

**TECHNICAL CRITERIA
FOR THE
DESTRUCTION OF STOCKPILED
PERSISTENT ORGANIC POLLUTANTS**



GREENPEACE

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Executive Summary

Governments of the world have agreed to negotiate a global, legally binding instrument to protect human health and the environment from persistent organic pollutants (POPs). One important way these pollutants enter the general environment is by escaping from stores, stocks and environmental reservoirs (including contaminated soils and sediments) of obsolete POPs chemicals (PCBs, pesticides, etc.) and of POPs-contaminated wastes (dioxins, PCBs, etc.).

There is now a growing consensus that stocks, stores and environmental reservoirs of obsolete chemicals and POPs-contaminated wastes must be rapidly identified, properly collected and properly destroyed in order to stem their continued migration into the general environment. This, in turn, opens up a debate on what constitutes proper means for the collection and destruction of these obsolete chemicals and wastes.

Many technologies are being commercialized to address the destruction of POPs and POPs-contaminated materials. The field is rapidly changing and much information is still not available. For that reason, this paper cannot be considered complete or final, but rather it is a contribution to an ongoing investigation. It is an evolving document exploring criteria for the destruction of persistent organic pollutants. It also looks at several destruction technologies, both historic and recently developed, including brief descriptions of their capabilities and, where available, their costs.

Greenpeace has concluded that to afford adequate protection of both local and distant populations of humans and wildlife, the technologies used for destroying stockpiles of persistent organic pollutants (POPs) must meet the following fundamental performance criteria:

- **Destruction efficiencies of effectively 100 percent for the chemicals of concern.** The determination of 100 percent destruction efficiency is necessarily based on findings of no detectable concentrations of the chemicals of concern in any and all residues, using the most sensitive analytical techniques available worldwide. Analyses of the unmodified residues must be carried out sufficiently frequently to ensure compliance with this criterion during startups, shutdowns and routine operations.
- **Complete containment of all residues** for screening and, if necessary, reprocessing to ensure that no residues contain detectable levels of chemicals of concern or other harmful constituents, such as newly formed persistent organic pollutants or other hazardous substances.
- **No uncontrolled releases.**

Combustion technologies that have historically been used to attempt the destruction of POPs stocks and POPs-contaminated materials have failed to

meet these criteria. Indeed, combustion technologies themselves are identified as major sources from which POPs and other hazardous substances are released to the environment.

In recent years, several international and national agencies and organizations have evaluated other destruction technologies, some of which are now in commercial-scale operation in one or more countries. Like the combustion technologies, these newer technologies have high resource demands and may otherwise exact a toll on the environment, the safety and health of workers, and the general public that renders them unacceptable for continued, long-term use, as in the disposal of wastes from ongoing domestic and industrial activities.

Some of these newer technologies (for example, gas-phase chemical reduction) do represent a substantial qualitative improvement over combustion for the destruction of stores, stocks and environmental reservoirs of obsolete POPs chemicals and POPs-contaminated wastes. In many cases, these newer technologies, if properly implemented, represent a better alternative than a decision to incinerate or to take no action and wait for a better POPs destruction technology to emerge.

Introduction

Eradicating persistent organic pollutants (POPs) from the global environment requires eliminating their sources, whether such sources are specific facilities, processes or materials. It also requires destruction of stockpiled POPs and associated environmental contamination.

POPs stockpiles are estimated to include more than one million tonnes of PCBs distributed globally^{1,2} and more than 100,000 tonnes of obsolete pesticides in countries that are not members of the Organization for Economic Cooperation and Development.³ No estimates have been made of stockpiles of dioxin^a-containing materials. However, accumulations of dioxin-contaminated materials can be expected to be quite large, particularly in countries where chlorine-based industries are heavily developed and where incineration has been relied on for waste disposal. Similarly, there are no estimates of the mass of contaminated soils and sediments that are associated with existing stockpiles of PCBs, obsolete pesticides and dioxin-containing materials.

POPs stockpiles and associated contamination impose enormous environmental, public health and economic burdens, especially in developing countries. Those responsible for the existence of these stockpiles – the manufacturers and/or the institutions that coordinated and funded distribution of POPs and POPs-generating technologies – must be held responsible for the destruction of the stockpiles and associated contamination.

In all circumstances, destruction of POPs stockpiles and decontamination of associated material must be accomplished in a manner that safeguards both nearby and distant human and wildlife populations as well as workers against further toxic exposure via direct pathways (e.g., inhalation) and indirect pathways (e.g., through the food chain). To achieve this, destruction technologies must meet certain stringent criteria and they must be expertly applied and regulated. If destruction takes place in a country without strong regulatory agencies and capacity, special, reliable oversight mechanisms should be implemented.

Criteria for the destruction of POPs stockpiles have not yet been established. However, global agreement was reached on the basic criteria for the destruction of another group of persistent chemicals -- those identified as ozone depleting substances (ODS):⁴

“[D]estruction ... must be accomplished in a manner that does not further degrade the environment (e.g., global warming, acid deposition, toxics, etc.).”

Technologies used for ODS destruction are also required to achieve a destruction efficiency of 99.99 percent, which is to be determined as follows:⁵

^a As used in this paper, the terms “dioxin” and “dioxins” are inclusive of both the polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans, i.e., both dioxins and furans, unless otherwise noted.

"Destruction Efficiency: The overall destruction of ODS is calculated on the basis of the total weight of ODS into the process, minus the sum of the ODS in all products, by-products, and environmental releases, divided by the ODS input. (DE is reported as a percentage.)"

[Limited available data show destruction efficiencies for modern hazardous waste incinerators ranging from 65 to 99.9 percent. The frequently reported higher values for such incinerators, in the range of 99.9999 percent, refer to "Destruction and Removal Efficiency" (DRE). DRE takes into account only stack emissions with no consideration of other releases and residues.]

Criteria for POPs destruction must be even more stringent than those for ODS. The initial list of twelve POPs was selected because these substances and groups of substances are toxic, persistent, and bioaccumulative. Technologies used for destroying existing stockpiles of these materials must demonstrate a level of performance that is commensurate with the capacity of these POPs to cause harm. Consequently, technologies that are appropriate for the destruction of POPs stockpiles must achieve the following basic performance criteria:

- **Destruction efficiencies of effectively 100 percent for the chemicals of concern.** The determination of 100 percent destruction efficiency is necessarily based on findings of no detectable concentrations of the chemicals of concern in any and all residues, using the most sensitive analytical techniques available worldwide. Analyses of the unmodified residues must be carried out sufficiently frequently to ensure compliance with this criterion during startups, shutdowns and routine operations.
- **Complete containment of all residues** for screening and, if necessary, reprocessing to ensure that no residues contain detectable levels of chemicals of concern or other harmful constituents, such as newly formed persistent organic pollutants or other hazardous substances.
- **No uncontrolled releases.**

Determining the extent to which a technology meets these criteria during both preliminary tests and routine operations has many aspects including but not limited to the following:

- scientific and engineering expertise;
- equipment and facilities for sampling and analysis of the materials to be destroyed and all residues of the destruction process;
- stringent operating guidelines; and
- comprehensive regulatory framework, including enforcement and monitoring requirements.

There may be circumstances where it is agreed that it is necessary to locate a destruction facility to address a particular contaminated site and/or POPs stocks and reservoirs in a specific region. In such circumstances, the facility must be located at or near the site. The facility must then be removed

when the specific destruction project is completed so that it will not become a magnet attracting wastes from other regions. Community-based public participation must be an integral part of the entire process starting with stockpile evaluation and site selection and continuing through monitoring and compliance.

Availability and costs are also crucial factors in the selection among appropriate destruction technologies. Such costs include not only expenditures associated with constructing and operating destruction facilities but also infrastructural costs. For example, oversight and regulation of such facilities requires dedicated staff, e.g., legal advisors to prepare regulatory frameworks, engineers and scientists to implement the regulations, as well as training and equipment for communications, chemical analyses, etc.

1.0 HISTORIC TREATMENT AND DISPOSAL TECHNOLOGIES

In the past, POPs and other materials that are difficult to destroy have commonly been managed by storage, burial in landfills, and/or burning in combustion systems (e.g., dedicated incinerators, industrial boilers or cement kilns). Also a few nations still allow injection in deep wells. Among these practices, only combustion systems accomplish some degree of destruction.

1.1 Storage

The scientific literature offers little information on the effectiveness of various methods of storage in preventing the escape of chemicals such as the twelve designated POPs. In addition to spills and leaks, volatilization of POPs from storage sites is problematic, particularly in tropical climates. For example, in Bangkok, Thailand, Watanabe et al. (1996) measured PCBs in ambient air outside a building where electrical capacitors were stored. Immediately downwind, the average PCB concentration in the air was 820 nanograms per cubic meter (ng/m^3). The PCB concentration was 570 ng/m^3 some 5 meters upwind.⁶ These levels are roughly 1000 times greater than those measured in urban air in the United Kingdom⁷ and from 15,000 to 48,000 times greater than those measured in the Arctic air.⁸ About 25 percent of the airborne PCBs were attributed to volatilization from the capacitors and the remainder from volatilization of PCBs spilled on the surrounding soil.⁹

Even in a cool, temperate climate, storage and handling of such chemicals are known to lead to releases into the environment despite the use of the best available preventive measures. For example, at a Canadian PCB disposal facility with well-constructed, closed buildings maintained under negative pressure with activated carbon exhaust filters, the filtered air still carried PCBs out into the ambient air.¹⁰

1.2 Burial in Landfills

For persistent substances, burial in landfills is not a destruction technology; it is only a method of containment. Moreover, it is a relatively ineffective method of containment. Constituents in buried wastes can and do escape into the surrounding environment, primarily through leaching into

groundwater and volatilizing into the air.

After decades of research, engineering innovations and great expense, the most modern, state-of-the-art landfills are still described as potential “time bombs” --:¹¹

“Isolation systems [landfills] are generally effective for the first 10 years and have a retarding effect after 25 years, but are almost comparable to a reference situation (i.e., no isolation) after 100 years. Thus, isolation systems for disposal sites and contaminated soils without contaminant immobilization may represent a delayed “time bomb” that could pose a danger in future to human health and the environment.”

and permanent threats --:¹²

*“A Permanent Threat
Hazardous waste and municipal solid waste dry-tomb landfills represent an ongoing threat to groundwater quality. Because the plastic sheeting used in the composite liners ... will eventually deteriorate, and because there is virtually no possibility that landfill covers of the type being constructed today will keep moisture out of the landfill for as long as the wastes represent a threat—that is, forever—it is inevitable that leachate will migrate through the liner to pollute the underlying groundwater.”*

POPs, such as PCBs, are known to escape from landfills by volatilizing into the surrounding air.¹³ Even some metals, e.g., elemental mercury, escape by the same route.¹⁴ PCBs and other semivolatile contaminants are known to evaporate more rapidly with increased moisture in soils and sediments and even with increased relative humidity of air.¹⁵ Volatilization has also been suggested when such substances are buried in landfills, with resulting contamination of surrounding vegetation.¹⁶

The United Nations Food and Agriculture Organization (FAO) (1996) described problems associated with burial of pesticides in landfills as follows:¹⁷

“Many countries that buried pesticides in the past are now experiencing severe environmental contamination and facing huge costs to recover the pesticides and to mitigate damage to the environment and public health.”

1.3 Deep Well Injection

Injection of hazardous chemicals down deep wells is not a widely used technology. In fact, FAO (1996) designated deep well injection as “unsuitable ... because of the environmental risk and lack of control.”¹⁸

In those few countries where this method of disposal is used, chemical releases from such deep wells are not uncommon. For example, at least 39 documented failures at hazardous waste injection wells had occurred in the

U.S. by 1989. Such failures ranged from leakage into deep aquifers, including groundwater used as drinking water sources, to earthquakes and explosive releases at the wellhead.^{19,20,21,22,23,24}

There are no methods for predicting the paths or speeds with which injected wastes may migrate into groundwater or escape to the surface. It is not possible to detect small vertical fractures in subterranean formations that can channel injected chemicals through nonporous layers into groundwater.

Little is known about the long-term chemical behavior of chemicals that have been injected down deep wells – potential reactions between hazardous waste and underground rocks, clay, sand, water, brines, oil, gas, etc., or the effects such reactions might have on migration and toxicity.

Once hazardous materials leave the well bore and enter the porous layer into which they are injected, it is not possible to track their movement. Their whereabouts become known only when they are found as groundwater contaminants.

1.4 Combustion Systems

Until industrialization, burning was regarded as an effective method for disposing of any unwanted materials that could be set afire. In this century, the nature of unwanted materials—wastes and discarded products generated through human activities— has undergone drastic change. As a result, increasingly complex and costly waste combustion systems have been built for the sole purpose of burning materials discarded by industrialized societies. Also, throughout the world some 60 cement kilns have been modified so that various wastes are burned along with conventional fuels.²⁵

FAO (1996) identified certain materials that are not recommended for disposal in incinerators and cement kilns, as shown in Table 1.²⁶ It is important to note that such “*not recommended*” materials include, in most cases, those containing chlorine, such as the current short-listed POPs.

Table 1: FAO Recommendations on Materials to be Excluded or Limited in Disposal by Burning in Dedicated Incinerators and in Cement Kilns²⁷

Incineration Method	Not recommended
High-temperature incineration, in general	Inorganic pesticides, pesticides containing mercury, and organometals
Small-scale incinerator without scrubber	Pesticides containing chlorine, phosphorus, sulfur or nitrogen and bulk quantities of pesticides in general
Small-scale incinerator and mobile incinerator with scrubber	Pesticides containing chlorine, bromine or other halogens, with some qualifications
Cement kiln	Pesticides containing chlorine, bromine or other halogens, including phenoxy acetic acid derivatives, with some qualifications

1.4.1 Dedicated Incinerators

In considering the use of incinerators for the destruction of POPs stockpiles, the *Ad Hoc* Working Group of the Intergovernmental Forum on Chemical Safety (IFCS) (1996) offered the following conclusion in their recommendations, which were subsequently adopted by the United Nations Environment Programme (UNEP) Governing Council (1997):^{28,29}

“IFCS concluded that present generation best technology waste incineration facilities are expensive to construct, sophisticated to operate and their widespread deployment in many developing countries is unlikely in the near future. Other options including transport to existing facilities and/or use of other proven disposal methodologies and/or materials policies should be further explored.”

Although “high tech” incinerators may be cost-prohibitive for many countries, cost is only one of several important limitations of this technology, as described by Hagh and Allen (1990):³⁰

- *“The chlorine atoms are effective flame retardants. They tend to quench the hydrogen free radicals, which propagate the reactions in the incinerator. Therefore it is difficult to achieve complete combustion.*
- *Incinerators have high operating costs due to high operating temperatures.*
- *The combustion stack gases present a severe corrosion problem at*

the high operating temperatures.

- *The problem of greatest concern is the generation of products of incomplete combustion, which are formed in trace quantities. When PCBs are burned, dioxins and chlorinated dibenzofurans (CDF) can be formed. Other materials contained in the stack effluents include HCl, CO, CO₂, NO_x, and O₂. Removing these materials from the stack gases can be very difficult and expensive.”*

Modern incinerators are commonly described as destroying POPs and similar chemicals very efficiently. However, recent tests suggest that incinerators achieve destruction efficiencies that are considerably lower than those achieved by certain non-combustion technologies, as discussed in Section 1.4.1.1. In addition, some incinerators burning POPs and other wastes are associated with the spread of undestroyed and newly formed POPs into the surrounding environment, contaminating air, soil, vegetation, wildlife and human populations (see Section 1.4.1.4).

FAO (1996) noted that large-scale, dedicated hazardous waste incinerators achieve high Destruction and Removal Efficiencies (see discussion in Section 1.4.1.1 below) and identified these combustion systems as the preferred method for destroying obsolete pesticides. Nonetheless, FAO (1996) also acknowledged that such incinerators are themselves known to be sources of certain POPs, such as the dioxins:³¹

“Inappropriate use of incinerators can create hazardous solid and airborne by-products that pose a severe threat to the environment and public health. Often such by-products are more toxic than the original product. Of particular concern is the formation of polychlorinated dibenzodioxins and polychlorinated dibenzofurans (often referred to as dioxins and furans), which are extremely toxic and persistent in the environment. Dioxins and furans are formed as the result of a reaction during the cooling of the stack gases. Factors that affect this reaction are: the temperature of the stack gas; the occurrence of chlorine or other halogens; and the presence of a catalyst.”

After considering the potential release in stack gases of dioxins and undestroyed chemicals of concern during the incineration of the U.S. chemical weapons stockpile, the National Research Council (1991) recommended that incinerator stack gases be treated by activated carbon adsorption at incinerators located in populated areas.³²

1.4.1.1 Incinerator Destruction Efficiency

In the earliest days of high temperature incinerators, the assumption was made that these combustors were destroying carbon-based chemicals, such as the currently listed POPs, with destruction efficiencies^b of 100 percent. However, with the development of relatively reliable methods for collecting and analyzing stack emissions, it was discovered that varying portions of the chemicals fed into the incinerators escaped destruction and were released in stack gases.

Some national regulatory agencies began evaluating incinerator performance by comparing the rate at which a selected chemical is fed into an incinerator with its rate of release from the incinerator stack. Even though this comparison has no relationship to an incinerator's ability to destroy a particular chemical, it was termed the "*destruction and removal efficiency*"^c (DRE). In other words, an incinerator with a highly effective stack gas cleaning system can demonstrate a high DRE even if little or no destruction is taking place. Ample data show that undestroyed chemicals are released not only in incinerator stack gases but also in fly ash, scrubber water, quench water and even, in some cases, bottom ash and slag. Nonetheless, the performance of incinerators and other combustion systems continues to be evaluated on the basis of DREs rather than destruction efficiencies.

It is also important to note that the terms "DRE" and "destruction efficiency" are sometimes used inappropriately. For example, in a recent paper describing the performance of a Dutch hazardous waste incinerator with lindane, hexachlorocyclohexane and PCBs, the authors compared inputs of known quantities of these chemicals with their emission rates in stack gases. The results were termed "destruction efficiencies," although the values presented were actually DREs.³³ In addition, Environment Australia (1997) recently described one non-incineration technology as achieving "*destruction*

^b Destruction efficiency (DE) is determined as follows:

$$DE = \frac{M_i - M_o}{M_i} \times 100$$

where M_i is the mass of a chemical fed into a destruction system during a specific period of time and M_o is the mass of that same chemical that is released in stack gases, fly ash, scrubber water, bottom ash, and any other incinerator residues. For example, if a chemical is fed into an incinerator at a rate of 400 kilograms per hour and it is released in stack gases, scrubber water, fly ash and bottom ash, cumulatively, at a rate of 4 kilograms per hour, the incinerator is achieving a destruction efficiency of 99 percent with that chemical.

^c Destruction and Removal Efficiency is determined as follows:

$$DRE = \frac{M_i - M_s}{M_i} \times 100$$

where M_i is the mass of a chemical fed into a destruction system during a known period of time and M_s is the mass of that chemical that is released in stack gases during the same period of time. For example, if a chemical is fed into an incinerator at the rate of 400 kilograms per hour and it is released in stack gases at the rate of 0.4 kilograms per hour, the incinerator is achieving a DRE of 99.9 percent with that chemical.

In addition, the residues were analyzed by relatively insensitive methods, which can result in underestimation of the concentrations of the chemicals present. Further, the DREs reflect the combined performances of a chain of thermal devices, not just one incinerator.

In a trial burn at another hazardous waste incinerator, DREs were determined using two chemicals that were selected as surrogates for the actual chemicals of concern. The surrogates were chosen based on evidence that they are more difficult to destroy than the chemicals of concern.^{39,40,41} As shown in Table 3 below, the destruction efficiencies achieved with the chemicals of concern, 65.4 to 83.7 percent, were far lower than the DREs achieved with the surrogate chemicals, 99.999871 to >99.99998 percent.

Table 3: Destruction Efficiencies (DEs) and Destruction and Removal Efficiencies (DREs) Achieved With Chemicals of Concern and Their Surrogates During Incinerator Trial Burn at Drake Chemical Superfund Site, Lock Haven, Pennsylvania, USA ⁴²

	Run 1	Run 2	Run 3	Run 4
<u>Chemicals of Concern</u>				
DE with Fenac (2,3,6-trichlorophenylacetic acid), %	75.3	71.8	65.4	83.7
DE with β -naphthylamine, %	na	94.3	98.7	98.8
<u>Surrogate Chemicals</u>				
DRE with 1,4-dichlorobenzene, %	99.999983	99.999961	>99.99998	99.999949
DRE with naphthalene, %	99.999941	99.999896	99.999935	99.999871

1.4.1.2 Incinerators and Waste Reduction

Incinerators have also been reputed to transform a volume of unwanted material into a far smaller volume of solid residues. However, this is not the case when chlorine-containing substances, such as the short-listed POPs, are burned.

When chlorine-rich wastes are burned, the resulting hydrogen chloride must be neutralized, which results in large quantities of residual salts, which may be contaminated with dioxins and other products of incomplete combustion as well as undestroyed chemicals of concern. For example, in burning wastes from the manufacture of the organochlorine pesticides, 2,4-D and 2,4,5-T, a U.S.-based hazardous waste incinerator generated a volume of dioxin-contaminated ash and salt that was approximately 80 percent greater than the volume of the materials burned.⁴³

In another case, an incineration facility burning chemical nerve agents generated approximately ten pounds of solid residues per pound of agent.^{44,45} Due to their toxic content, the ashes and salts produced during the incineration of the nerve agents as well as those produced from the incineration of the organochlorine pesticides were considered to be hazardous wastes. The residues from the incineration of nerve agents were sent to a specially constructed hazardous waste landfill, while those from the organochlorine pesticides remain in a large aboveground storage facility.

1.4.1.3 By-Products of Combustion

As noted earlier by FAO, one of the larger concerns in burning hazardous wastes is the generation of new, sometimes exquisitely toxic chemicals during and subsequent to combustion—so-called products of incomplete combustion (PICs). Among the PICs that have been identified, dioxins and furans are commonly regarded as the greatest threat to public health and the environment. These and other POPs, including PCBs⁴⁶ and hexachlorobenzene,⁴⁷ are created when chlorine-containing materials are burned.

Studies suggest that the populations of the U.S. and some European countries now carry body burdens of dioxins and furans that are at or near those levels at which health effects are known to occur in humans.⁴⁸ Gaseous emissions from the combustion of human-made, chlorine-containing materials have been identified as the primary source of these dioxins and furans.⁴⁹ Indeed, numerous studies with both laboratory and pilot-scale combustion systems have shown that increased input of chlorine-containing materials is accompanied by greater output of dioxins and furans.^{50,51,52,53,54,55,56,57} The same association has been demonstrated in studies with full-scale incinerators.^{58,59,60,61,62,63,64}

In some developed countries, concentrations of dioxins in the stack emissions of the more advanced, expertly operated incinerators are now reported to fall routinely below 0.1 ng TEQ^d/m³, a concentration which is presumably no longer a matter of concern for the health of the general public and wildlife. It is important to note, however, that such a presumption ignores the more important factor: the mass of dioxins released in stack gases over time.

For example, stack gases were emitted at the rate of some 1,500 m³ per minute during trial burns at one of the larger, more modern hazardous waste incinerators in the U.S. With an average dioxin content of 0.14 ng TEQ/m³, this incinerator was releasing more than 300,000 ng TEQ per day.⁶⁵ At this rate, this incinerator was releasing into the open air each day a quantity of dioxins that was equivalent to the acceptable daily intake for 1 to 4 million adults, based on the World Health Organization's recently revised acceptable daily intake for dioxins of 1-4 picograms per kilogram of body weight per day.⁶⁶

1.4.1.4 Incinerator Impacts on Public Health and the Environment

Proximity to incinerators burning chlorine-containing materials has been linked to increased levels of dioxins in the surrounding environment and nearby populations:

- In Japan, where municipal waste contains relatively high levels of the organochlorine plastic, PVC,⁶⁷ high dioxin concentrations in soils surrounding a municipal waste incinerator were found to be “*well correlated*” with high cancer rates among the surrounding population.⁶⁸
- A team of doctors reported elevated levels of these POPs in the breastmilk of women who live downwind from certain incinerators in Germany.⁶⁹
- U.S. federal and state agencies assessed the levels of dioxins in the blood lipids of people living near an incinerator burning waste from the manufacture of two organochlorine pesticides, 2,4-D and 2,4,5-T.^{70,71} Over a three-year period, concentrations of the most toxic form of dioxin, 2,3,7,8-TCDD, increased by an average of 25 percent among more than 60 percent of the study participants.⁷²
- Authorities in Spain determined that, over a period of two years,

^d There are 75 polychlorinated dibenzo-p-dioxins (PCDDs) and 135 polychlorinated dibenzofurans (PCDFs), among which seven PCDDs and ten PCDFs are thought to be of greatest toxicological concern. Among these seventeen PCDD/Fs, 2,3,7,8-tetrachlorodibenzo-p-dioxin (2,3,7,8-TCDD) is considered the most toxicologically potent. This most potent dioxin has been assigned a toxic equivalency factor (TEF) of 1 and the remaining sixteen have been given individual TEFs reflecting each chemical's toxicological potency relative to that of 2,3,7,8-TCDD. The concentrations of each of the seventeen PCDD/Fs multiplied by the designated TEFs and the resulting values are summed to yield the toxic equivalency (TEQ) value.

dioxins in the blood lipids of people living near an incinerator burning urban wastes increased by 10 to 15 percent. In addition, their blood lipid levels of PCBs increased by about 5 percent.⁷³

- In Canada, health officials advised against the consumption of wild game taken within a 30 kilometer radius of the Swan Hills PCB incinerator because of the accumulation of dioxins released from that facility.⁷⁴
- Under a program coordinated by FAO, some stockpiles of obsolete pesticides in developing countries are being burned in European incinerators. At one of these incinerators, the Rechem facility in the U.K., where PCBs and other wastes are burned, studies have found elevated levels of dioxins in air, soil and foods in the surrounding area. Eggs from ducks and bantam chickens had levels of dioxins that were 4.7 and 20 times higher, respectively, than background levels. Dioxin levels in the ambient air at a nearby house were 3.5 times background, while soil concentrations were three times background. Dioxin concentrations in apples grown in the same district as the incinerator carried dioxin levels 2.3 times background. The scientists estimated that, compared with background exposures, people in this district were taking in 2.4 times more dioxin in their milk, 1.3 times more in their potatoes and 3.2 times in soils.⁷⁵

Given the situation at the Swan Hills and Rechem facilities, FAO's recommendation to ship POPs stockpiles to a dedicated hazardous waste incinerator in an industrialized country⁷⁶ may not be the safest, most effective strategy for eliminating POPs contamination. Rather, this method of disposal may result in the transformation of some portion of one group of POPs, e.g., PCBs or chlorine-containing pesticides, into another, e.g., dioxins, while shifting the environmental and public health burden from one community to another.

It is also important to note that gaseous emissions represent only a relatively small fraction of the total quantity of dioxins generated by the combustion of chlorine-containing materials. In one study of eleven full-scale municipal waste combustors in Germany, stack emissions carried only 12 percent of the total yield of these POPs, while the remainder was distributed among the other incinerator residues.⁷⁷

The common practice of burying incinerator residues in landfills cannot be expected to prevent the eventual release of these POPs into the broader environment, as pointed out by Acharya et al. (1991):⁷⁸

“Capture and removal transfers the PCDD/PCDF [dioxins and furans] from the stack gas to other residual streams ... that are then reintroduced back into the environment.”

For example, scientists in Japan found that dioxins were leaching into water resources from municipal waste incinerator ash that had been buried in landfills.⁷⁹

1.4.2 Cement Kilns

Cement kilns are inclined rotating cylinders lined with refractory brick that are internally fired. They are designed and constructed to heat various materials, such as limestone, clay, shale, sand, etc., to produce "clinker" which is ground up with a small amount of gypsum to produce cement. Such kilns can reach more than 250 meters in length and 8 meters in diameter. The raw feed materials are fed into the higher, elevated or "cool" end of the kiln. As the kiln slowly rotates, the raw meal tumbles down toward the hot lower, or "flame" end and is gradually altered physically and chemically at temperatures as high as 1,500 °C. Under this intense heat, which is ordinarily provided by burning coal or fuel oil, the raw materials blend and form a pebble-like substance -- "clinker". Once cooled, the clinker is ground up with a small amount of gypsum to produce cement.

Combustion gases enter the kiln at the hot lower end and flow upward, heating the raw materials flowing in the opposite direction as they pass over, and exit the kiln at the top end. The gases then pass through air pollution control devices before entering the atmosphere. These devices are typically either a fabric filter or electrostatic precipitator, both of which function to remove the particulate matter entrained in the gas stream before the gases are emitted into the atmosphere. This particulate matter is referred to as cement kiln dust (CKD).

Cement is produced by either wet or dry processes. The older, wet process entails mixing the raw materials with water to form a slurry, which is pumped into the kiln. The wet process requires heat input of 5 to 7 trillion BTUs per ton of clinker product to evaporate the slurry water.⁸⁰ Dry process kilns are more energy efficient, requiring an average of 4.4 million BTU, roughly equivalent to 400 pounds of coal, per ton of cement.⁸¹ Dry process kilns also generally have a higher capacity.⁸²

1.4.2.1 General Impacts of Cement Kilns

Irrespective of the materials burned for heat energy, cement kilns pose threats to the health of workers, surrounding populations, and the environment, primarily through the impacts of cement kiln dust (CKD). For example, a study of workers at cement plants in the United Arab Emirates found them to suffer from chronic cough, chronic bronchitis, burning, itching and runny eyes, headache and fatigue.⁸³ Cement plant workers in another study exhibited a higher prevalence of chronic respiratory symptoms and reduced ventilatory capacity.⁸⁴

USEPA (1995) found evidence of groundwater contamination at all cement plants for which groundwater monitoring data were available as well as 36 cases of documented damage to air from CKD. The Agency summarized as follows:⁸⁵

"[O]ther evidence (i.e., damage cases) indicates that fugitive CKD

emissions are a substantial contributor to environmental damages in the form of air quality degradation. ... EPA has concluded that additional control of CKD is warranted in order to protect the public from human health risks and to prevent environmental damage resulting from current disposal of this waste. The primary environmental concerns to be addressed through additional controls are documented damages to ground water and potable water supplies, and potential human health risks from inhalation of airborne CKD and ingestion via food chain pathways ... Significantly, releases to ground water were observed at all sites for which EPA has received ground water monitoring data. ... [T]he Agency's risk assessment studies also indicated potentials for adverse aquatic ecological effects due to possible chemical releases to streams and lakes adjacent to some cement plants."

1.4.2.2 Burning Hazardous Materials in Cement Kilns

Cement kilns in some industrialized countries have begun augmenting or even fully replacing conventional fuels with industrial hazardous waste. However, as noted in Table 1, FAO recommend against burning chlorinated pesticides in cement kilns in some cases. FAO also warn that disposal of hazardous materials, such as obsolete pesticides, by burning in cement kilns is "*often not applicable in a safe and/or cost-effective manner,*" going on to note as follows:⁸⁶

"Many of the older types of cement kilns are not suitable. Only a few of the cement kilns in developing countries meet the technical requirements that, in principle, would make them suitable for incineration of certain groups of pesticides. Expert advice is needed to assess whether kilns can be used and special equipment is required to inject the pesticides into the kiln. Such equipment is expensive and should only be installed and used under expert supervision."

1.4.2.2.1 Performance of Cement Kilns Burning Hazardous Waste

According to USEPA (1998), the "*conditions inherent in the cement kiln mimic conditions of hazardous waste incineration*".⁸⁷ As such, some of the general limitations of hazardous waste incinerators that were discussed earlier may be equally applicable to cement kilns that burn hazardous wastes. For example, a review of test burns in eight cement kilns found DREs for a variety of specific chemicals to range from 91.043 to 99.9999 percent, with an average DRE of 99.53 percent.⁸⁸ However, as discussed earlier, only stack emissions of undestroyed chemicals are considered in determining DREs. I.e., the quantities of undestroyed chemicals deposited in CKD, clinker and other residues were not taken into consideration. Consequently, the actual destruction efficiencies were undoubtedly lower.

1.4.2.2.2 Products of Incomplete Combustion Released from Cement Kilns

When hazardous chemicals, wastes and similar materials are burned

in cement kilns, products of incomplete combustion (PICs) are released in stack gases as well as adsorbed to or incorporated into the CKD captured by air pollution control devices. Dioxins are among the PICs that have been identified in stack emissions from cement kilns.

Cement kilns release particularly large volumes of stack gases. For example, the stack gas flowrate of an U.S. cement kiln burning wastes was some 5,500 dry cubic meters per minute.⁸⁹ If this cement kiln were meeting the European dioxin emission standard for incinerators, 0.1 ng TEQ/m³, it would release dioxins into the open air at the rate of 792,000 ng/day. This quantity of dioxins is equivalent to the acceptable daily dioxin intake for 2.8 to 11.3 million adults, based on the World Health Organization's acceptable daily intake of 1 to 4 picograms per kilogram of body weight per day⁹⁰. CKD, which contains higher levels of dioxins when chlorinated materials are burned, is another source of dioxin releases to the environment via fugitive emissions and other routes, such as reincorporation in the cement product.

1.4.2.2.3 Impacts of Burning Hazardous Waste in Cement Kilns

The impacts of hazardous waste burning cement kilns can be compared to those of cement kilns that burn conventional fuels, as follows:

- Dioxins are emitted from cement kiln stacks, whether the kiln is fired with conventional fuels or with hazardous waste. However, according to USEPA, cement kilns that burn hazardous waste emit dioxins in their stack gases at rates more than 80 times higher than those of cement kilns that burn conventional fuels. In the U.S., cement kilns burning hazardous waste are listed as the fifth largest source of dioxin emissions to the air, while those that do not burn hazardous wastes are the tenth largest source.⁹¹ The relatively high ranking of the latter may be due in part to the common practice of burning other chlorine-containing materials such as tires and municipal solid waste, as documented in one database.⁹²
- Similarly, dioxins are found in CKD from cement kilns that burn conventional fuels as well as those burning hazardous waste. USEPA recently reported that CKD from cement kilns burning hazardous waste carries dioxins at concentrations about 100 times higher than CKD from kilns burning only conventional fuels.⁹³ According to the Agency, one cement plant reported “a total dioxins concentration in CKD as high as 16 ppb [parts per billion], with a TEQ value for the managed CKD of 195 ppt [parts per trillion].”⁹⁴
- Cement kilns that burn hazardous waste produce more CKD, as documented by the U.S. Environmental Protection Agency.⁹⁵

“Finally, the Agency also found that the burning of hazardous waste is correlated with the volume of dust that is actually disposed. Kilns that burn hazardous waste remove from the kiln system an average of 75 to 104 percent more dust per ton of clinker than kilns that do not burn hazardous waste.”

- From 15 to 90 percent of CKD has a diameter below 10 microns (μm), which is within the respirable range for humans.⁹⁶ As these fine particles are carried to the stack, the portion that is not captured by pollution control devices is released directly to the air. Some fraction of the captured CKD also escapes during transfer and disposal. One cement kiln burning 90 tons of hazardous waste per day was found to produce CKD at the rate of 200 tons per day.⁹⁷
- The smaller CKD particles are those most likely to escape capture by pollution control devices or to be resuspended or washed from CKD stored in piles or pits. These particles are also the most likely to lodge deeply in the lungs. Airborne particles smaller than 2 μm have been linked to high rates of pneumonia, pleurisy, bronchitis, and asthma.⁹⁸ In their briefing paper on burning hazardous waste in cement kilns, the American Lung Association drew attention to the issue of CKD as follows:⁹⁹

“Particulate matter is a health concern because inhaling even relatively low airborne concentrations of dust can cause or aggravate lung diseases such as asthma or emphysema, and is associated with premature death. ... Since CKD collected in air pollution control devices typically has a small particle size, poorly managed cement kiln dust handling, transport and disposal has been shown to cause severe fugitive dust and air pollution problems.”

- Dioxins have also been found in the clinker from both hazardous and non-hazardous waste facilities.¹⁰⁰
- Emissions of airborne particulates increased by 66 percent when hazardous wastes were burned in cement and aggregate kilns and by 203 percent when the hazardous wastes also contained chlorine sources.¹⁰¹
- When hazardous wastes containing both chlorinated chemicals and metals were burned, metals emissions from cement kilns increased.^{102,103}
- Burning chlorinated chemicals in cement kilns increases the likelihood of upsets, since the presence of additional chlorine encourages the formation of “rings” in the kilns. When the rings detach or break, the sudden release of solids in the kilns can result in upsets which are accompanied by increased emissions of unburned wastes and products of incomplete combustion, or even more severe consequences.¹⁰⁴

“In a very severe upset, the flame at the firing end of the kiln can be extinguished. Upsets are not uncommon. The kiln we studied averaged three upsets a month”

- Fugitive emissions are substances that volatilize or, if adsorbed to particulates, such as CKD, blow or wash into the surrounding environment during waste transfer and storage. At one cement kiln burning hazardous waste, fugitive emissions were reported to be 20,074 pounds per year.¹⁰⁵

- Spills, both on-site and off-site, are also a concern at cement plants where hazardous materials are burned. A report commissioned by the New York State Legislature on waste-burning in cement kilns assessed the likelihood of repeated spills: ¹⁰⁶

“[I]t is virtually impossible to completely prevent small spills of hazardous waste during unloading and pumping of waste fuels. These spills may be caused by equipment failures, maintenance operations, or operator error.”

2.0 Modern Destruction Technologies

Evidence of the environmental and public health impacts of incinerators, cement kilns and similar combustion systems has created strong public opposition to incineration. This factor as well as increasing infrastructural needs, particularly those associated with the management of air emissions and other residues, has encouraged the development of other destruction technologies.

Some of the more recently developed technologies offer significant advantages in both performance and costs over combustion in dedicated incinerators and cement kilns. It is important to note, however, that the resource demands for facility siting and construction, performance testing, operation, routine monitoring of operations, and other infrastructural needs of both conventional and modern destruction technologies render both unsuitable for continued, long-term use, as in the disposal of domestic and industrial wastes.

A selection of modern destruction technologies and their brief descriptions are given in Table 4.

Table 4: Selection of Modern Destruction Technologies

Technology	Process
Gas-phase chemical reduction	Hydrogen reacts with chlorinated organic compounds, such as PCBs, at high temperatures, yielding primarily methane and hydrogen chloride. High destruction efficiencies. All emissions and residues are captured for assay and reprocessing, if needed.
Electrochemical oxidation	At low temperature and atmospheric pressure, electrochemically-generated oxidants react with organochlorines to form carbon dioxide, water and inorganic ions. High destruction efficiencies. All emissions and residues can be captured for assay and reprocessing, if needed.
Molten metal	Organochlorines and other materials are oxidized in a vat of molten metal, yielding hydrogen, carbon monoxide, ceramic slag and metal by-products. Destruction efficiencies are not known, but DREs are high. ^e
Molten salt	Organochlorines and other materials are oxidized in a vat of molten salt, yielding carbon dioxide, water, molecular nitrogen, molecular oxygen, and neutral salts. Destruction efficiencies may be high.
Solvated electron process	Free electrons in a solvated electron solution convert contaminants to relatively harmless substances and salts. Destruction efficiencies vary from 86 to 100 percent. All emissions and residues can be captured for assay and reprocessing, if needed.
Supercritical water oxidation	Under high pressure and temperature, organochlorines and other materials are oxidized in water. Destruction efficiencies are unknown, but DREs are high. ^e All emissions and residues can be captured for assay and reprocessing, if needed.
Plasma arc	Organochlorines and other materials are oxidized at very high temperatures. Destruction efficiencies are unknown, but DREs are high. ^e Dioxins have been identified in process residues.
Catalytic hydrogenation	Organochlorines are reacted with hydrogen in the presence of noble metal catalysts, yielding hydrogen chloride and light hydrocarbons. High destruction efficiencies.
Base catalyzed dechlorination	Organochlorines are reacted with an alkaline polyethylene glycol, forming a glycol ether and/or a hydroxylated compound, which requires further treatment, and a salt. Dioxins have been identified in process residues. Destruction efficiencies are not high.

2.1 Evaluations of Selected Destruction Technologies

^e Destruction efficiencies are determined by considering the occurrence of undestroyed chemicals of concern in all gaseous, liquid and solid residues; for DREs, only gaseous residues are considered.

Australia holds a leading position in the use of technologies other than combustion for the destruction of intractable wastes, obsolete pesticides and contaminated environmental media. As a result, Environment Australia has evaluated a wide range of these newer technologies.

Other organizations, agencies and institutions have also assembled valuable compilations of information on destruction technologies. In 1991, Greenpeace presented a literature review of detoxification methods in use or in varying states of development that had potential application to the destruction of chemical weapons stockpiles.¹⁰⁷ Responding to strong public pressure, the U.S. Congress passed a law in 1996 directing the Department of Defense to evaluate non-incineration technologies for the disposal of chemical weapons.¹⁰⁸ Other agencies, including FAO and the U.S. Department of Energy, have also evaluated these new technologies.

2.1.1 Environment Australia

Environment Australia (1997) recently published its final review of 16 technologies for the destruction of wastes such as POPs stockpiles as part of the Australian and New Zealand Environment and Conservation Council (ANZECC) National Scheduled Waste Program.¹⁰⁹ The review does not directly compare technologies for specific wastes and detailed evaluations must conform to the ANZECC National Protocol "Approval/Licensing of Commercial-Scale Facilities for the Treatment/Disposal of Schedule X Wastes."¹¹⁰

2.1.2 United Nations Food and Agriculture Organization

FAO (1996) acknowledged the technologies listed below as "*promising new developments*".¹¹¹ It is useful to note, however, that FAO based its evaluations of these processes on DREs, in which releases of undestroyed chemicals in only gaseous emissions are considered, rather than the more comprehensive measure, destruction efficiency, which encompasses undestroyed chemical releases in all process residues.

- Gas-phase chemical reduction reactor by Eco Logic which has DREs ranging from "99.9 to 99.99999 percent," is operating at "commercial-scale" in Australia.
- Molten metal technology, which is described as "moving into its commercial phase."
- Molten salt oxidation process, which achieves DREs "up to 99.99999 percent," is "[s]uitable for the destruction of pesticides but not for treatment of contaminated soils," but "is not yet available on a commercial scale."
- Plasma energy pyrolysis, which "can handle pesticides and their containers," achieves "[h]igh DRE values," but is "complex and still very expensive."

2.1.3 United States Department of Defense

As part of the U.S. Department of Defense program to destroy existing stockpiles of unitary chemical warfare agents, U.S. Army representatives and a panel of experts evaluated eleven non-incineration destruction technologies.

Their objective was to identify non-incineration technologies for destroying chemical agent HD, an organochlorine, at one stockpile site and VX, an organophosphate, at a second site. The following three received a unanimous recommendation from the panel as well as U.S. Army Major General Orton:¹¹²

- High temperature gas phase reduction (Eco Logic International, Inc.),
- Molten metal (M4 Environmental L.P.), and
- Electrochemical oxidation (Sub Sea International, Inc.)

In addition to these processes, the U.S. Army is evaluating three other destruction technologies: supercritical water oxidation, ultraviolet oxidation and electron beam oxidation.

2.1.4 United States Department of Energy

The U.S. Department of Energy (DOE) and Office of Technology Development have been evaluating appropriate waste destruction technologies for a variety of waste streams as well. DOE explained their reasons for engaging in this process as follows:¹¹³

... DOE is concerned about the current difficulty of permitting and siting incinerators. Public acceptance and perceptions associated with air emissions of toxic metals and organics are major issues. ... [T]echnologies capable of treating DOE organically contaminated mixed wastes and which may be more easily permitted ... have the potential of alleviating stakeholder concerns by decreasing off-gas volumes and the associated emissions of particulates, volatilized metals and radionuclides, PICs, NO_x, SO_x, and recombination products (dioxins and furans).

DOE has evaluated approximately 30 alternative technologies, based on information gleaned from the open literature, government reports, and discussions with principal investigators and developers. Evaluation criteria included the following: a) capability of treating a variety of wastes with varying constituents with minimal pretreatment or characterization; b) secondary waste stream volumes that are significantly smaller than the original waste stream volumes and which contain no toxic reaction byproducts; c) complete mineralization of organic contaminants; d) offgas and secondary waste composition; e) cost; and f) risk.¹¹⁴

2.2 Gas-Phase Chemical Reduction

Eco Logic International has developed and patented a process based on the gas-phase, thermochemical reduction reaction of hydrogen with organic and chlorinated organic compounds. At temperatures of 850 °C and higher, chlorinated hydrocarbons, such as PCBs, are reduced to methane and hydrogen chloride, while non-chlorinated organic contaminants, such as polycyclic aromatic hydrocarbons (PAHs), are reduced to methane and minor amounts of light hydrocarbons.¹¹⁵

Because the reaction takes place in a reducing atmosphere devoid of oxygen, the possibility of dioxin and furan formation is said to be eliminated. Maintaining greater than 50 percent hydrogen (dry basis) can prevent the formation of PAHs.¹¹⁶

In commercial-scale performance tests in Canada, the gas-phase reduction process achieved destruction efficiencies and DREs with high-strength PCB oils and chlorobenzenes as shown below in Table 5. Dioxins that were present as contaminants in the PCB oil were destroyed with efficiencies ranging from 99.999 to 99.9999 percent.¹¹⁷

When chemical concentrations in gases and other residues fall below limits of detection, they are reported as “less than” values, not as zero. As a consequence, values calculated for destruction efficiency approach, but never reach zero. In other words, based on the data in Table 5, gas-phase chemical reduction can achieve destruction efficiencies of effectively 100 percent.

Table 5. ECO LOGIC Gas-Phase Reduction Process: Destruction Efficiencies and Destruction and Removal Efficiencies (DREs) Achieved with PCBs and Chlorobenzenes

Chemicals of Concern	Test 1	Test 2	Test 3
PCBs			
Destruction Efficiency, %	99.9999996	99.9999985	99.9999808
DRE, %	99.9999996	99.9999985	99.9999997
Chlorobenzenes			
Destruction Efficiency, %	99.9999836	99.9999972	99.9999971
DRE, %	99.9999842	99.9999985	99.9999977

As explained in Section 1.4.1.1, destruction efficiencies are determined by comparing the quantity of a chemical of concern fed into a treatment system and the total quantity of that same chemical that is released in all gaseous, liquid and solid residues. DREs are a comparison of the quantity of a chemical of concern that is fed into the system and the quantity of that chemical that is released in stack gases only.

In similar tests at a commercial installation in Australia, a DRE of 99.999998 percent was achieved with high-strength PCB oils. However, destruction efficiency was not reported.¹¹⁸ This unit is described as successfully processing transformer fluids, bulk PCB solids including electrical capacitors, and high-strength DDT waste pesticide mixtures.¹¹⁹ Environment Australia characterizes the process as follows:¹²⁰

“The process is non-discriminatory; that is organic molecules such as PCBs, PAHs, chlorophenols, dioxins, chlorobenzenes, pesticides, herbicides and insecticides are quantitatively converted to methane. Approximately 40% of the methane produced can be subsequently converted to hydrogen via the water shift reaction and the remaining methane converted to hydrogen in the catalytic steam reformer. Thus, the process can operate without an external supply of hydrogen. For highly concentrated wastes (eg pure Askarel) the process produces an excess of methane.”

Residues generated by the process include product gas from the reactor, scrubber water and sludge from product gas treatment, and small quantities of grit from the reactor. Product gas is either catalytically reformed to recover hydrogen or burned as fuel in one or more of the auxiliary systems – the boiler, catalytic reformer and sequencing batch vaporizer.¹²¹ During typical operations, 30 to 50 percent of the product gas is burned as fuel for the boiler or other auxiliary units.¹²²

If either the product gas or the ambient air used for combustion air for the boiler or similar units contains hydrogen chloride or other chlorinated species, dioxins may be generated during their combustion. In order to meet the fundamental technical criteria for POPs destruction, both the product gas and combustion air must be treated to remove such chlorine donors and so prevent dioxin formation.

At the Canadian facility, the product gas was found to contain no detectable PCBs, while concentrations of total chlorobenzenes and dioxins were similar to those of the blanks. This suggests that the product gas did not contain quantifiable levels of these substances. When the product gas was burned in the steam reformer, dioxins were emitted from the reformer stack at a concentration of 15 pg TEQ /m³. This dioxin formation was attributed to the use of PCB-contaminated air from the site for the reformer’s combustion air. The proposed solutions are drawing combustion air from off-site or filtering the ambient air through carbon before using it for combustion.¹²³

In their recent application to destroy PCB-containing materials in Ontario, Canada, Eco Logic International stated as follows:¹²⁴

“All outputs from the destruction of PCB-contaminated waste using the ECO LOGIC Process can be contained and tested. There are no uncontrolled emissions from the Process which could result in releases of PCB-contaminated air, solids, or liquids to the surrounding environment. Releases of PCBs to the environment could only occur during waste handling prior to treatment, where the possibility of spillage exists. ... The ECO LOGIC Process is a mobile technology, and is generally expected to operate at the sites where the PCB wastes are stored.”

Environment Australia (1997) offers the following caveats for circumstances in which volatile organic solvents are being processed:¹²⁵

“Care would be required to avoid high rates of gas generation which could over-pressurise the systems, the process has limited surge capacity: over-pressurisation could result in release of waste material.”

According to DOE, this system can handle most types of waste, including landfill leachates, lagoon bottoms, soils, sludges, liquids, and gases. However, DOE has cautioned that reaction byproducts and intermediate reduction products need to be monitored in the offgas from both the reduction process and the boiler. DOE also noted that the need to determine the fate of mercury and other volatile inorganics.¹²⁶

DOE estimates treatment costs, in U.S. dollars, of \$400/ton for soils and \$2000/ton for liquids that are 100 percent PCBs.¹²⁷ Environment Australia cites treatment costs, in Australian dollars, as follows: \$250 - \$500/tonne for soil;¹²⁸ \$4000 - \$6000/tonne for organochlorine pesticide (OCP) solids; \$4000 - \$8000/tonne for PCB and OCP liquids; \$6000 - \$11000/tonne for PCB contaminated capacitors.¹²⁹

2.3 Electrochemical Oxidation

This technology, the Dounreay Electrochemical Silver (II) Process, was initially developed for the high-efficiency conversion of a wide range of radioactive organic wastes into environmentally acceptable waste streams. In tests with chemical warfare agents, this process, sometimes referred to as mediated electrochemical oxidation (MEO), was successful in destroying an organophosphorus nerve agent to non-detectable levels after one hour and an organochlorine agent, mustard, after two hours.¹³⁰

An electrochemical cell is used to generate oxidizing species at the anode in an acid solution, typically nitric acid. These oxidizers and the acid then attack any organic compounds, converting most of them to carbon dioxide, water and inorganic ions at low temperature (< 80 °C) and atmospheric pressure. The organic content of the feed, which can be soluble or insoluble organic liquids or solids, can vary between 5 and 100 percent without

affecting the process unduly. Likewise, the water content of the waste can vary over a wide range. Compounds that have been destroyed by this process include aliphatic and aromatic hydrocarbons, phenols, organophosphorous and organosulfur compounds, and chlorinated aliphatic and aromatic compounds.¹³¹ Data describing concentrations in gaseous, liquid and solid residues of dioxins and other POPs potentially formed by this process were not available for review.

According to DOE, this technology appears to be proven and ready to be commercialized for destruction of a variety of organic materials.¹³² Capital cost data are not currently available. However, for destruction of the U.S. stockpile of unitary chemical warfare agents, overall costs are estimated to be some 30 percent of the current estimate of demilitarization through incineration, with demonstration of working systems within 1 to 3 years.

2.4 Molten Metal Pyrolysis

Molten Metal Technology (MMT) has developed the Catalytic Extraction Process (CEP) in which molten metal acts as both solvent and catalyst. Waste and selected co-reactants are introduced into a refractory-lined, metal-filled vessel. According to DOE, the solid, liquid and gas output streams from this reactor vary considerably depending on the operating variables, e.g., oxidizing or reducing atmosphere. Typically, outputs include 1) a metal product that may be recycled; 2) slag that contains oxidized metals; 3) gases consisting of products of volatilization, oxidation and decomposition; and 4) particulates and metals entrained in the offgas. There are liquid wastes only if wet scrubbers are used to control air emissions.¹³³

MMT describe their process as a recycling technology that allows organic, organometallic, metallic and inorganic feeds to be recycled into useful materials of commercial value. The company has carried out commercial-scale processing of several types of waste including spent metal/electronic components; chlorinated waste streams; and biosolids from wastewater treatment.¹³⁴

Specific waste streams processed using CEP include chlorotoluene, polyvinyl chloride (PVC), surplus metal and weapons components, and heavy residuals from ethylene dichloride and vinyl chloride production. DREs greater than 99.9999 percent were achieved with specific chemicals of concern.¹³⁵ It is important to note that the developer of CEP has not yet presented data describing the concentrations of undestroyed chemicals found in the end products, other than gases, and other process residues. I.e., the destruction efficiencies achieved by this technology are as yet unknown. The primary end products of CEP are described as follows:

- Gases, primarily comprised of hydrogen, carbon monoxide and up to 1 percent ethylene, with smaller amounts of other light hydrocarbons;
- Ceramic slag phase consisting of silica, alumina and calcium chloride, which

- is skimmed off the top of the bath; and
- Metal by-products.

Dioxins and furans were reported as non-detectable in product gases at the 0.1 ng TEQ/Nm³ standard.¹³⁶ However, MMT officials failed to respond to repeated requests for the actual analytical data and for similar data for other process residues. In other words, no data are yet available to describe the concentrations in process residues of dioxins and other POPs potentially formed by this process.

According to MMT, the gases can be used in the synthesis of organic chemicals, such as methanol; the ceramic materials can be used or buried in landfills; and the metal by-products, which remain as a ferroalloy, can be recovered for use.¹³⁷ However, the National Research Council has observed as follows:¹³⁸

“The metal furnace does not eliminate the need for a combustion process; the product gases would be oxidized in a separate unit. These gases would likely be very dirty, containing soot from the metal pyrolysis and possibly some slag particulate matter. Gas cleanup will be required before the gas is released.”

In their evaluation of this technology, DOE cautions that, with induction heating of the metal bath, the method apparently used by MMT, the process must be carefully controlled to prevent equipment damage and possible explosion. Other issues raised are as follows:¹³⁹

...[T]he potential for over-pressure due to rapid gas evolution of volatile bulk materials; ... and development of instrumentation, control, and monitoring systems, including on-line feedback of metal and slag compositions and offgas components.

Recently, USEPA recognized MMT's process as achieving the Best Demonstrated Available Technology (BDAT) for processing wastes for which incineration was previously the only approved processing method.¹⁴⁰

DOE estimated capital costs for a typical MMT facility to range from \$15 to \$50 million, in U.S. dollars, depending on the volume and composition of the waste stream. For example, the MMT unit at Clean Harbors, which has a capacity of 30,000 tons of waste per year, is estimated to cost between \$25 and \$35 million.¹⁴¹ MMT is currently designing facilities for four commercial customers: Hoechst-Celanese (chlorinated plant waste), Clean Harbors (hazardous waste), SEG (ion-exchange resin), and Martin Marietta. MMT and Martin Marietta have formed a new business, M4 Environmental, L.P., to commercialize CEP for applications for the U.S. Department of Defense and the U.S. Department of Energy.

2.5 Molten Salt Oxidation

The molten salt process has been used on a small scale since

1950.¹⁴² In the process, a bed of alkaline molten salt, usually sodium carbonate, oxidizes organic materials at a temperature of 900 to 1000°C. Any chlorine, sulfur, phosphorous, or ash products in the feed are converted to inorganic salts and retained in the salt bed. This process cannot treat soils and other materials with a high content of inert material.¹⁴³

With bench and pilot scale systems, liquid 1,2,4-trichlorobenzene (58.6 weight percent chlorine) was destroyed in molten sodium carbonate/sodium chloride with efficiencies of 99.9999970 and 99.9999932 percent at bed temperatures of 900°C and 1000°C respectively. With chlordane, the pilot scale system achieved DREs of 99.99983 percent when samples were taken before the baghouse and >99.9999988 percent when sampled after the baghouse.¹⁴⁴ Destruction efficiency with chlordane was apparently not determined. Indeed, the use of both performance measures, “destruction efficiency” and DRE, in describing the performance of this technology suggests that one may have been used inaccurately. I.e., destruction efficiency can be determined only if all process residues are analyzed for the presence of undestroyed chemicals of concern. It is also important to note that no data were presented describing the concentrations in process residues of dioxins or other POPs potentially formed by the process.

One hazard of the process is potential superheated-vapor explosions when liquid wastes are introduced. Gaseous emissions may require filtering due to the entrainment of very fine salt particles (possibly smaller than 1 µm), and the total salt requiring disposal may be several times the weight of the wastes destroyed.¹⁴⁵

Depending on chlorine content as well as the capacity of the facility, the cost (in Australian dollars) of treating organochlorine wastes vary from \$1200 to \$2000 per tonne. The residuals from the process are not useful, and must be disposed of properly in a secure landfill. For a feed rate of 1000 kg/h, the cost is in the order of \$1150/tonne. The above costs do not include effluent treatment costs, residuals and waste shipping costs handling and transport costs, analytical costs, and site restoration costs.¹⁴⁶

2.6 Solvated Electron Process

Solvated electron technology (SET) uses an alkali or alkaline earth metal dissolved in a solvent such as ammonia, or certain amines or ethers to produce a solution containing free electrons and metal cations. Chlorine and other halogens are selectively stripped from organic halides by free electrons and captured by the metal cations to form salts (e.g., CaCl₂).¹⁴⁷ For example, a PCB molecule can be converted to biphenyl in a rapid reaction at ambient temperatures.¹⁴⁸

The application of solvated electron technology to waste treatment has been developed by Commodore Applied Technologies Inc., which has resulted in a proprietary reagent known as Agent 313.¹⁴⁹ The technology has been demonstrated in the destruction of a wide variety of halogenated organic compounds including PCBs, dioxins, pesticides, chlorofluorocarbons (CFCs)

and chemical warfare agents (e.g., GB, HD, VX and Lewisite).¹⁵⁰ Some of the materials that have been treated by SET, their treatment residues and the fate of those residues are given below in Table 6.¹⁵¹

Table 6: Solvated Electron Technology: Materials Treated and the Nature and Fate of Treatment Residues

Material Treated	Products	Disposal Options
Concentrated PCBs	Biphenyl, calcium hydroxide, calcium chloride.	Landfill as salts.
PCBs in soils	Biphenyl, calcium hydroxide, calcium chloride, clean soil.	Return soil to ground.
PCBs on surfaces	Biphenyl, calcium hydroxide, calcium chloride.	Collect salts and landfill.
PCB/oil mixtures	Biphenyl, calcium hydroxide, calcium chloride, oil.	Reuse oil. Landfill salts.
Concentrated HCB	Benzene, sodium chloride, sodium hydroxide.	Separate benzene and landfill salts.
HCB in soils	Benzene, sodium chloride, sodium hydroxide, clean soil.	Separate benzene and return soil with salt to ground.

Decontaminated soils are said to be suitable for return to the site, enriched in nitrogen from trace amounts of residual ammonia. Proponents claim destruction efficiencies of 100 percent for organochlorine pesticides such as DDT, Dieldrin, 2,4-D, and 2,4,5-T. With a few pesticides – Carbaryl, Paraquat, PMA, and Zineb -- destruction efficiencies as low as 86 percent were achieved.¹⁵²

It is important to note that no data were available that identify and chemically characterize all gaseous, liquid and solid residues of this process. I.e., no information was found that describe the concentrations in process residues of dioxins and other POPs that may potentially be formed during this process.

Costs, in Australian dollars, for treating PCB-contaminated soils are \$300-340/tonne, while those for concentrated wastes are \$12,000-\$20,000/tonne.¹⁵³

2.7 Supercritical Water Oxidation

Supercritical water oxidation (SCWO) is a high temperature and pressure technology that uses the properties of supercritical water in the destruction of organic compounds and toxic wastes. Under supercritical conditions, carbon is converted to carbon dioxide; hydrogen to water; chlorine atoms derived from chlorinated organic compounds to chloride ions; nitro-compounds to nitrates; sulfur to sulfates; and phosphorus to phosphate.¹⁵⁴

The unique properties of super critical water are the key to the operation of this process. Gases including oxygen and organic substances are

completely soluble in super critical water, whereas inorganic salts exhibit greatly reduced solubility under process conditions. Organic substances dissolve in the super critical water, and oxygen and the organic substances are brought into intimate single phase contact at temperatures and molecular densities that allow the conventional oxidation reactions to proceed rapidly to completion.

Process residues are contained and consist of water, gas and solids if the waste contains inorganic salts or organics with halogens, sulfur or phosphorous. The effluent gases contain no oxides of nitrogen or acid gases such as hydrogen chloride or sulfur oxide. The process generates no particulates and less than 10 ppm carbon monoxide has been measured.¹⁵⁵

The National Research Council (1993) has pointed out that this system must be constructed of materials capable of resisting corrosion caused by halogen ions. They also note that the precipitation of salts may cause plugging problems in the system.¹⁵⁶

DREs of greater than 99% have been reported for the treatment of numerous hazardous organic compounds using SCWO. For example, bench scale tests have shown DREs of 99.999% or higher for chlorinated solvents, PCBs and pesticides, and >99.99994% for dioxin contaminated MEK.¹⁵⁷ No data have yet been found that allow the destruction efficiencies of this technology to be determined. I.e., the concentrations of undestroyed chemicals in process residues have not been reported for process residues other than gaseous emissions. Similarly, no data were presented describing the concentrations in all process residues of dioxins and other POPs potentially generated.

Environment Australia (1997) notes that end products such as ash and brine require disposal. The Agency also finds that the technology is limited to the treatment of waste that is liquid or has a particle size less than 200 μm , and it is most applicable to wastes with an organic content of less than 20%.¹⁵⁸

SCWO has been applied to a broad range of materials, e.g., aqueous waste streams, sludges, contaminated soils, industrial organic chemicals, plastics, synthetics, paints and allied products, industrial organics, agricultural chemicals, explosives, petroleum and coal products, and rubber and plastic products. It is applicable to the treatment of a range of contaminants including acrylonitrile wastewater, cyanide wastewater, pesticide wastewater, PCBs, halogenated aliphatics and aromatics, aromatic hydrocarbons, MEK and organic nitrogen compounds.¹⁵⁹

Costs, in U.S. dollars, range from \$120 to \$140 per dry ton assuming some pretreatment and certain operating conditions.¹⁶⁰

2.8 Plasma Arc

In plasma arc treatment directing an electric current through a low-pressure gas stream creates a thermal plasma field. Plasma arc fields can reach 5000 to 15000°C. The intense high temperature zone can be used to

dissociate waste into its atomic elements by injecting the waste into the plasma, or by using the plasma arc as a heat source for combustion or pyrolysis.¹⁶¹

The National Research Council (1993) described the waste streams from plasma arc destruction of wastes as *“essentially the same as those from incineration...”* such as combustion by-products and salts.¹⁶²

Various plasma reactors have been developed for the thermal destruction of hazardous waste. Environment Australia considered three available plasma systems in its review of appropriate technologies for the destruction of hazardous wastes. These are:

- PACT (Plasma Arc Centrifugal Treatment)
- PLASCON (In-Flight Plasma Arc System)
- STARTECH (Plasma-electric waste converter)

2.8.1 PACT

The Plasma Arc Centrifugal Treatment (PACT) process developed by Retech uses heat generated from a plasma torch to melt and vitrify solid feed material, including contaminated soils. Organic components are vaporized and decomposed by the intense heat of the plasma and are ionized by the air used as the plasma gas, before passing to the off-gas treatment system. Metal-bearing solids are vitrified into a monolithic non-leachable mass. Gases travel through the secondary combustion chamber and then through a series of air pollution control devices.¹⁶³

Liquid and solid organic compounds can be treated by this technology and it is appropriate for treatment of hard-to-destroy organic compounds and wastes contaminated with metals. DREs for organic compounds are greater than 99.99%. However, volatile metals and products of incomplete combustion (PIC) can be generated and may need to be removed by an appropriate scrubber.¹⁶⁴ No data were found to describe the concentrations of undestroyed chemicals in process residues other than gaseous emissions. As a consequence, the destruction efficiencies achieved by this technology are as yet unknown. Similarly, no data were found to describe the concentrations in process residues of dioxins and other POPs that may potentially be formed by this process.

The system can be operated under pyrolytic conditions with a reducing atmosphere to avoid or minimize dioxin formation in the primary chamber and the volume of gases produced in the process have been calculated to be as little as 2 percent of the volume of an incinerator of equivalent capacity. However, it is usual to follow primary combustion with secondary combustion where dioxins can be formed. Since total air emission volumes are less than for conventional combustion processes, the potential impact of emissions is expected to be lower. Treated soils and other materials from this process are generally converted into ash and as such can be returned to the site.¹⁶⁵

The PACT system can be expected to have a relatively high capital

cost as well as high operating cost (\$4000 - \$8000 per tonne).¹⁶⁶

2.8.2 PLASCON

In the PLASCON system, a liquid or gaseous waste stream together with argon is injected directly into a plasma arc. Organic chemicals in the waste disassociate into elemental ions and atoms, recombining in the cooler area of the reaction. End products include gases and an aqueous solution of inorganic sodium salts.¹⁶⁷

PLASCON is not currently configured to treat a range of waste types (e.g., contaminated soil, capacitors, etc.) However, in conjunction with appropriate preprocessing (e.g., thermal desorption) its applicability is broadened. Bench scale tests achieved DREs ranging from 99.9999 to 99.999999 percent. Like the other plasma arc process, no data were found describing the concentrations of undestroyed chemicals in process residues other than gaseous emissions so that the destruction efficiency of this technology remains unknown. However, dioxins were found to occur in scrubber water and stack gases in the part per trillion range.¹⁶⁸

The PLASCON system has been operating at Nufarm, an herbicide manufacturing works in Laverton, Victoria, Australia, since early 1992. Totally organic wastes containing a variety of organochlorine compounds are being treated on a small throughput basis. Typically, the waste averages 30% w/w of chlorine. A second PLASCON unit has been commissioned to cope with the increased plant throughput (200 kW system). This system is currently being used to destroy stockpiled CFCs and halons.¹⁶⁹

Operating costs including labor vary depending on the work to be treated and the location of the site. These costs, in Australian dollars, are estimated to be under \$3000/tonne but typically range from \$1500 - \$2000/tonne.¹⁷⁰

2.9 Catalytic hydrogenation

The potential destruction of chlorinated wastes by hydrogenation over noble metal catalysts has been recognised for many years.¹⁷¹ However, noble metal catalysts are particularly susceptible to poisoning by a range of elements found in real world situations, thus limiting the applicability of the technology.

The CSIRO Division of Coal and Energy Technology has developed a process for the regeneration of PCB contaminated transformer fluids using hydrogenation catalysts based on metal sulphides, which are extremely robust and tolerant of most catalyst poisons.¹⁷² The process is also claimed to destroy a wide range of chlorinated hydrocarbons, yielding hydrogen chloride and light hydrocarbons as by-products.

In recent trials relatively high concentrations of pure POPs compounds were treated in a hydrocarbon solvent and all were destroyed to below the detection limit of analysis, as shown in Table 7. The proponents claim that the variations in destruction efficiencies reflect differences in the limits of

detection rather than real differences in the extent of destruction.¹⁷³

Most gaseous effluents are recycled through the reactor, although purge gases are discharged through a catalytic combustor. The proponents claim that no dioxins or furans have been detected leaving the catalytic combustor in gaseous emissions and that PCBs were less than 15 ng/m³. No data have been found describing the concentrations of dioxins and other POPs in other process residues.

Table 7: Catalytic Hydrogenation – Destruction Efficiencies Achieved with Organochlorines¹⁷⁴

Compound	Feed Concentration (mg/kg)	Product Concentration (mg/kg)	Destruction Efficiency, %
PCB	40 000	<0.027	>99.99993
DDT	40 000	<0.004	>99.99999
PCP	30 000	<0.003	>99.99999
HCB	1 340	<0.005	>99.9996
1,2,3,4-TCDD	46	<0.000004	>99.99999

Environment Australia notes that there is insufficient information publicly available to determine limitations or risks associated with the process.¹⁷⁵ However, the National Research Council has observed that the exact nature of waste streams would have to be determined. I.e., gaseous products may represent safety and toxicity hazards and combustion products may require scrubbing, which would generate aqueous wastes.¹⁷⁶

No cost estimates are available at this time.

2.10 Base catalyzed dechlorination (BCD)

The base catalyzed dechlorination (BCD) process was developed by the USEPA to remediate soils and sediments contaminated with chlorinated organic compounds, especially PCBs, dioxins, and furans. The original BCD process involved the addition of sodium bicarbonate to the contaminated medium, which was then heated to 330 °C in a reactor to partially decompose and volatilize the contaminants; which then require separate treatment.¹⁷⁷

Further development of the BCD process, incorporated an alkaline polyethylene glycol (APEG) reagent (e.g., potassium polyethylene glycol) as the base. The APEG reagent dehalogenates the contaminant to form a glycol ether and/or a hydroxylated compound and an alkali metal salt. Destruction efficiencies are described as “*not as high*” as some other technologies.¹⁷⁸

The BCD/APEG process was successfully demonstrated at the Wide Beach Superfund site in 1991, where approximately 42,000 tons of stockpiled soil contaminated with PCBs, mainly Arochlor 1254, at concentrations ranging from 10 to 5,000 mg/kg, were treated. Gaseous emissions, which are very small compared with combustion systems,¹⁷⁹ were treated with cyclone,

baghouse, acid gas scrubber, and activated carbon adsorption. Table 8 shows dioxin and furan stack gas emissions measured during the SITE Demonstration.¹⁸⁰ No data were presented to describe the concentrations in stack gases of other POPs potentially formed during the process or the concentrations of such substances in other process residues.

ADI Services, a BCD licensee in Australia, has developed a variation of the BCD reaction (called the 'ADOX' reaction) in which an 'accelerator' replaces the patented BCD catalyst. In the ADOX reaction the nature of the reaction changes dramatically in that organochlorines are decomposed completely to carbon. The reaction, which takes place rapidly, can be applied to much higher concentrations of organochlorines than the conventional BCD process and without the requirement for the addition of oil.¹⁸¹ No data were presented identifying and chemically characterizing all residues from this process. I.e., the concentrations in all residues of undestroyed chemicals and dioxins and other POPs potentially formed during this process were not revealed.

Table 8: Base Catalyzed Dechlorination – Dioxins in Stack Gases¹⁸²

Dioxins and Furans	Stack Gas, ng/dscm*
Tetrachlorinated dibenzo-p-dioxins (TCDD)	0.14
Tetrachlorinated dibenzofurans (TCDF)	4.8
Pentachlorinated dibenzo-p-dioxins (PeCDD)	0.96
Pentachlorinated dibenzofurans (PeCDF)	0.72
Hexachlorinated dibenzo-p-dioxins (HxCDD)	0.17
Hexachlorinated dibenzofurans (HxCDF)	0.077
Heptachlorinated dibenzo-p-dioxins (HpCDD)	0.25
Heptachlorinated dibenzofurans (HpCDF)	0.032
Octachlorinated dibenzo-p-dioxins (OCDD)	2.34
Octachlorinated dibenzofurans (OCDF)	0.032
Total Dioxins and Furans	9.52
Total TEQs	0.707

* dscm = dry standard cubic meter

The New Zealand Ministry of the Environment has noted as follows:¹⁸³

“The ADI thermal desorption process produces a variable amount of dust (usually less than 5% of the original soil feed) and condensates, both containing dioxins. While these are captured and contained within the system, they must be able to be safely decomposed for the total process to be considered effective.”

In the recent trials in New Zealand, the solid residues were fed back into the system. This resulted in a reduction of the dioxin levels from an initial level of 1280 ppb TEQ to a value below 0.1 ppb TEQ.

While generally considered to be a relatively low risk technology, a BCD plant in Melbourne, Australia was rendered inoperable following a fire in 1995, as described below:¹⁸⁴

“The fire damaged the treatment system and building. It is understood that the fire resulted from a combination of factors. The nitrogen blanket was in place over the reactor, however, on discharge of hot oil into a storage vessel without an adequate nitrogen blanket, the fire occurred in the storage vessel. The auto ignition point of the hot oil was lower than expected and was exceeded.”

The plant has been rebuilt and is operating on a commercial basis, focusing on PCB contaminated oils, transformers and capacitors, following approval by the regional environmental agency.

As the BCD process essentially involves stripping chlorine from the waste compound, the treatment process may result in an increased concentration of lower chlorinated species (e.g., higher congeners are replaced by lower congeners).¹⁸⁵ This is of potential concern in the treatment of dioxins and furans, where the lower congeners are significantly more toxic than the higher congeners. It is therefore essential that the process be appropriately monitored to ensure that the reaction continues to completion.

For contaminated soils, costs are said to range from \$250 to \$400 per tonne, in Australian dollars. Costs for PCB contaminated oils are around \$1000 per tonne.¹⁸⁶

References

- ¹ Bracewell, J., Hepburn, A., and Thomson, C., **1993**. Levels and distribution of polychlorinated biphenyls on the Scottish land mass. *Chemosphere* 27:1657-1667.
- ² Johnston, P., and Stringer, R., **1994**. Environmental Significance and Regulation of Organochlorines. Exeter, U.K.: Greenpeace International, 5 September 1994.
- ³ United Nations Food and Agriculture Organization, **1998**. Press Release, "Agro-chemical industry to pay some of clean-up costs for obsolete pesticides in developing countries," March 11, 1998.
- ⁴ United Nations Environment Programme, **1992**. *Ad-Hoc* Technical Advisory Committee on ODS Destruction Technologies. Geneva; United Nations Environment Programme, May 1992.
- ⁵ United Nations Environment Programme, **1992**.
- ⁶ Watanabe, S., Laovokul, W., Boonyathumanondh, R., Tabucanon, M., and Ohgaki, S., **1996**. Concentrations and composition of PCB congeners in the air around stored used capacitors containing PCB insulator oil in a suburb of Bangkok, Thailand. *Environ. Pollution* 92:289-297.
- ⁷ Halsall, C., Burnett, V., Davis, B., Jones, P., Pettit, C., and Jones, K., **1993**. PCBs and PAHs in UK urban air. *Chemosphere* 26:2185-2197.
- ⁸ Halsall, C., Stern, G., Bailey, R., Barrie, L., Muir, D., Fellin, P., Rosenberg, B., and Grift, N. **1997**. Polychlorinated biphenyls (PCBs) and organochlorine pesticides (OCs) in the Arctic atmosphere. *Organohalogen Cpd.* 33:225-229.
- ⁹ Watanabe et al., **1996**.
- ¹⁰ Clearstone Engineering, Lt., **1995**. An Assessment of Fugitive PCB Emissions. Prepared for: Alberta Special Waste Management System. Alberta, Canada, June 9, 1995.
- ¹¹ Diependaal, M., Klein, A., Oude Boerrigter, P., van der Meij, J., and de Walle, F., **1993**. Long-term effectiveness of isolation techniques for contaminated soils. *Waste Management & Research* 11:481-492.
- ¹² Lee, G., and Jones-Lee, A., **1994**. A groundwater strategy for lined landfills. *Environ. Sci. Technol.* 28:584A-585A.
- ¹³ Bracewell, J., Hepburn, A., and Thomson, C., **1993**. Levels and distribution of polychlorinated biphenyls on the Scottish land mass. *Chemosphere* 27:1657-1667.
- ¹⁴ Gould, J., Cross, W., and Pohland, F., **1990**. Factors Influencing Mobility of Toxic Metals in Landfills Operated with Leachate Recycle. *Emerging Technologies in Hazardous Waste Management*, D.W. Tedder and E.G. Pohland (eds.), Washington, DC: American Chemical Society.
- ¹⁵ Chiarenzelli, J., Scudato, R., Bush, B., Carpenter, D., and Bushart, S. **1998**. Do large-scale remedial and dredging events have the potential to release significant amounts of semivolatile compounds to the atmosphere? *Environ. Health Persp.* 106: 47-49.
- ¹⁶ Sheppard, M., Sheppard, S., and Amiro, B. **1991**. Mobility and plant uptake of inorganic ¹⁴C and ¹⁴C-labelled PCB in soils of high and low retention. *Health Phys.* 61: 481-492.
- ¹⁷ United Nations Food and Agriculture Organization, **1996**. Disposal of Bulk Quantities of Obsolete Pesticides in Developing Countries. **Error! Reference source not found.**
- ¹⁸ United Nations Food and Agriculture Organization, **1996**.
- ¹⁹ Stryker, A., and Collins, A., **1987**. State of the Art Report: Injection of Hazardous Wastes into Deep Wells. EPA 600/8-87/013, Washington, DC: U.S. Environmental Protection Agency.
- ²⁰ U.S. Environmental Protection Agency, Office of Drinking Water, **1985**. Report to Congress on Injection of Hazardous Waste. Washington, DC: U.S. Environmental Protection Agency.
- ²¹ U.S. General Accounting Office, **1987**. Hazardous Waste: Controls Over Injection Well Disposal Operations. GAO/RCED-87-170, Washington, DC: U.S. General Accounting Office.

-
- ²² Gordon, W., and Bloom, J., **1985**. Deeper Problems: Limits to Underground Injection as a Hazardous Waste Disposal Method. Washington, DC: Natural Resources Defense Council.
- ²³ Monastersky, R., **1989**. Waste wells implicated in Ohio quake. *Science News* 134:
- ²⁴ Brower, R., and Visocky, A., **1989**. Evaluation of Underground Injection of Industrial Waste in Illinois. ENR AD-94 and UI-8501, Department of Natural Resources and Illinois State Geological Survey, Illinois Scientific Surveys Joint Report 2, Champaign, Illinois.
- ²⁵ Stowe, R., **1997**. The Use of Hazardous Waste as an Alternative Fuel in Cement Kilns – A Working Document. Copenhagen, Denmark: Danish Environmental Protection Agency, February 1997.
- ²⁶ United Nations Food and Agriculture Organization, **1996**.
- ²⁷ United Nations Food and Agriculture Organization, **1996**.
- ²⁸ United Nations Environmental Programme, **1997**. International Action to Protect Human Health and the Environment Through Measures Which Will Reduce and/or Eliminate Emissions and Discharges of Persistent Organic Pollutants, Including the Development of an International, Legally-Binding Instrument. Decision Taken By Nineteenth Session of the UNEP Governing Council, Nairobi, 7 February, 1997, Geneva: United National Environmental Programme, February 1997.
- ²⁹ Intergovernmental Forum on Chemical Safety, **1996**. IFCS Ad Hoc Working Group on Persistent Organic Pollutants Meeting: Final Report. Geneva: IFCS Secretariat, c/o World Health Organization, 21-22 June 1996.
- ³⁰ Hagh, B., and Allen, D. **1990**. Catalytic Hydrodechlorination. In Freeman, H. (ed), Innovative Hazardous Waste Treatment Technology Series: Physical/Chemical Processes, Vol. 2, Lancaster, Pennsylvania: Technomic Publishing Company.
- ³¹ United Nations Food and Agriculture Organization, **1996**.
- ³² National Research Council. **1991**. Review of Monitoring Activities within the Chemical Demilitarization Program. Committee on Review and Evaluation of the Army Chemical Stockpile Disposal Program. Washington, DC: National Academy Press.
- ³³ van Hasselt, H., and Costerus, A. **1998**. Developments and operating experience in oilcleaning: Thermal treatment of soils contaminated with lindane, and solvent extraction of soil contaminated with lindane. Presented at the Fifth HCH and Pesticides Forum, Bilbao, Basque Country, 25-27 June 1998.
- ³⁴ Environment Australia, **1997**. Appropriate Technologies for the Treatment of Scheduled Wastes, Review Report Number 4 – November 1997. Canberra, Australia.
- ³⁵ Costner, P., 1998. Correlation of chlorine input and PCDD/PCDF emissions at a full-scale hazardous waste incinerator. *Organohalogen Cpd.* 36: 147-151.
- ³⁶ United Nations Environment Programme, **1992**. *Ad-Hoc* Technical Advisory Committee on ODS Destruction Technologies. Geneva, May 1992.
- ³⁷ OHM Remediation Service, **1995**. Trial Burn Report for the Baird & McGuire Superfund Site, Holbrook, Massachusetts. Contract No. DACW45-92-C-0047. Holbrook, MA: OHM Remediation Services. March 10, 1995.
- ³⁸ OHM Remediation Service, **1995**.
- ³⁹ Midwest Research Institute, **1997a**. Test Report for Trial Burns No. 1 and No. 2 on the Drake Chemical Superfund Site's Mobile On-Site Hazardous Waste Incinerator, Volume 1 – Technical Report. For OHM Remediation Services Corp., MRI Project No. 3620-13/23, Kansas City, Missouri, September 12, 1997.
- ⁴⁰ Midwest Research Institute, **1997b**. Test Report for Trial Burn No. 1 and No. 2 on the Drake Chemical Superfund Site's Mobile On-Site Hazardous Waste Incinerator, Volume 2 – Appendices A through B. For OHM Remediation Services Corp., MRI Project No. 3620-13/23, Kansas City, Missouri, September 12, 1997.

-
- ⁴¹ Midwest Research Institute, **1997b**.
- ⁴² Midwest Research Institute, **1997a&b**.
- ⁴³ U.S. Environmental Protection Agency, Region VI, **1996**. Engineering Evaluation/Cost Analysis Addendum, Vertac Superfund Site, Jacksonville, Arkansas. Dallas, Texas: U.S. Environmental Protection Agency, March 1996.
- ⁴⁴ Menke, J., Carlson, H., Flinn, M., Macrae, S., Medville, D., and Tripler, D., **1991**. Evaluation of the GB Rocket Campaign: Johnston Atoll Chemical Agent Disposal System Operational Verification Testing. MTR-91W00030, McLean, Virginia: MITRE Corporation, June 1991.
- ⁴⁵ Macrae, S., Carlson, H., Hermes, M., Scherer, L., Tripler, D., and Wassmann, R., **1992**. Evaluation of the VX Rocket Test: Johnston Atoll Chemical Agent Disposal System Operational Verification Testing. McLean, Virginia: MITRE Corporation, November 1992.
- ⁴⁶ Fiedler, H., **1993**. Sources of Dioxins and Furans. *Conference Reports, Dioxin '93*, Vienna, Austria, 1993.
- ⁴⁷ Dellinger, B., Taylor, P., Tiery, D., Pan, J., and Lee, C., **1988**. Pathways of PIC Formation in Hazardous Waste Incinerators. *Land Disposal, Remedial Action, Incineration and Treatment of Hazardous Waste: Proceedings of the Fourteenth Annual Research Symposium*, EPA 600/9-88/021, Washington, DC: U.S. Environmental Protection Agency, July 1988.
- ⁴⁸ DeVito, M., Birnbaum, L., Farland, W., and Gasiewicz, T., **1995**. Comparisons of estimated human body burdens of dioxinlike chemicals and TCDD body burdens in experimentally exposed animals. *Environ. Health Persp.* 103:820-831.
- ⁴⁹ U.S. Environmental Protection Agency, **1998**. The Inventory of Sources of Dioxin in the United States. Review Draft. EPA/600/P-98/002Aa, Washington, DC, April 1998.
- ⁵⁰ Kanters, M., Van Nispen, R., Louw, R., and Mulder, P., **1996**. Chlorine input and chlorophenol emission in the lab-scale combustion of municipal solid waste. *Environ.Sci.Technol.* 30:2121-2126.
- ⁵¹ Wikstrom, E., Lofvenius, G., Rappe, C., and Marklund, S., **1996**. Influence of level and form of chlorine on the formation of chlorinated dioxins, dibenzofurans, and benzenes during combustion of an artificial fuel in a laboratory reactor. *Environ. Sci. Technol.* 30:1637-1644.
- ⁵² Halonen, I., Tarhanen, J., Ruikojarvi, P., Tuppurainen, K., and Ruuskanen, J., **1995**. Effect of catalysts and chlorine source on the formation of organic chlorinated compounds. *Chemosphere* 30:1261-1273.
- ⁵³ Burns, D., **1993**. Final Report Consolidated Incineration Facility Metals Partitioning Test (U). WSRC-TR-93-623, Savannah River Technology Center, Aiken, SC, August 31, 1993
- ⁵⁴ Halonen, I., Tarhanen, J., Oksanen, J., Vilokki, H., Vartiainen, T., and Ruuskanen, J., **1993**. Formation of organic chlorinated compounds in incineration of pulp and paper mill biosludges. *Chemosphere* 27:1253-1268.
- ⁵⁵ Halonen, I., Tarhanen, J., Kopsa, T., Palonen, J., Vilokki, H., and Ruuskanen, J., **1993**. Formation of polychlorinated dioxins and dibenzofurans in incineration of refuse derived fuel and biosludge. *Chemosphere* 26:1869-1880.
- ⁵⁶ Wagner, J., and Green, A., **1993**. Correlation of chlorinated organic compound emissions from incineration with chlorinated organic input. *Chemosphere* 26: 2039-2054.
- ⁵⁷ Fangmark, I., van Bavel, B., Marklund, S., Stromberg, B., Berge, N., and Rappe, C., **1993**. Influence of combustion parameters on the formation of polychlorinated dibenzo-p-dioxins, dibenzofurans, benzenes, and biphenyls and polyaromatic hydrocarbons in a pilot incinerator. *Environ. Sci. Technol.* 27: 1602-1610.
- ⁵⁸ Manninen, H., Perkio, A., Vartiainen, T., and Ruuskanen, J., **1996**. Formation of PCDD/PCDF: Effect of fuel and fly ash composition on the formation of PCDD/PCDF in the co-combustion of refuse-derived and packaging-derived fuels. *Environ. Sci. & Pollut. Res.* 3:129-134.

-
- ⁵⁹ Huotari, J., and Vesterinen, R. **1996**. PCDD/F emissions from co-combustion of RDF with peat, wood waste, and coal in FBC boilers. *Haz. Waste & Haz. Materials* 13:1-9.
- ⁶⁰ Vesterinen, R., and Flyktman, M., **1996**. Organic emissions from co-combustion of RDF with wood chips and milled peat in a bubbling fluidized bed boiler. *Chemosphere* 32: 681-689..
- ⁶¹ Moller, S., Larsen, J., Jernes, J., Faergemann, H., Ottosen, L., and Knudsen, F., **1995**. Environmental Aspects of PVC. Environmental Project No. 313. Denmark: Ministry of the Environment, Danish Environmental Protection Agency, 1995.
- ⁶² Thomas, V., and Spiro, T., **1995**. An estimation of dioxin emissions in the United States. *Toxicol. Environ. Chemistry* 50: 1-37.
- ⁶³ Takeshita, R., Akimoto, Y., and Nito, S., **1992**. Relationship between the formation of polychlorinated dibenzo-p-dioxins and dibenzofurans and the control of combustion, hydrogen chloride level in the flue gas and gas temperature in a municipal waste incinerator. *Chemosphere* 24:589-598.
- ⁶⁴ Kopponen, P., Torronen, R., Ruuskanen, J., Tarhanen, J., Vartiainen, T., and Karenlampi, S., **1992**. Comparison of cytochrome P450IA1 induction with the chemical composition of fly ash from combustion of chlorine containing material. *Chemosphere* 24:391-401.
- ⁶⁵ WTI, **1993**. REDACTED VERSION, Performance Testing Results for the Enhanced Carbon Injection System, August 30, 1993, under cover letter from Heidi J. Dugan for D.M. Rushin, Environmental Manager, WTI, to Valdas Adamkus, Regional Administrator, USEPA Region 5: "Re: Waste Technologies Industries, EPA ID OHD 980 613 541, Preliminary Testing Results and Certification," August 30, 1993.
- ⁶⁶ World Health Organization, **1998**. WHO experts re-evaluate health risks from dioxin. WHO Press Release, 3 June 1998.
- ⁶⁷ Muto, H., Saito, K., Shinada, M., Takizawa, Y. **1991**. Concentrations of polychlorinated dibenzo-p-dioxins and dibenzofurans from chemical manufacturers and waste disposal facilities. *Environ. Research* 54: 170-182.
- ⁶⁸ Ohta, S., Kuriyama, S., Nakao, T., Aozasa, O., Miyata, H., Tanahashi, M. **1997**. Levels of PCDDs, PCDFs and non-ortho coplanar PCBs in soil collected from high cancer causing area close to batch-type municipal solid waste incinerator in Japan. *Organohalogen Cpd.* 32: 155-160.
- ⁶⁹ Knebusch, R., **1994**. Dioxins, Furans, Biphenyls and Other Chlororganic Compounds in the Breastmilk Downwind of Incinerators: A Comparative Study in Kehl/Strasbourg. Kehl, Germany, 12 October 1994.
- ⁷⁰ U.S. Department of Health and Human Services, Agency for Toxic Substances and Disease Registry, and Arkansas Department of Health, **1995**. Exposure to Dioxin-like Compounds Among Residents Near the Vertac/Hercules Superfund Site, Jacksonville, Arkansas. Interim Report, Little Rock, Arkansas, March 1995.
- ⁷¹ Arkansas Department of Health, **1995**. Interim Report on ADH/ATSDR Studies Related to Vertac/Hercules Superfund Site, Jacksonville, Arkansas. Draft for Public Comment, Little Rock, Arkansas, June 1995.
- ⁷² Costner, P., **1995**. The Incineration of Dioxin-Contaminated Wastes in Jacksonville, Arkansas: A Review of the Inhalation Exposure Assessment. Washington, DC: Greenpeace International, 7 August 1995.
- ⁷³ Gonzalez, C., Bleda, J., Kogevinas, M., Ladona, M., Gadea, E., Huici, Al., Solans, X., and Bosch, A., **1998**. Monitoritzacio Biologica dels Residents de Mataro Que Viuen Prop de la Incineradora de Residus Solids Urbans del Maresme. PASS Institut de Recerca, Epidemiologica I Clinica, IREC: Mataro, Spain, February 1998.
- ⁷⁴ Alberta Health, **1996**. News Release: Wild Game Public Health Advisory, Edmonton, Alberta, December 13, 1996.

-
- ⁷⁵ Foxall, C., Lovett, A., Creaser, C., and Ball, J. **1997**. Environmental levels of PCDD/Fs and PCBs in Panteg District of South Wales, UK and their implications for human exposure. *Organohalogen Compounds* 31:342-347.
- ⁷⁶ Wodagenah, A., **undated**. The FAO Project for prevention and disposal of obsolete pesticide stocks in Africa and the Near East. <http://193.43.36.7/waicent/FaolInfo/Agricult/AGP/AGPP/Pesticid/Disposal/guides.htm>
- ⁷⁷ Huang, H., and Beukens, A., **1995**. On the mechanisms of dioxin formation in combustion processes. *Chemosphere* 31(9): 409-417.
- ⁷⁸ Acharya, P., DeCicco, S., and Novak, R., **1991**. Factors that can influence and control the emissions of dioxins and furans from hazardous waste incinerators. *J. Air Waste Manage. Assoc.* 41:1605-1615.
- ⁷⁹ Hiraoka, M., Tanaka, M., Matsuzawa, Y., Miyaji, K., Kawanishi, T., Matumoto, S., Horii, Y., and Ihara, H., **1993**. Concentrations of PCDD/PCDF in leachates from disposal sites and their removal characteristics during leachate treatment. *Organohalogen Compounds* 11:409-412.
- ⁸⁰ U.S. Environmental Protection Agency, **1998**. The Inventory of Sources of Dioxin in the United States. EPA/600/P-98/002Aa. Washington, DC, April 1998.
- ⁸¹ Richardson, M., **1995**. Recycling or Disposal? Hazardous Waste Combustion in Cement Kilns: A Briefing Paper of the American Lung Association Hazardous Waste Incineration Project. Washington, DC: American Lung Association.
- ⁸² U.S. Environmental Protection Agency, **1993**. Report to Congress on Cement Kiln Dust, Vol. II: Methods and Findings. Washington, DC, December 1993.
- ⁸³ Abou-Taleb, A., Musaiger, A., and Abdelmoneim, R., **1995**. Health status of cement workers in the United Arab Emirates. *J. R. Soc. Health* 115:378-381.
- ⁸⁴ Yang C., Huang, C., Chiu, H., Chiu, J., Lan, S., and Ko, Y., **1996**. Effects of occupational dust exposure on the respiratory health of Portland cement workers. *J. Toxicol. Environ. Health* 49:581-588.
- ⁸⁵ U.S. Environmental Protection Agency, **1995**. Regulatory Determination on Cement Kiln Dust. 40 CFR Part 261, Federal Register: February 7, 1995.
- ⁸⁶ United Nations Food and Agriculture Organization, **undated**. The Problem of Obsolete Pesticides. <http://www.fao.org/ag/agp/agpp/pesticid/disposal/v7460e/02.htm>
- ⁸⁷ U.S. Environmental Protection Agency, **1998**.
- ⁸⁸ Mournighan, R. and Branscome, M., **1987**. Hazardous Waste Combustion in Industrial Processes: Cement and Lime Kilns. EPA-68-03-3149. Washington, DC: U.S. Environmental Protection Agency.
- ⁸⁹ California Integrated Waste Management Board, **1992**. Tires as a Fuel Supplement: Feasibility Study: Report to the Legislature. Sacramento, California, USA, January 1992.
- ⁹⁰ World Health Organization, **1998**.
- ⁹¹ U.S. Environmental Protection Agency, **1998**.
- ⁹² Rigo, H., Chandler, A., and Lanier, W., **1995**. The Relationship Between Chlorine in Waste Streams and Dioxin Emissions from Waste Combustor Stacks. CRTD-Vol 36. New York, NY: American Society of Mechanical Engineers.
- ⁹³ U.S. Environmental Protection Agency, **1998**.
- ⁹⁴ U.S. Environmental Protection Agency, **1995**. Regulatory Determination on Cement Kiln Dust. 40 CFR Part 261, Federal Register: February 7, 1995.
- ⁹⁵ U.S. Environmental Protection Agency, **1995**.

-
- ⁹⁶ U.S. Environmental Protection Agency, **1993**. Report to Congress on Cement Kiln Dust, Vol. II: Methods and Findings. Washington, DC, December 1993.
- ⁹⁷ Murphy, B., and Mix, T., **1984**. Risks associated with waste-fuel use in cement kilns. *Environmental Progress* 3:64-70
- ⁹⁸ Pope, C., **1989**. Respiratory disease associated with community air pollution and a steel mill, Utah Valley. *Am. J. Public Health* 79: 623-628;
- ⁹⁹ Richardson, M., **1995**. Recycling or Disposal? Hazardous Waste Combustion in Cement Kilns: A Briefing Paper of the American Lung Association Hazardous Waste Incineration Project. Washington, DC: American Lung Association, April, 1995.
- ¹⁰⁰ U.S. Environmental Protection Agency, **1992**. Cement Kiln Dust Report to Congress: Briefing for Sylvia Lowrance, Office Director, OSWER. Washington, DC
- ¹⁰¹ Mournighan, R. and Branscome, M., **1987**. Hazardous Waste Combustion in Industrial Processes: Cement and Lime Kilns. EPA-68-03-3149. Washington, DC: U.S. Environmental Protection Agency.
- ¹⁰² Mournighan, R., and Branscome, M., **1987**.
- ¹⁰³ Murphy, B., and Mix, T., **1984**. Risks associated with waste-fuel use in cement kilns. *Environmental Progress* 3:64-70.
- ¹⁰⁴ California Air Resources Board, **1987**. Evaluation of Combustion Process for Destruction of Organic Wastes -- General Portland. ARB/SS-87-02 (10- 15-87), Sacramento, California.
- ¹⁰⁵ Systech Environmental Corporation, **1990**. Non-point air emissions estimates for 1987 from National Cement Company, Lebec, CA. Toxics Release Inventory (on-line database). Bethesda, MD: National Library of Medicine.
- ¹⁰⁶ Beers, A., **1987**. Hazardous Waste Incineration: The Cement Kiln Option. Prepared for the Legislative Commission on Toxic Substances and Hazardous Wastes, State of New York, Albany, NY.
- ¹⁰⁷ Picardi, A., Johnston, P., and Stringer, R., **1991**. Alternative Technologies for the Detoxification of Chemical Weapons: An Information Document. Washington, D.C.: Greenpeace International.
- ¹⁰⁸ U.S. Congress, **1997**. National Defense Appropriations Act for Fiscal Year 1997 Public Law 104-208. Washington, D.C.
- ¹⁰⁹ Environment Australia, **1997**. Appropriate Technologies for the Treatment of Scheduled Wastes, Review Report Number 4 – November 1997. Canberra, Australia.
- ¹¹⁰ Australian and New Zealand Environment and Conservation Council, **1993**. Approval/Licensing of Commercial-Scale Facilities for the Treatment/Disposal of Schedule X Wastes. Canberra, Australia.
- ¹¹¹ United Nations Food and Agriculture Organization, **1996**. Disposal of Bulk Quantities of Obsolete Pesticides in Developing Countries. **Error! Reference source not found.**
- ¹¹² U.S. Army, **1996**. U.S. Army Chemical Demilitarization and Remediation Activity -- Delivery Order Number 136, Combined Third and Fourth Quarterly Report. Washington, D.C., 9 February 1996.
- ¹¹³ Schwinkendorf, W., McFee, J., Devarakonda, M., Nenninger, L., Fadullon, F., Donaldson, T., and Dickerson, K., **1995**. Alternatives to Incineration: Technical Area Status Report. Prepared for the Mixed Waste Integrated Program, U.S. Department of Energy, Office of Technology Development, Washington, D.C., April 1995.
- ¹¹⁴ Schwinkendorf et al., **1995**.
- ¹¹⁵ Environment Australia, **1997**.
- ¹¹⁶ Schwinkendorf et al., **1995**.

-
- ¹¹⁷ Kummling, K., Festarini, L., Woodland, S., Kornelsen, P., and Hallett, D., **1997**. An evaluation of levels of chlorinated aromatic compounds in ECO LOGIC process stack outputs. *Organohalogen Cpd.* 32: 66-71.
- ¹¹⁸ ELO Eco Logic International, Inc., **1996**. PCB Treatment Using the ECO LOGIC Process at General Electric Canada, Inc., Davenport Facility, Volume A: Application for Technology Approval, and Volume B: Application for Siting Approval. Toronto, Canada, 5 February 1996.
- ¹¹⁹ Business Wire, Inc., **1996**. ELI Eco Logic, Inc. Announces Commercial PCB Waste Destruction. Toronto, Canada, 9 February 1996.
- ¹²⁰ Environment Australia, **1997**.
- ¹²¹ ELI Eco Logic, International, Inc., **1995**. Permit Application: PCB Treatment Using the ECO LOGIC Process at General Electric Canada, Inc., Davenport Facility. Toronto, Canada, 15 December 1995.
- ¹²² Kummling, K., ECOLOGIC, Rockwood, Ontario, Private Communication, October 6, **1998**.
- ¹²³ Kummling, K., Kornelsen, P., Woodland, S., Festarini, L., Campbell, K., and Hallett, D., **1997**. Characterization and source of chlorinated aromatic compounds in ECO LOGIC process stack outputs. *Organohalogen Cpd.* 32: 457-462.
- ¹²⁴ ELI Eco Logic International, Inc., **1996**.
- ¹²⁵ Environment Australia, **1997**.
- ¹²⁶ Schwinkendorf et al., **1995**.
- ¹²⁷ Schwinkendorf et al., **1995**.
- ¹²⁸ Australia Environment Protection Agency, **1995**. Appropriate Technologies for the Treatment of Scheduled Wastes, Review Report Number 2, Canberra, Australia, November 1995.
- ¹²⁹ Environment Australia, **1997**.
- ¹³⁰ Batey, W., Jarvies, I., Soilleux, R., and Warren, N., **1995**. The Application of the Dounreay Electrochemical Silver (II) Process to the Demilitarisation of Chemical Munitions. *Proceedings of the Workshop on Advances in Alternative Demilitarization Technologies*, Reston, Virginia, 25-27 September 1995.
- ¹³¹ Schwinkendorf et al. **1995**.
- ¹³² Schwinkendorf et al., **1995**.
- ¹³³ Schwinkendorf et al., **1995**.
- ¹³⁴ Mather, R., Steckler, D., Kimmel, S., and Tanner, A., **1995**. Integrated Recycling of Industrial Waste Using Catalytic Extraction Processing at a Chemical Manufacturing Site. Presented at the Spring National Meeting of the American Institute of Chemical Engineers, Houston, Texas, March 23, 1995.
- ¹³⁵ Chanenchuk, C., Protopapas, A., and Alexopoulos, G., **1994**. Catalytic extraction process application to chlorinated waste streams. Presented at the I&EC Special Symposium, American Chemical Society, Atlanta, Georgia, September 19-21, 1994.
- ¹³⁶ Chanenchuk et al., **1994**.
- ¹³⁷ Chanenchuk et al., **1994**.
- ¹³⁸ National Research Council, **1993**. Alternative Technologies for the Destruction of Chemical Agents and Munitions. Washington, D.C.: National Academy of Sciences.
- ¹³⁹ Schwinkendorf et al., **1995**.
- ¹⁴⁰ Molten Metal Technology, **1996**. News release: "EPA Grants Molten Metal Technology Best Demonstrated Available Technology Status for All Wastes Previously Requiring Incineration," Waltham, Massachusetts, March 12, 1996.
- ¹⁴¹ Schwinkendorf et al., **1995**.

-
- ¹⁴² National Research Council, **1993**.
- ¹⁴³ Environment Australia, **1997**.
- ¹⁴⁴ Environment Australia, **1997**.
- ¹⁴⁵ National Research Council, **1993**.
- ¹⁴⁶ Environment Australia, **1997**.
- ¹⁴⁷ U.S. Environmental Protection Agency, **1997**. Vendor Information System for Innovative Treatment Technologies (VISITT 6.0). Washington, DC.
- ¹⁴⁸ Environment Australia, **1997**.
- ¹⁴⁹ Environment Australia, **1997**.
- ¹⁵⁰ U.S. Environmental Protection Agency, **1997**.
- ¹⁵¹ Environment Australia, **1997**.
- ¹⁵² Environment Australia, **1997**.
- ¹⁵³ Environment Australia, **1997**.
- ¹⁵⁴ Environment Australia, **1997**.
- ¹⁵⁵ Thomason T.B., Hong, G.T., Swallow, K.C. & Modell, M., **1990**. The MODAR supercritical oxidation process." In: Freeman, H.M.(ed). Innovative Hazardous Waste Treatment Technology Series. Volume 1: Thermal Processes. Technomic Publishing Inc.
- ¹⁵⁶ National Research Council, **1993**.
- ¹⁵⁷ US Congress, **1991**, cited in Environment Australia, 1997.
- ¹⁵⁸ Environment Australia, **1997**.
- ¹⁵⁹ Environment Australia, **1997**.
- ¹⁶⁰ Environment Australia, **1997**.
- ¹⁶¹ Environment Australia, **1997**.
- ¹⁶² National Research Council, **1993**.
- ¹⁶³ Environment Australia, **1997**.
- ¹⁶⁴ Environment Australia, **1997**.
- ¹⁶⁵ Environment Australia, **1997**.
- ¹⁶⁶ Environment Australia, **1997**.
- ¹⁶⁷ Environment Australia, **1997**.
- ¹⁶⁸ Environment Australia, **1997**.
- ¹⁶⁹ Environment Australia, **1997**.
- ¹⁷⁰ Environment Australia, **1997**.
- ¹⁷¹ Musoke, G., Roberts D., and Cooke, M. 1982. *Bull. Environ. Contam. Toxicol*, 28: 467
- ¹⁷² Duffy, G., and Fookes, C., **1997**. Development of a catalytic process for the regeneration of transformer oils and the destruction of chlorinated hydrocarbons. Presented at the I&EC Special Symposium, American Chemical Society, Pittsburgh, Pennsylvania, September 15-17, 1997.
- ¹⁷³ Duffy, G., and Fookes, C., **1997**.
- ¹⁷⁴ Duffy, G., and Fookes, C., **1997**.
- ¹⁷⁵ Environment Australia, **1997**.
- ¹⁷⁶ National Research Council, **1993**.
- ¹⁷⁷ U.S. Army Environmental Center, **1997**. Remediation Technologies Screening Matrix and Reference Guide, 3rd Edition, Report No. SFIM-AEC-ET-CR-97053, October 1997.

¹⁷⁸ Environment Australia, **1997**.

¹⁷⁹ Environment Australia, **1997**.

¹⁸⁰ U.S. EPA Risk Reduction Engineers Laboratory, **1993**. Draft Applications Analysis Report for the SoilTech Anaerobic Thermal Processor at the Wide Beach Development and Waukegan Harbor Superfund Sites, Cincinnati, Ohio, May 1993.

¹⁸¹ New Zealand Ministry for the Environment, **1997**. Organochlorines Programme Bulletin No. 5, July 1997

¹⁸² U.S. EPA Risk Reduction Engineers Laboratory, **1993**.

¹⁸³ New Zealand Ministry for the Environment, **1997**.

¹⁸⁴ Environment Australia, **1997**.

¹⁸⁵ Environment Australia, **1997**.

¹⁸⁶ Environment Australia, **1997**.