Chapter 5
Technology and Cost Summary

The foregoing analysis by the Office of Technology Assessment (OTA) has covered two fundamental categories of dioxin treatment technologies-thermal and nonthermal. In addition to these, however, OTA has also considered other approaches such as stabilization or storage (where the technique is aimed at preventing migration rather than destroying the contaminants) and technologies that combine two or more techniques. The following summarizes the overall conclusions concerning each technology, based on OTA's technical analyses.

THERMAL TREATMENT TECHNOLOGIES

Several incineration techniques have been developed in the last decade for treating dioxin-contaminated soil and debris. They include rotary kiln incineration, liquid injection incineration, fluidized bed/circulating fluidized bed, high-temperature fluid wall destruction (advanced electric reactor), infrared destruction, plasma arc pyrolysis, supercritical water oxidation, and in situ vitrification.[1] Of these, only rotary kiln incineration has been fully demonstrated, is commercially available, and is permitted for cleaning up dioxin in soil such as that found at Times Beach, Missouri. This technology has the ability to treat containerized and noncontainerized solid and liquid wastes, individually or simultaneously. It has been used in at least three successful dioxin cleanup projects and appears to be able to perform in other situations (e.g., Times Beach) within current regulatory requirements.

Rotary kiln incinerators are divided into two types based on their specific design features: 1) land based (or stationary) and 2) mobile (or transportable). In addition to the obvious difference between the two types, mobile incinerators have been specifically designed with features to meet special requirements for dioxin treatment, whereas the stationary incinerators have not.

Commercially available mobile incineration facilities have participated in cleanup of various dioxin-contaminated sites. One firm offers three mobile incineration units capable of treating dioxin-contaminated soil at a maximum estimated rate of 5 tons per hour[2] with setup times of 24 hours and decontamination/demobilization times of about 72 hours. These systems have been successfully employed to treat dioxin contamination at the American Cross Arms Site (Chehalis, Washington); Fort A.P. Hill (Bowling Green, Virginia); Rocky Boy Post & Pole Site (Rocky Boy, Montana); and Black Feet Post & Pole Site (Browning, Montana). Another firm also has three mobile incinerators, two of which are operating on related cleanup work.

Today, there are four land-based rotary kiln incinerator units operating in the United States with the potential to treat dioxin-contaminated materials. Thus far, however, they have been permitted to treat only polychlorinated biphenyls (PCBs) under the authority of the Toxic Substances Control Act (TSCA). None of these facilities has treated dioxins because of the lack of appropriate operating permits under the Resource Conservation and Recovery Act (RCRA).

In addition to the above developed or operating technologies for thermal treatment of dioxins, several other options are in various stages of development. None of these, however, are available commercially as full-scale, tested systems.

Liquid incineration (LI) technology is employed in many industrial and manufacturing sectors for treatment of hazardous organic and inorganic waste. Regardless of their design (vertical LI units are preferred for treating waste that generates extensive ash; horizontal LI units are generally used for low ash-generating waste), LI incinerators are applicable only to combustible liquid wastes and thin slurries. To date, the only documented use of LI technology for dioxin destruction involves Environmental Protection Agency (EPA) -sponsored tests aboard the ocean incinerator M/T *Vulcanus in 1977.* Of the operating LI incinerator facilities in the United States today, only three have been shown to meet the criteria required to treat dioxin; however,

[1]Although in situ vitrification is traditionally regarded as a solidification/stabilization technology, for the purpose of this paper it was included waler thermal treatment technologies because of the high temperature required.

[2]Patrick Phillips, Executive Vice-president, Vesta Technologies, Ltd., personal communication, Mar. 25, 1991.

their operators have yet to apply for permits that would allow them to incinerate dioxin-contaminated liquid waste.

Traditionally, fluidized-bed combustion incineration (FBC) has been used for treatment of waste and sludge generated by municipal wastewater treatment plants, oil refineries, pulp and paper mills, and pharmaceutical plants. Of the approximately 25 FBC facilities built in the traditional design, only a few are employed today for treating hazardous waste. None of these facilities is permitted to treat dioxins.

Process modifications recently developed by two different firms have given FBC technology the capability of treating dioxin-contaminated materials. One firm, for example, modified the system to use a granular bed composed of a mixture of combustion catalyst and limestone rather than sand. This system has been tested successfully with dioxins; developers, however, plan to request a permit that would allow the application of the FBC unit now available only to PCB-bearing waste.

A second modification of FBC technology involves the use of a high-velocity air flow to suspend bed particles and attain more effective thermal treatment. The particle bed in this system is made up of the waste to be treated. Pilot-scale testing has demonstrated the ability of this modified FBC unit, known as the circulating-bed combustion incinerator, to meet the performance criteria required for successful dioxin destruction. Developers of the circulating-bed combustion facility are currently permitted to burn PCB-bearing waste; and even though two additional units are under construction, no plans exist at this time for requesting a permit to burn dioxins.

High-temperature fluid wall destruction advanced electric reactor (AER) technology consists of a porous tube or reactor enclosed in a hollow cylinder through which heat is radiated for waste treatment. Although originally designed by Thagard Research (California), the AER technology is known as the Huber Process because of proprietary modifications incorporated into the original design by J.M. Huber Corp. (Texas). Two of the most relevant advantages of AER with respect to dioxin treatment are: 1) the destruction of dioxins is accomplished by pyrolysis rather than oxidation as in most thermal treatment; and 2) the absence of oxygen and low gasflow rates allow for longer residence times, thus reducing the production of toxic off-gases.

The only two AER reactors available today, one stationary and one transportable, have proved successful in treating dioxin-contaminated materials, including soil at Times Beach. The developer obtained a permit to use its stationary AER unit for dioxin treatment in 1986. The firm, however, has not applied this technology since 1987, opting instead to invest in other treatment processes with greater market potential. This decision, a company official points out, would not have been made if a program to aid R&D of dioxin treatment technologies had been available.

Infrared radiation incineration was developed by Shirco Infrared Systems, Inc. (Dallas, Texas). The process involves exposing dioxin-contaminated materials to electrically heated silicon carbide elements, followed by the treatment of off-gases and the removal of ashes. A transportable pilot-scale unit was tested at Times Beach for the treatment of dioxin-contaminated soil in 1985. Test results showed that the Shirco system was able to treat dioxin-containing soil to levels exceeding those established by EPA for thermal treatment. Considerably larger treatment units (100 tons per day) have also been tested with varying degrees of success at several contaminated sites.[3] Most of the success associated with infrared incineration comes from Europe, particularly Germany, and there are no permitted facilities operating in the United States.

Plasma arc pyrolysis (PAP) incineration works much the same as incineration at high temperature by exposing the waste to a thermal plasma field. Bench-scale units developed thus far can process nearly 10 pounds per minute of contaminated solids or 55 gallons per hour of centaminated liquid waste. PAP technology is applicable only to liquid waste and contaminated soil or sludge with viscosity, similar to or lesser than 30- to 40-weight motor oil. Only one firm offers this technology today. Although the process has not been tested specifically with dioxins, certain wastes containing PCB dioxins, furans, and other chlorinated contaminants have been successfully treated to part-per-trillion levels

[3] Although the testing of a full-scale unit at Peak Oil site (Florida) and a pilot-scale unit at Township-Demode Road (Michigan) was successful, results of an EPA-funded field demonstration test of a full-scale unit were discouraging.

on bench-scale tests. Although promising for the treatment of liquid waste contaminated with dioxins, the real applicability of PAP to dioxin-containing waste is still questionable because additional research on a much larger scale is required.

Supercritical water oxidation (SCWO) technology is based on the oxidizing effect of water on organic compounds (which become extremely soluble) and inorganic substances (which become sparingly soluble) at high temperature (350 to 450 'C) and pressure (more than 218 atmospheres). A major limitation of SCWO is its ability to treat only dioxin-contaminated liquid waste or slurries/sludges with small-sized particles. One possibility suggested by developers to address dioxins in soil is to grind and pulverize the soils and make them into a slurry that can then be treated by the SCWO process. This practice, however, needs to be successfully demonstrated in larger units. Laboratory- and bench-scale test results from liquid waste contaminated with dioxins have met the criteria required for dioxin treatment. Development plans for commercializing SCWO technology began in 1989; today, its vendor offers two engineering packages for small (5,000 gallons per day) and medium-sized plants (20,000 gallons per day).

In situ vitrification (ISV) units now exist on a variety of scales: bench, engineering, pilot, and large. ISV has been tested in the United States and Canada on various soil types, some of which contain dioxins. In bench-scale tests, ISV has been able to treat dioxin-contaminated soil to levels exceeding EPA's performance requirement (99.9999 destruction and removal efficiency (DRE)). Additional research is required, particularly on pilot and large scales, for gathering the data needed to further understand this technology and fully demonstrate its effectiveness in treating dioxin-contaminated materials. Support by the U.S. Department of Energy and the EPA have been essential to the development of this technology.

NONTHERMAL TREATMENT TECHNOLOGIES

The study and application of dechlorination dates back more than 70 years when it was first used for the commercial production of phenols. Only recently have scientists begun to look at dechlorination as a viable technology for treating dioxin-contaminated materials. Five of the dechlorination methods developed thus far are highly promising for dioxin destruction: KPEG[4], APEG-PLUS, base-catalyzed decomposition, thermal resorption/UV destruction, and thermal gas-phase reductive dechlorination, which combine dechlorination and incineration.

Pilot-scale tests with KPEG and APEG-PLUS have shown, with a certain degree of success, the ability of these processes to attain the cleanup levels required for dioxin-contaminated soil. Still, 'most pilot-scale applications of the KPEG technique have involved remediation of PCB-contaminated sites. The APEG-PLUS system, on the other hand, is currently available through full-scale mobile units capable of treating 40 tons of contaminated soil daily; several additional units are being constructed. Despite these developments, both KPEG and APEG-PLUS dechlorination treatment technologies have yet to be fully demonstrated for remediating dioxin-contaminated sites.

Base-catalyzed decomposition (BCD), is a dechlorination process developed by EPA's Risk Reduction Engineering Laboratory as an alternative to KPEG and APEG-PLUS. The BCD process seems promising, not only in terms of dioxin destruction but also in terms of cost-effectiveness, because the costs of the reagents required are minimal compared to those of most dechlorination techniques. Early results from laboratory tests on dioxin-containing chlorinated materials indicate that BCD is a promising technology for the cleanup of dioxin-contaminated sites. Field demonstration tests are currently underway.

Thermal gas-phase reductive dechlorination was designed as a thermochemical reduction technology to treat a variety of contaminated matrices including harbor sediment, landfill leachate, and lagoon sludge. A full-scale reactor capable of treating 15 to 20 tons per day is now available, and a 50-ton-capacity unit is planned for 1992. Thus far, bench scale and laboratory-scale tests with various chlorinated compounds have been successful. Preliminary results from field tests in Canada also demonstrate the effectiveness of this technology in treating contaminated harbor sediments. Some consider this technology highly promising because of its

[4] Potassium Polyethylene Glicolate.

ability to chemically/thermally treat soil, liquid, and more importantly, sediment and sludge, which are considered by many to be the largest sources of dioxin contamination in the United States. At present, however, relatively few data to support this claim exist.

The thermal desorption/UV destruction (photolysis) process involves the use of heat to remove the dioxin from soil particles into a solvent solution for treatment. Once in the solvent, dioxin is exposed to ultra violet radiation and decomposed. In spite of its wide range of other uses, this technology has only been tested on a few military sites with dioxin-contaminated soils. Additional field testing and development is required before this technology could be selected for full-scale cleanup of dioxin-contaminated soils.

Bioremediation continues to be a promising technology over the long term for cleaning up dioxin-contamin ated sites. However, because of the limited research to date, most experts think that considerable work is required before bioremediation techniques can be applied successfully. A number of technical obstacles continue to limit the application of bioremediation: 1) only very specialized biological systems may be effective against the high toxicity, low volubility, and high absorptivity of dioxin; 2) a very stringent cleanup standard must be met; and 3) it may be difficult to find a microorganism that can effectively deactivate dioxins under the different conditions present at existing dioxin-contaminated sites. Experts still believe that these obstacles will be overcome by future achievements in biochemistry, the development of genetically engineered microorganisms, and increased knowledge of the chemistry of dioxin surrogates. Right now, bioremediation is regarded as an attractive possibility for cleaning up dioxin-contaminated soil, but its real applicability and effectiveness is unknown.

Soil washing is also considered an attractive approach because it can be employed to extract dioxin from soil and other contaminated materials for subsequent treatment by other technologies. Despite its recent introduction to the remediation field, at least two firms already offer soil washing techniques for the treatment of soils contaminated with organics, heavy metals, and even radionuclides. Soil washing promises to make remediation more cost-effective because its application would result in the need to chemically or thermally treat smaller volumes of contaminated materials. Unfortunately, data on the efficacy of this technique on dioxin-contaminated soil are scarce; and no full-scale soil washing system is currently available in the United States on a commercial basis for dioxin treatment.

Solidification and stabilization (S/S) techniques have been employed in the United States for more than two decades to treat certain liquid industrial chemical wastes. Earlier S/S techniques consisted of mixing two or more products (e.g., cement, lime, kiln dust, asphalt) to limit the volubility or mobility of contaminants in the medium, sometimes irrespective of the level of chemical reaction achieved. More recently, the application of S/S techniques has been expanded to include treatment of contaminated soil and incineration residues. Today, researchers are focusing on developing proprietary additives to increase the strength of the mixture; enhance the interaction between cement particles and contaminants; and alter the chemical structure of the contaminants.

Selection of S/S processes as the remediation treatment has occurred at several Superfund sites contaminated with organic waste and heavy metals. S/S techniques are commonly employed for stabilization of residues that result from the treatment of dioxin-contamin ated waste. Little information is available on the actual effectiveness of S/S technology for dioxin-contaminated material. In addition, none of the processes now available are considered by EPA to be an "alternative disposal method to incineration. If current research efforts continue, however, the future of S/S treatment may be more promising.

COST ESTIMATES OF DIOXIN TREATMENT

Developing reliable cost estimates for comparing technologies to treat dioxin-contaminated materials is difficult. Cleanup technology experts point out the following reasons for this: the limited number of proven technologies now available; the limited

[5] U.S. Environmental Protection Agency, office of Research and Development, Risk Reduction Engineering Laboratory, *International Waste Technolgies/Geo-Con In Situ Stabilization/Solidi ification—Applications Analysis Report, a* Superfund Innovative Technology Evaluation (SITE) report, EPA/540/A5-89/004 (Cincinnati, OH: August 1990), p. 20.

number of applications to date; the varying nature of contaminated materials and sites; and the different types of dioxins/furans found in these materials.

Experts also argue that in addition to operational factors, cost estimation of thermal and nonthermal technologies may be further complicated by the various regulatory (permitting) and technical factors that must be considered during site remediation. The most relevant examples of operational conditions that make cost estimation of thermal technologies difficult include the following:

1. throughput of the incineration system;
2. handling capacity required (the lower the handling capacity, the lower the labor costs);
3. term or duration of cleanup (the longer the term, the higher the cost);
4. caloric and moisture contents of the material to be treated, because these characteristics determine how much waste can be treated per day (the higher the heat and moisture contents, the higher the costs);
5. degree of contamination present in the waste, coupled with level of cleanup required (highly halogenated wastes are more costly because they are difficult to treat and require additional treatment and pollution control equipment);
6. costs incurred from purchasing electric power, fuel, oxygen, or reagents that are essential for operating the chosen technology; and
7. interruption of operations due to equipment malfunctioning, inclement weather, or lack of appropriate personnel.

Another important factor affecting dioxin incineration costs is the amount of reagent required to treat off-gases and residues resulting from the combustion of dioxin-contaminated materials. Costs incurred from improving incineration processes,[6] developing engineering designs for cleanup, transporting and setting up the equipment at a given location, and obtaining the necessary operating permits also make cost estimation of thermal technologies difficult.[7] Treatment depth (the deeper, the less costly because more soil can be treated) also affects the treatment costs for in situ vitrification.[8]

Although cost estimates are available for some of the thermal technologies examined in this paper, limited application of the technologies continues to hamper the development of more accurate cost figures. For example, the operating and maintenance costs of mobile rotary kiln incinerators, on the average, range from $400 to $600 per ton of dioxin-contaminated Soil.[9] This range, however, does not include costs incurred in transporting and setting up equipment, excavating soil, and disposing of treated material and residue. After these costs have been factored in, the total cost of mobile incineration could reach $1,500 per ton or more. No treatment costs exist for land-based rotary kiln incinerators because no stationary kiln has yet been permitted to incinerate dioxins.

The lack of meaningful and reliable cost estimates for rotary kiln incineration is also typical of most other thermal treatment technologies. In liquid injection incineration, for example, EPA reported in 1986 that treatment costs ranged from $200 per ton for halogenated solvents to $500 per ton for PCB-containing oils; the cost for dioxin-contaminated material was expected to be similar to that of PCBs.[10] More recent estimates, however, seem to indicate that the cost of treating dioxin-contaminated liquid waste could now exceed $1,500 per ton.[11]

The search for reliable, up-to-date dioxin treatment cost estimates for the remaining thermal technologies addressed in this paper yielded even more discouraging results. For instance, in the different applications of fluidized-bed incineration technology conducted to date, cost figures were available only for the treatment of chlorinated sludge and PCB-contaminated soil ($27 to $60 and

[6] ENSCO, for example, reported that improving the handling and particle removal capability of its mobile incinerators resulted in higher treatment costs.

[7] U.S. Environmental Protection Agency, Hazardous Waste Engineering Research Laboratory, *Treatment Technologies for Dioxin-Containing Wastes, EPA/600/2-86/096 (Cincinnati,* OH: USEPA, October 1986), p. 4.1.

[8] Geosafe Corp., "Application and Evaluation Considerations for In Situ Vitrification Technology: A Treatment Process for Destruction and/or Permanent Immobilization of Hazardous Materials," April 1989, pp. 13,28-29.

[9] Phillips, op. cit., footnote 2.

[10] U.S. Environmental Protection Agency, op. cit., footnote 7, p. 4.38.

[11] Paul E. des Rosiers, Chairman, Dioxin Disposal Advisory Group, U.S. Environmental Protection Agency, personal communication, June 10,1991.

$100 to $300 per ton, respectively[12]). Treatment costs of $365 to $565 per ton[13] were suggested for advanced electric reactor technology even though it has not been used since 1987. Preliminary estimates of treatment costs using infrared incineration technology are roughly $200 per ton of treated waste.[14] Relatively lower estimates ($60 to $225 per ton[15]) were estimated for supercritical water oxidation soil treatment; however, these calculations were made on the basis of bench-scale units. Finally, cost data for in situ vitrification of soil contaminated with dioxins do not exist at this time.[16]

The conditions that most commonly determine soil remediation costs for nonthermal treatment methods, such as chemical dechlorination, include:

1. the level of cleanup required;
2. the organic carbon content, moisture content, and particle size distribution of the soil;
3. the chemical forms (isomers) of chlorinated compounds present in the soil;
4. the temperature and duration of the chemical reaction;
5. the type of reagent formulation used; and
6. the length of time during which contaminated soil is exposed to the reagents.

These factors, as well as the recyclability of reagents and the cleanup level required, greatly affect total remediation costs.[17]

Of the dechlorination methods addressed, only the KPEG and APEG-PLUS processes seems to offer cost information, although with the same degree of uncertainty as thermal technologies.

Based on hypothetical scenarios developed by Galson Remediation Corp. and EPA, KPEG treatment costs are estimated to range from $91 in batch systems to about $300 for in situ applications.[18] More recently, based on the dechlorination of PCB-contaminated soil at the Wide Beach Superfund site, New York, Canonie Environmental officials suggested that treatment costs for dioxin-contaminated soil may range from $250 to $350 per ton.[19]

According to existing data, the processing costs of PCB-contaminated soil using APEG-PLUS have been estimated to be about $800 per ton. Based on the similarities between PCB and dioxins, experts suggest that the costs of APEG-PLUS treatment of dioxins may be somewhat higher.

Developers of **base-catalyzed decomposition** claim that dioxin treatment costs for this technology will be lower than those of alcohol-based dechlorination processes (KPEG, APEG-PLUS) because this technology employs cheaper reagents and eliminates the need to use costly polyethylene glycol as a component. The developer has estimated that the application of base-catalyzed decomposition to dioxin-contaminated soil would cost about $245 per ton.[20]

Developers of **thermal gas-phase reductive dechlorination** claim that operating costs associated with this technology will be three to five times cheaper than incineration. If proven, such processing costs for dioxin-contaminated soil or sediment could range between $350 and $500 per ton. No post-treatment and transportation costs need to be added

[12] U.S. Environmental protection Agency, op. cit., footnote 7, p. 4.51; Brenda M. Anderson and Robert G. Wilbourn, Ogden Environmental Services, "Contaminated Soil Remediation by Circulating Bed Combustion: Demonstration Test Results," November 1989, p. 7; Sharin Sexton, Ogden Environmental Services, Inc., San Diego, CA, personal communication, Jan. 25, 1991.

[13] Jim Boyd, J.M. Huber Corp., Huber, TX, personal communication, Jan. 25, 1991.

[14] U.S. Environmental Protection Agency, op. Cit., footnote 7, p. 4.64.

[15] Brian G. Evans, P.E., Development Manager, ABB Lummus Crest, Inc., personal communication, Apr. 2, 1991; Terry B. Thomason et d., "The MODAR Supercritical Water Oxidation Process," paper submitted for publication to *Innovative Hazardous Waste Treatment Technology Series, Nov. 3, 1988,* p. 22. This paper was found in MODAR, Inc., *MODAR Information, an* undated company report.

[16] Geosafe Corp., op. cit., footnote 8, pp. 13,28-29.

[17] Paul E. des Rosiers, "Chemical Detoxification of Dioxin-Contaminated Wastes Using Potassium Polyethylene Glycolate," *Chemosphere,* vol. 18, No. 1-6, 1989, p. 351; and U.S. Environmental Protection Agency, op. cit., footnote 1, p, 5.12.

[18] U.S. Environmental protection Agency, op. cit., footnote 7, pp. 5.12-5.13.

[19] Alister Montgomery, Canonie Environmental me., personal communication, Mar. 20, 1991.

[20] Charles Rogers, Us. Environmental Protection Agency, Risk Reduction Engineering Laboratory, personal communication, Dec. 17, 1990.

because no contaminated residues remain after processing.[21]

In addition to conditions affecting soil remediation costs for the chemical dechlorination methods described earlier, treatment costs for **bioremediation methods are** also affected by the nature (high acute toxicity, low volubility) and distribution (generally very low concentrations) of dioxins in soils. At present, no cost data are available for **bioremediation** of dioxin-centaminated soil. One significant reason for this is that no field testing has been conducted to date; treatment of chlorinated dibenzo-p-dioxins was demonstrated only on a bench scale in '1985.

At present, no cost data are available for dioxin treatment by soil washing. The relatively recent introduction of soil washing techniques to the hazardous waste remediation field is the primary reason for the unavailability of cost estimates, as well as for the lack of information on the performance of this technology on a large scale. Developing such information may take some time because the processes now available have yet to be considered for evaluation at a dioxin-contaminated site.

Developing cost estimates for **solidification/ stabilization** technologies has thus far been extremely difficult because their application has been limited to a few laboratory studies or sites. The few data available on dioxin treatment also make cost comparisons between batch processes (which require excavation, treatment, and redisposal of soil) and in situ processes difficult. For instance, a study conducted in 1987 identified and evaluated" the potential applicability and costs of several S/S technologies at three dioxin-contaminated sites in eastern Missouri;[22] however, additional in-depth studies on their long-term performance were suggested.[23] Although not specifically developed for treatment of dioxin or its residues, costs for the application of certain S/S methods are projected to range somewhere between $110 and $200 per ton of soil.

[21]D.J. Hallett and K.R. Campbell, "Thermal Gas-Phase Reduction of Organic Hazardous Wastes in Aqueous Matrices," U.S. Environmental Protection Agency Abstract Proceedings: Second Forum on Innovative Hazardous Waste Treatment Technologies: Domestic and International—Philadelphia, PA, May 15-17, 1990, Superfund EPA/500/2-90/009; D.J. Hallett and K.R. Campbell, "Demonstration Testing of a Thermal Gas Phase Reduction Process," U.S. Environmental Protection Agency, proceedings of the Third Forum on Innovative Hazardous Waste Treatment Technologies: Domestic and International, June 11-13, 1991, Dallas, TX, in press.

[22]Treatment CONS estimated during this study ranged from $5 to $10 per cubic meter for emulsified asphalt to $11 to $13 per cubic meter for Portland cement.

[23]Paul E. des Rosiers, ''Evaluation of Technology for Wastes and Soils Contaminated With Dioxins, Furans, and Related Substances,' *Journal of Hazardous Materials,* vol. 14, No. 1, 1987, pp. 121-122.