial burn, the first few questions that come to mind are: What does a trial burn involve? What types of sampling and analysis are typically involved? What skills, equipment, and facilities are needed? What is involved in actually conducting a trial burn? What are the major cost factors associated with a trial burn? These considerations are discussed here.

What does a trial burn involve?

From the cement kiln operators' perspective, key trial-burn considerations are the regulatory limits that must be achieved; operating and permit conditions that may be imposed; POHCs in both the wastes and emissions during the trial burn; types, characteristics, and quantities of waste; the extent of sampling and analysis activities; and time required for the trial burn. These considerations are briefly discussed here.

Regulatory limits in the United States generally include DREs for the POHCs (>99.99 percent), particulate emission control (<180 mg/dscm [dry standard cubic meter] corrected to 7 percent O₂), and HCl emissions standard (<4 lb/hr or 99 percent removal efficiency).

Usually, the trial burn involves testing at conditions that meet the cement plant's operating needs while attempting to meet the three regulatory limits for emissions as stated earlier (Gorman et al. 1986; Branscome et al. 1985). It may be necessary to test at more than one operating condition in order to satisfy all of these needs. For example, it might be difficult to achieve a high heat input rate with a waste feed that contains high levels of Cl and ash. Hence, specific operating conditions for a specific trial burn may be chosen from a wide range of options, for example:

- Wastes with both high- and medium-heating values;
- Different levels of concentrations for selected POHCs;
- Different rates of waste feed;
- Maximum and minimum combustion airflow rates with minimum and maximum residence time, respectively;
- Maximum and minimum combustion temperature;
- Maximum and minimum thermal input (Btu/hr);
- Different levels of Cl content of waste feed;
- Maximum and minimum for other operating conditions (e.g., gas residence time).

Making such choices are an important part of planning for the trial burn. The operating conditions for a trial burn may subsequently be specified as part of operating permit conditions. Preliminary testing and "miniburns" can be extremely valuable in helping to select operating conditions for the trial burn. The following suggestions concerning "miniburns" may be helpful.

Those POHCs hardest to burn can be used at high concentrations in a miniburn that is conducted at lowest temperature with highest CO level. If the results show a DRE exceeding 99.99 percent, then it is likely that 99.99 percent DRE will be achieved regardless of any other operating conditions (Gorman et al. 1986; Mournighan and Branscome 1988).

Achieving the particulate limit is frequently more difficult than achieving acceptable DREs (Branscome et al. 1984). A pretest with EPA Method 5 (described earlier) will help identify problems and help in

selecting operating conditions for the trial burn. The pretest can also uncover specific sampling and analysis problems that may not be readily apparent.

Pretesting can be done prior to submitting a trial-burn plan. However, pretesting must be approved by the regulatory agency. In some cases, pretesting can be part of an approved trial-burn plan.

POHCs for a trial burn should be selected early during development of the trial-burn plan. The selection is usually in conformance with the regulatory approach laid out in the USEPA Guidance Manual (1985b) for hazardous waste incineration. In addition to meeting regulatory criteria, the following two precepts for a trial-burn plan are suggested: (1) plan the burn so that the subsequent permit will have maximum flexibility for operating conditions, and (2) plan the burn so that there will be ease of sampling and analysis during the burn. Test results of trial burns conducted in the United States, Canada, and elsewhere may serve as guidelines for the selection of POHCs.

The quantity of waste required for the trial burn is dependent on the waste feedrate to be used during each run, the number of runs, and the duration of each run. Waste feedrate and the number of runs are specified in the trial-burn plan. The sampling time required in each run is usually 3 to 4 hours, plus 1 hour to prepare the kiln and equipment before testing begins. A 1- to 2-hour contingency in any trial-burn plan should be allowed for any problems concerning plant operation or sampling (Branscome et al. 1985). The time for a run depends partly on POHC concentration in fuel, DRE required, and analytical detection limit (including recovery). For example, if CCl_4 is the POHC and 99.99 percent DRE is required, and 100 to 200 ppm is the waste concentration in fuel, then 3 to 4 hours would be insufficient sampling time to collect a measurable sample. Waste sufficient for 8 hours of operation should be available for each run. If the trial burn involves only three runs at one set of operating conditions, then waste sufficient for 24 hours of operation should be available. At some facilities, it is prudent to have more than needed for actual tests. This allows for shortages that may arise due to kiln upsets and equipment breakdown.

Each type of waste must have all the specific characteristics that are required to meet selected operating conditions. For example, the waste to be burned during a trial burn might include both continuous feeding of an organic liquid and intermittent feeding of drummed solids. However, each of these wastes must meet certain specifications selected for the trial burn, including POHC concentrations, heating value, and Cl and ash content (Table 1).

Three methods can be used in the test burn to prepare mixed quantities of wastes possessing correct characteristics. These methods are (1) use actual wastes, (2) prepare trial-burn wastes from actual wastes mixed with purchased chemical compounds (i.e., certain POHCs) as a surrogate, or (3) continuously spike POHCs into the wastes during the trial burn (Gorman et al. 1986). All these methods require that the waste feeds be thoroughly mixed. Adequate time must be allowed for numbering, weighing, and sampling of drummed solids before a trial burn.

Each test run in a trial burn includes sampling of waste feeds and stack emissions. These samples are then split into a series of subsamples to be analyzed for POHCs by methods that include gas chromatography/mass spectrometry (GC/MS) analyses. These analyses, along with waste feedrates and stack gas flow rates measured during each run, are used to calculate DREs. Usually, samples of ash and scrubber waters are also taken and analyzed for the POHCs. Some regulatory agencies may impose other additional sampling and/or analysis requirements. Some of the sampling and analytical procedures conducted during the trial burn in the United States and Canada are included in Appendix A.

A major consideration in planning and conducting a trial burn is time. Often, trial burns take more time and effort than an operator anticipates. Many steps are involved in the trial-burn sequence (Gorman et al. 1986; Mournighan 1988). General guidelines for time requirements in the United States are listed here.

- Pre-kiln survey and evaluation of all conditions at a specific cement plant (1 month);

- Prepare trial-burn plan and submit to environmental agencies (1 month for plan preparation and 3 to 6 months for plan approval by agency);
- Prepare responses to environmental agencies' questions (if any) or deficiencies in the trial-burn plan (1 month);
- Make any additions or modifications to plant that may be necessary (1 to 3 months);
- Prepare for the trial burn:
 - Select sampling and analytical contractors (2 months)*
 - Select date for trial burn, in concert with sampling and analytical staff or contractor (select date at least 1 month prior to test)
 - Notify all appropriate regulatory agencies (1 month)
 - Obtain required quantities of wastes having specified characteristics
 - Calibrate all critical kiln instrumentation (2 weeks)
- Conduct trial burn (5 to 7 days);
- Sample analysis (1 to 1-1/2 months);
- Calculate trial-burn results (10 days);
- Document results and submit operating permit application to environmental agency (15 to 25 days);
- Obtain operating permit.

In specific instances, greater amounts of time may be required.

What types of sampling and analysis are typically involved?

The primary objectives of the sampling and analysis (S&A) program are (1) to quantify POHC input and output rates to determine whether DRE requirements are met; (2) to measure input and output rates of chlorides; (3) to determine stack emission particulate concentrations;

*It is essential that a quality assurance/quality control (QA/QC) program be established prior to selecting a contractor. The analysts must be able to demonstrate compliance with the QA/QC program prior to receipt of waste samples.

and (4) to identify and quantitate PICs of regulatory significance.

The two most important considerations are selecting the streams to be sampled and identifying appropriate S&A methods (Branscome et al. 1985; Ahling 1979). Table B.1 presents sampling methods and analytical parameters typically used during the trial burn. A brief description of the sampling and analytical procedures is included in Appendix A. Detailed discussions can be found in the EPA procedures manual (USEPA 1978).

Adverse stack sampling conditions are frequently encountered during waste burning. Problems typically encountered include cyclonic flow, very high temperature stacks (1,600° to 1,800° F), and high moisture content (saturated with H₂O at 150° F with droplet carryover). These potential problems should be considered during planning, and appropriate actions should be taken.

What skills, equipment, and facilities are needed to conduct a trial burn?

Specialized sampling and analyses required in a trial burn are generally beyond the capability of most cement plants. At a minimum, the trial-burn staff should be knowledgeable in stack sampling, have experience in analysis of organic emissions, and be familiar with calculating and reporting trial-burn results. Personnel required for sampling during the trial burn usually number between 5 and 10, depending on the complexity of sampling and operating conditions (Branscome et al. 1985; Mournighan 1988; Gorman et al. 1986). Typical requirements for sampling personnel are presented in Table B.2.

One must give thought to the physical facilities required to collect, characterize, receive, handle, mix, and prepare waste for blending with or injecting independently into the kiln during a trial burn. The facilities and equipment usually necessary for trial-burn sampling and analysis are presented in Table B.3. According to most regulatory agencies in Canada, the United States, and Europe, cement plants or incinerators burning hazardous waste are required to have the equipment/instrumentation shown in Table B.4.

Table B.1. Sampling methods and analysis parameters

Sample	Sampling frequency for each run	Sampling method ^a	Analysis parameter ^b
Liquid waste feed	Grab sample every 15 min	S004	V&SV-POHCs, Cl ⁻ , ash, ult. anal., viscosity, HHV
Solid waste feed	Grab sample of each drum	S006, S007	V&SV-POHCs, Cl ⁻ , ash, HHV
Chamber ash	Grab 1 sample after all 3 runs are completed	S006	V&SV-POHCs, EP toxicity
Stack gas	Composite	MM5 (3 hr)	SV-POHCs, particulates, H ₂ O, HCl
	Three pairs of traps, 40 min each pair	VOST (2 hr)	V-POHCs
	Composite in Tedlar gas bag	S011	V-POHCs ^c
	Composite in mylar gas bag	M3 (1-2 hr)	CO ₂ and O ₂ by Orsat
	Continuous (3 hr)	Continuous monitor	CO (by plant's monitor)

Sources: Gorman et al. (1986).
Branscome et al. (1985).

^aVOST = volatile organic sampling train

MM5 = EPA Modified Method 5

M3 = EPA Method 3

SXXX = sampling methods found in "Sampling and Analysis Methods for Hazardous Waste Combustion"

^bV-POHCs = volatile principal organic hazardous constituents

SV-POHCs = semivolatile POHCs

HHV = higher heating value

^cGas bag samples may be analyzed for V-POHCs, only if VOST samples are saturated and not quantifiable.

Table B.2. A typical example of sampling personnel required

Job	Number of personnel	Experience required
Sample liquid feed (once every 15 min)	1	Technician with sampling experience and safety training
Drum solid sampling and recording (once every 5-10 min)	1	Technician with sampling experience and safety training
Sampling ash and scrubber waters every 1/2-1 hr	1	Technician with safety training
Stack sampling MM5	2	Experienced console operator and technician for probe pushing
VOST	1	Experience with VOST operation
Process monitor to record operating data every 1/4-1/2 hr and determine waste feed-rates	1	Engineer or other person experienced in plant operations and trial-burn requirements
Field laboratory	1	Experienced chemist for check-in and recovery of all samples, and preparation of sampling equipment for each run
Crew chief	1	Person experienced in all aspects of trial-burn sampling to direct all activities and solve problems that may occur

Source: Gorman et al. (1986).

Table B.3. Capabilities necessary for trial-burn sampling and analysis

Sampling equipment for solid waste feeds (especially drummed wastes)

Stack sampling equipment, usually including the following:

EPA Method 5 equipment and all associated test equipment (e.g., EPA Methods 1, 2, and 3)

Method 5 equipment adaptable to Modified Method 5 (greaseless) and associated XAD resin preparation, extraction, and analysis facilities

Volatile Organic Sampling Train (VOST) Equipment with at least 18 pairs of VOST traps; also, all facilities needed for preparing, checking, and analyzing the traps

Gas bags and associated sampling equipment

Field laboratory equipment for sample recovery

Facilities for analyzing all samples, including:

Laboratories containing relevant safety equipment such as hoods and equipped with sample preparation equipment including Soxhlet extractors, separatory funnels, continuous extractors, blenders, Sanifiers or other equipment to homogenize waste-feed samples, sodium sulfate drying tubes, Kuderna-Danish glassware

Equipment for preparing VOST traps to allow simultaneous heating and purging of the traps; ideally the traps should be prepared and stored in an organic-free laboratory

All required compounds to prepare calibration standards and surrogate recovery spiking solutions

Computerized GC/MS instrumentation

Established QA procedures for assessing precision and accuracy of analytical methods

Knowledge and preferably experience in all of the sampling and analysis methods and calculation/reporting of results

Process monitoring experience, especially quantification of waste feedrates and documentation of plant operating conditions

Source: Branscome et al. (1985).

Table B.4. Incinerator equipment/instrument requirements for trial burn

Equipment to maintain particulate emissions below 0.08 grain/dscf
Equipment to maintain 99% HCl removal or HCl emissions below 4 lb/hr
Equipment that provides 99.99% DRE on POHCs
Stack test ports and scaffolding
Valves, taps, etc., for sampling all waste feeds, liquid effluents, ash, etc.
Equipment to maintain noncyclonic flow in stack when testing
Continuous CO monitor
Continuous waste feed flow monitor
Continuous monitor for combustion gas velocity or air input rate
Continuous combustion temperature monitor
Automatic interlock system to shut off waste feed under the following situations:
Low combustion temperature
High CO concentration ^a
High combustion airflow to incinerator or high combustion gas velocity

Source: Gorman et al. (1986).

^aEstablished based on trial-burn results or state statutory limitations

In general, preparations for the trial burn are complex. Several of the most important items are prekiln survey, scheduling, sampling crew activities, equipment preparation and calibration, facility readiness, process data, data sheets and labels, and safety precautions. Typically in the United States and Canada, trial burns are planned for a minimum of 3 days and a maximum of 7 days, depending on operating conditions and number of runs. One potential problem that should be addressed during preparation is how to coordinate with observers during the trial-burn process.

What are the major cost factors associated with a trial burn?

The three major cost components of the trial burn are planning and preparation, sampling and analysis, and quality assurance. Each of these components must be included in the trial-burn budget.

Planning and preparation cost includes the cost of the trial-burn plan, the cost of any plant additions and modifications needed to comply with environmental regulations, and the cost of acquiring and storing the types and quantities of wastes necessary for the trial burn.

The major cost factor is the sampling and analysis required for the trial burn. This cost ranges from \$30,000 to \$150,000, depending on the number of runs, the number of samples to be taken in each run, and the analysis required for each sample.

Ordinarily field sampling activity, including all preparation for sampling, accounts for one-fourth to one-third of the sampling and analysis cost. Analysis of samples usually accounts for one-third to one-half of the cost, whereas the remaining costs are for data calculation and reporting of results.

Conducting the Trial Burn

Facility readiness is critical to conducting the test as planned. Checking operational readiness of the cement plant and its components,

including critical instruments (especially flow meters), is vital and should be done early enough to correct any problems identified. Other facility readiness needs are identified during the pretest site survey. The survey should be conducted at least 1 month prior to the test to allow time for modifications to the facility. Facility readiness also includes preparation of all wastes to be used in the tests.

Three steps are recommended for process monitoring. These steps include (1) determining what process data must be taken and reported to the environmental agency, (2) recording all possible data during the trial burn to help identify any problems during the test, or in the test results, (3) before the test, establishing the acceptable range for each critical operating parameter.

Recording of process data during the trial burn is of equal importance with sampling activity, for two reasons: (1) process data are necessary for computation of DREs, (2) some process readings recorded during the trial burn may, and probably will, become limits specified in the operating permit (Gorman et al. 1986; Branscome et al. 1985). Many data sheets are needed for a trial burn (see Table B.5). Units of measure must be indicated for every item on every data sheet. Labels must be kept ready and must be posted on samples with detailed descriptions (e.g., the number of run, time, date, types of sample).

During the test, one person who knows the conditions under which sampling should be interrupted, and who is in radio contact with the stack test crew at all times, should be responsible for process monitoring.

Immediately after each run, the sampling crew must recover all samples, properly label each, and package them for storage and shipment. Samples are usually double-bagged with protective wrapping and stored in coolers. After that work is completed, all sampling equipment must be prepared for the next run. Some of the problems that may occur during trial burns include plant operating problems, determination of waste feedrates, weather, and sampling equipment problems.

Table B.5. List of data forms

Traverse Point Locations
Preliminary Velocity Traverse
Method 5 Data Sheets
Isokinetic Performance Work Sheet
M5 Sample Recovery Data
Integrated Gas Sampling Data (Bag)
Orsat Data Sheet
VOST Sampling Data

Drum Weighing Record
Drum Sampling Record
Liquid Waste Feed Sampling Record
Fuel Oil Sampling Record
Drum Feed Record

Process Data (Control Room)
Miscellaneous Process Data (In-Plant)
Tank Level Readings

Log of Activities

Ash Sampling Record
Scrubber Waters Sampling Record
Sample Traceability Sheets
GC/MS Data Calculation Sheets

Sources: Gorman et al. (1986).
Branscome et al. (1985).

Note: Units of measure must be shown for each item on each data sheet

Samples taken during a trial burn are usually brought to the analytical laboratory for transfer to an analytical task leader. At that point, when the samples are checked in and transferred, the project leader needs to ensure that each sample taken in the field has arrived and is intact.

The analytical results are reported in a format, which includes all information and data necessary to calculate final results, and presented in as clear and succinct format as possible. The report typically includes a description of the operating system; operating conditions during the test; measured quantities of POHCs, HCl, and particulate in all samples; and calculated results (Branscome et al. 1985, Mournighan 1988).

Most QA/QC plans require the use of blind, spiked surrogates. This then requires an external auditor to observe and prepare the final report upon reliability of the analytical process.

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