Thermal Treatment Technologies

Thermal technologies involve the use of heat as the primary treatment agent. During thermal destruction or incineration, organic materials in the waste are reduced to carbon dioxide (CO_2) and water vapor (both of which exit through a stack). Other chemicals such as chlorine and phosphorus are captured by the pollution control equipment, whereas noncombustible materials are captured in the ash.

The Environmental Protection Agency (EPA) began to consider incineration the preferred technology for treating dioxin-containing materials after laboratory studies showed that dioxins broke down easily when exposed to temperatures in excess of 1,200 °C.[1] To test this process on a much larger scale, EPA built a mobile research incinerator specifically designed to treat recalcitrant organic chemicals. The success of this research, in which the destruction and removal efficiency (DRE)[2] of dioxin in treated waste exceeded 99.9999 percent, led EPA to adopt thermal treatment as the appropriate method for destroying dioxin-containing waste.

Extensive research has resulted in the development of several incineration technologies. The most noteworthy in relation to dioxin treatment are rotary kilns, liquid injection, fluidized bed/circulating fluidized bed, high-temperature fluid wall destruction (advanced electric reactor), infrared thermal destruction, plasma arc pyrolysis, supercritical water oxidation, and in situ vitrification.

ROTARY KILN INCINERATION

The variety of containerized and noncontainerized solid and liquid wastes that can be treated individually or simultaneously in kiln incinerators has made this thermal technology the most versatile and popular in the United States. Rotary kilns in use today are classified into two major categories: stationary (land based) and mobile (transportable).

The key component of the system, the rotary kiln, is a refractory-lined cylinder that rotates at a horizontal angle of 5 degrees or less and at a speed of 1 to 5 feet per minute. Other features of kiln incinerators include a shredder, a waste feed system, a secondary combustion chamber or afterburner, air pollution control equipment, and a stack. Operators may also make use of auxiliary heat systems to heat the kiln to the desired operating temperature.[3]

As shown in figure 2-1, the solid and liquid wastes fed into the rotating kiln are partially burned into inorganic ash and gases. The ash is discarded in an ash bin, and the gaseous products in which uncombusted organic materials still reside are sent to the secondary combustion chamber for complete destruction.[4]

Rotary kilns in which combustion gases flow opposite to waste flow through the incinerator (called countercurrent rotary kilns) are preferred to those in which gases flow in the same direction (concurrent). Countercurrent rotary kilns have a lower

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

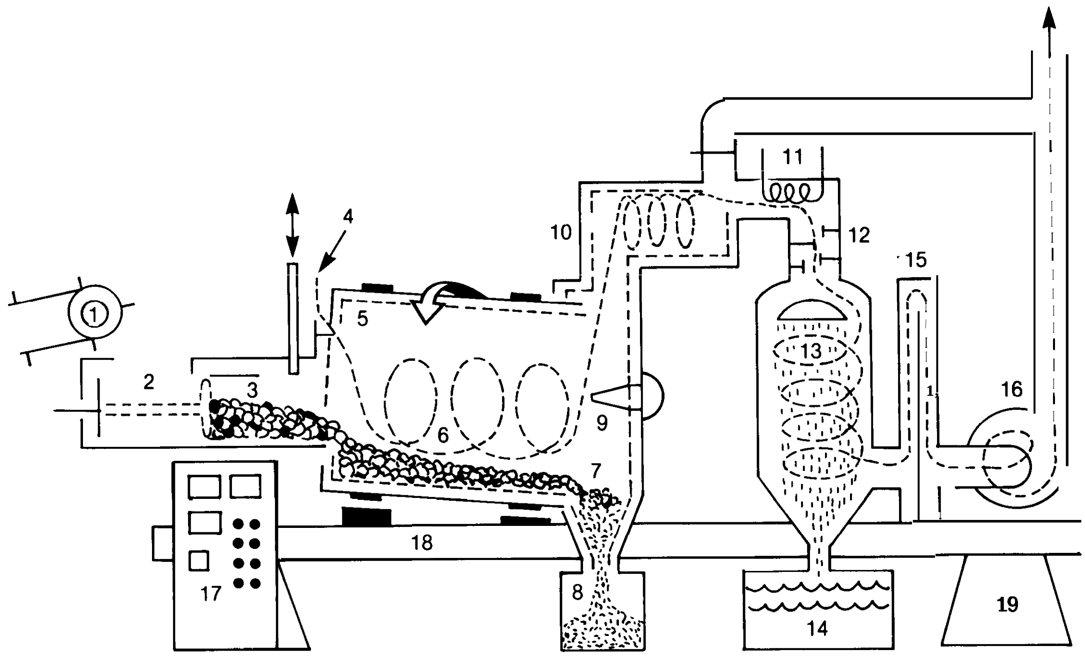
[2] DRE is a major performance standard that, when applied to thermal treatment of dioxin-containing materials, corresponds to a destruction and removal efficiency of dioxin at a 99.9999 percent level (or "six nines"). DRE is a function relating the concentrations of a contaminant t prior to and after treatment. Because treatment residues must not contain dioxins or furans exceeding the EPA standard for land disposal (1 part per billion (ppb); see note below), it is imperative to know in advance if residues from exhaust gases, scrubber water, filter residues, and ash generated by the treatment chosen will be in compliance.

NOTE: If the dioxin waste is characterized as an acutely hazardous Resource Conservation and Recovery Act (RCRA) listed F-waste, see ch. 1, table 1-4 for treatment standards; if such material is not an F-waste, then the required level of treatment is to a dioxin concentration of less than 1 ppb 2,3,7,8-tetrachlorodibenzo-*p*-dioxin equivalents (TCDDe). For instance, when incinerating RCRA non-F waste (e.g., PCBs, pentachlorophenol), the facility operator is required to calculate DREs from measurements of chlorodibenzo-*p*-dioxins and chlorodibenzofurans (CDDs/CDFs) made in the field, followed by their conversion into TCDDe, because these contaminants are known to contain a variety of CDDS and CDFS.

[3] Calvin R. Brunner, *Incineration Systems—Selection and Design* (New York, NY: Van Nostrand Reinhold, 1984), p. 239; and U.S. Environmental Protection Agency, op. cit., footnote 1, p. 4.4,

[4] U.S. Environmental Protection Agency, op. cit., footnote 1, p. 4.4.

Figure 2-I—Rotary Kiln



1. Material handling system
2. Auto-cycle feeding system: feed hopper, door, ram feeder
3. Waste to incinerator
4. Combustion air
5. Refractory-lined, rotating cylinder
6. Tumble-burning action
7. Incombustible ash
8. Ash bin
9. Auto-control burner package: programmed pilot burner
10. Afterburner chamber
11. Heat recuperation
12. Precooler
13. Scrubber package: stainless steel, corrosion-free scrubber
14. Recycle water, fly ash sludge
15. Neutralization column
16. Exhaust fan and stack
17. Self-compensating instrumentation and controls
18. Support frame
19. Support piers

SOURCE: Calvin R. Brunner, Incinerator Systems-Selection and *Design (New* York, NY: Van Nostrand Reinhold, 1984), p. 239.

potential for overheating because the auxiliary heat burners are located opposite the incinerator.[5]

The use of rotary kiln incineration for dioxin-containing waste is more common in Europe than in the United States. An example of this is the treatment of 2,500 kilograms of toluene still bottoms waste[6] in the CIBA-Geigy incinerator in Basel, Switzerland. This waste was from the Icmesa reactor in Seveso, Italy, and it contained approximately 600 grams of 2,3,7,8-tetrachlorodibenzo-p-dioxin(TCDD). The treatment achieved residual levels below limits of detection (0.05 to 0.2 part per billion (ppb)). Another example is the treatment of dioxin- and furan-contamin ated oils generated during the conversion of lindane waste through 2,4,5 -TCP[7] to 2,4,5-T[8], which leaked out of a landfill in Hamburg, Germany. The dioxins and furans were reported to be present in the waste at levels exceeding 42,000 ppb.[9]

Stationary or Land-Based Rotary Kiln Incinerators

As the name indicates, stationary or land-based facilities are built to remain at one site. At present, several stationary rotary kiln facilities have permits to burn waste containing toxic constituents such as

[5] Ibid.

[6] This waste resulted from a process designed to produce 2,4,5 -trichlorophenol from alkaline hydrolysis of 2,3,4,6-tetrachlorophenol.

[7] 2,4,5-trichlorophenol.

[8] 2,4,5-trichlorophenoxyacetic acid.

[9] Harmut S. Fuhr and J. Paul E. des Rosiers, "Methods of Degradation, Destruction Detoxification, and Disposal of Dioxins and Related Compounds," *Pilot Study on International Information Exchange and Related Compounds (North* Atlantic Treaty Organization Committee on the Challenges of Modem Society, Report No. 174, August 1988), pp. 23,24-25.

those permitted under the authority of the Toxic Substances Control Act (TSCA) for polychlorinated biphenyls (PCBs); these include the Rollins Incinerator in Deer Park, Texas; the Waste Chem incinerator in Chicago, Illinois; the ENSCO incinerator in El Dorado, Arkansas; and the Aptus incinerator in Coffeyville, Kansas. To date, none of these facilities has been used to burn dioxins because of the likelihood of strong public opposition and the lack of appropriate operating permits under the Resource Conservation and Recovery Act (RCRA).[10] Only one application-submitted by Rollins in October 1988 and still awaiting EPA approval—has been filed with EPA to obtain a RCRA permit for burning dioxin-containing waste.[11] Other stationary incinerators, however, may be able to be upgraded to treat dioxins if they can satisfy permit requirements.

Other firms also have plans to build and operate such incinerators. For example, Ogden Environmental Services-in combination with American Envirotech, Inc.-plans to construct a RCRA incinerator to destroy hazardous waste at a location in Texas. Construction costs are estimated to be about $60 million, and operation is expected to begin by 1993 pending permit approval. A draft Part B RCRA permit has already been issued by the Texas Water Commission.[12] If built, this facility could eventually be used for dioxin incineration if its design meets permit requirements.

Rollins' Rotary Kiln Incinerator

An example of current stationary incinerator technology is the stationary rotary kiln incinerator facility owned by Rollins, Inc., located in Deer Park, Texas. As shown in figure 2-2, solids are conveyed or fed into a rotary kiln in 55-gallon metal or fiber drums, whereas liquid waste is atomized directly into the secondary combustion chamber or afterburner. The latter unit normally operates between 1,300 and 1,500 'C. After being burned, combustion gases are passed to a combination venturi scrubber/ absorption tower for particle removal. Fans are employed to drive scrubber gases through the stack and into the atmosphere.[13] Maximum feed rates for the Rollins incinerator are l,440 pounds per hour for solids and 6,600 pounds per hour for liquids.[14]

Rollins Environmental Services already has a RCRA permit to store and dispose of hazardous waste; therefore, it intends to add only the incinerator unit to its current permit.[15] Granting of a new permit is expected within a year. According to a company official, however, the real challenge is to gain the approval of the general public and public officials to begin operations.[16] If this system is permitted, it may also be able to meet requirements for dioxin treatment.

Cost Estimates for Land-Based Rotary Kiln Incineration

No cost figures on the treatment of dioxin-containing waste are available because to date no stationary kiln has been permitted to incinerate dioxins. However, because of the similarities between PCBs and dioxins, one could expect the costs to be relatively similar to those listed in table 2-1 for the Rollins incinerator.

Mobile Rotary Kiln Incinerators

The primary purposes of designing and building a mobile (transportable) incinerator are: 1) to facilitate temporary field use for treating waste resulting from cleanup operations at uncontrolled hazardous waste sites; 2) to promote the application of cost-effective and advanced technologies; and 3) to reduce the potential risks associated with transporting waste over long distances.[17]

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[10] Jerry Neill, Rollins Environmental Services, Texas, personal communication Jan. 9, 1991 and July 16, 1991; Diane Schille, APTUS, Kansas, personal communication, July 11, 1991; Keith Paulson, Westinghouse Environmental Systems and Services Division, Pittsburgh, personal communication Feb. 11, 1991; U.S. Environmental Protection Agency, op. cit., footnote 1, p. 4.9.

[11] Neill, op. cit., footnote 10.

[12] Press release issued by Ogden Projects, Inc., Oct. 22, 1990.

[13] Ibid., p. 4.5.

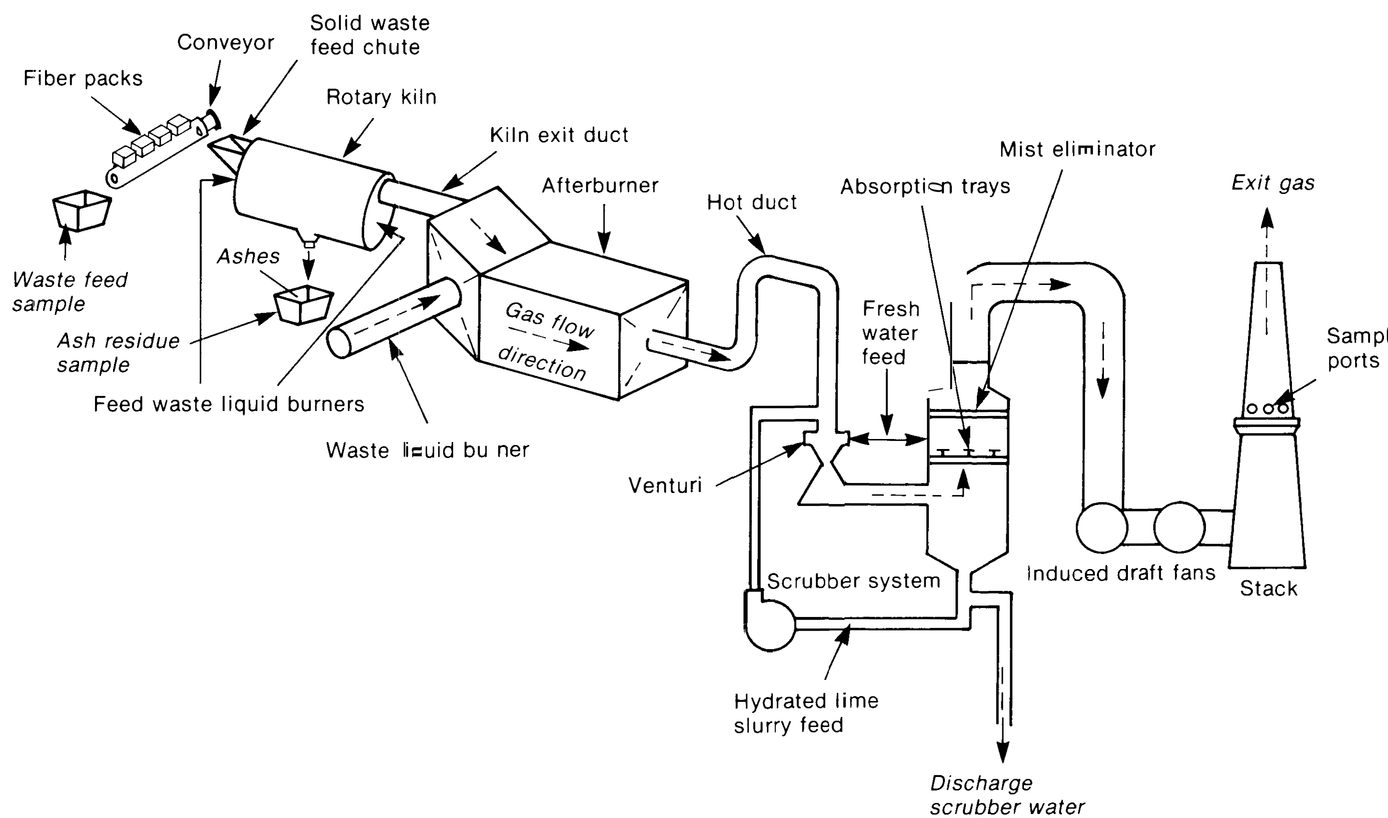
[14] Ibid., p. 4.15.

[15] Because of difficulties in obtaining permits, most companies now apply fo, regional or national, rather than statewide, permits under TSCA for burning PCBs and PCB-contaminated waste. Unlike TSCA, RCRA authorizes EPA to grant only site-specific permits for treating dioxin-containing waste.

[16] Neill, op. cit., footnote 10.

[17] U.S. Environmental Protection Agency, Risk Reduction Engineering Laboratory, "EPA's Mobile Incineration System for Cleanup Of Hazardous Wastes-Fact Sheet," January 1989.

Figure 2-2—Rollins Environmental Services Rotary Kiln Incineration System



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

Table 2-l—Estimated Average Cost Per Pound To Incinerate PCB Waste

Concentration (ppm)[a]	Liquids	Solids
0-50	$0.25	$0.40
50-1,000	$0.30	$0.45
1,000-10,000	$0.35	$0.50
10,000-100,000	$0.40	$0.60
100,000	$0.45	$0.70

[a]ppm = parts per million.

SOURCE: U.S. Environmental Protection Agency, Hazardous Waste Engineering Research Laboratory, *Treatment Technologies for Dioxin-Containing Wastes, EPA/600/2-86/096* (Cincinnati, OH: October 1986), p. 4.14.

History of EPA's Mobile Incinerator

In 1985, EPA sponsored research on dioxin incineration technology by using a stationary facility in Jefferson, Arkansas to conduct pilot-scale studies.[18] Two burns of waste containing dioxin-contaminated toluene still bottoms from the Vertac Chemical facility in Jacksonville, Arkansas were performed in late 1985 in a rotary kiln research unit. Although monitoring and sampling detection limits were too high at both waste burns,[19] EPA concluded that rotary kiln incineration technology could be utilized in the destruction of dioxin if emission controls were improved. Results of the tests included the following:

- concentration levels of the most toxic dioxin species (2,3,7,8 -TCDD) were found to be negligible in scrubber blowdown water (1 part per trillion (ppt)) and kiln ash;
- most dioxin forms were undetected at the detection limits used; and
- no tetra-, penta-, hexa-, or heptachlorodibenzo-p-dioxins or chlorodibenzofurans were detected in kiln ash samples at detection limits of 1.3 to 37 ppt.[20]

In light of these results, EPA concluded that residues from incineration treatment of dioxin- and furan-contaminated materials with this type of system could be considered nonhazardous.[21] 22

After these early tests in Arkansas, EPA developed a mobile incinerator system with equivalent technology specifically to treat dioxin-contaminated material.

After successful trial burns of the mobile incinerator in Edison, New Jersey and laboratory studies to establish optimum conditions for soil incineration, the EPA mobile incinerator was transferred in 1985 to the Denney Farm site in Missouri for a series of tests using 2,3,7,8 -TCDD. At the conclusion of the experiment, EPA had achieved DREs of 99.9999 percent, with process wastewater and treated soil containing dioxins at insignificant levels. To date, the EPA mobile incinerator unit, the best known transportable rotary kiln in the United States, has successfully incinerated more than 12 million pounds of dioxin-contaminated soil and 230,000 pounds of dioxin-contaminated liquid waste.[23] The presence of state-of-the-art pollution control systems, claim cleanup experts, makes mobile (transportable) incinerators less controversial and safer than other systems that have not had the same design and development attention.[24]

Although EPA has invested more than $10 million in this unit, other mobile incinerator systems have been constructed at much lower costs through the experience and data gained from it. Research with the mobile unit was instrumental in the design and modification of several incineration components, including enlargement of the feeding system, reduction in gas velocity, addition of cyclones between kiln and afterburner so that less material accumulates in the latter, and addition of a venturi

18R.W. Ross II et al., Acurex Corp., Energy and Environmental Division, "Combustion Research Facility: Pilot-Scale Incineration Test Burn of TCDD-Contaminated Toluene Stillbottoms From Trichlorophenol Production From the Vertac Chemical Co," paper prepared for the U.S. Environmental Protection Agency, Office of Research and Development, Hazardous Waste Engineering Research Laboratory, under EPA contract No. 68-03-3267, Work Assignment O-2, Acurex Technical Report TR-86-100/EE, January 1986; Richard A. Carries and F.C. Whitmore, "Characterization of the Rotary Kiln Incinerator System of the U.S. EPA Combustion Research Facility (CRF),'' *Hazardous* Wrote, vol. 1, No. 2, 1984, pp. 225-236.

19Other problems encountered were clogging of the waste feed system and malfunction of the emission monitoring system.

20U.S. Environmental Protection Agency, op. cit., footnote 1, pp. 4.12413.

21For additional information on EPA's research incinator facility, see also: Carnes and Whitmore, op. cit., footnote 18, and R.W. ROSS, II, F.C. Whitmore, and R.A. Carries, "Evaluation of the U.S. EPA CFR Incinerator as Determined by Hexachlorobenzene Incineration' Hazardous *Waste*, vol. 1, No. 4, 1984, pp. 581-597.

22At the time of this pilot study, however, EPA screening levels had not been promulgated; they had only been proposed in the *Federal Register*. [For details, see "Hazardous Waste Management System; Land Disposal Restrictions; Proposed Rule," 51 *Fed. Reg.* 1602 (1986)]

23G.D. Gupta, "Mobile Incinerator for Toxic Wastes," *Environmental Science& Technology*, vol. 24, No. 12, 1990, p. 1776.

24Patrick Phillips, Executive Vice-President, Vesta Technologies, Ltd., personal communication, Mar. 25$1991.

and wet electrostatic precipitators to reduce air emissions.[25]

The EPA system is designed to achieve full combustion of organic, inorganic, and debris materials, including halogenated compounds such as PCBs and dioxins.[26] Several existing commercial mobile incinerator facilities are based on the EPA system.

Components of EPA's Mobile Incinerator

The EPA mobile incinerator system consists of specialized incineration equipment mounted on four heavy-duty semitrailers and auxiliary pads. The first ***trailer*** contains: 1) a waste feed system for solids, consisting of a shredder, a conveyor, and a hopper (liquids are injected directly into the afterburner); 2) burners; and 3) the rotary kiln.[27] Organics are burned in this portion of the system at about 1,600 ‘C.

Once the waste has been incinerated, incombustible ash is discharged directly from the kiln, and the gaseous portion of the waste-now fully vaporized and completely or partially oxidized-flows into the secondary combustion chamber or ***second trailer in*** which it is completely oxidized at 2,200 ‘F (1,200 ‘C) and a residence time of 2 seconds. Flue gas is then cooled by water sprays to 190 ‘F, and excess water is collected in a sump.

Immediately after being cooled, the gas passes to the ***third trailer*** on which the pollution control and monitoring equipment is located. At this junction, gases pass through a wet electrostatic precipitator (WEP) for removal of submicron-sized particles and an alkaline mass-transfer scrubber for neutralization of acid gases formed during combustion. Cleaned gases are drawn out of the system through a 40-foot-high stack by an induced-draft fan whose other function is to keep the system under negative pressure to prevent the escape of toxic particles. Efficient and safe system performance is maintained through the use of continuous monitoring instrumentation, which includes computerized equipment and multiple automatic shutdown devices.[28]

The EPA mobile incinerator unit consumes 15 million British thermal units (Btu) per hour and handles up to 150 pounds of dry solids, 3 gallons of contaminated water, and nearly 2 gallons of contaminated fuel oil per minute.[29] It is concurrently located at EPA's Edison Laboratory in Edison, NJ. EPA no longer plans to employ it for combustion of waste.[30]

Commercially Available Mobile Rotary Kiln Incinerators

Only a few private companies have actually built and operated mobile incinerators for dioxin treatment using EPA research as a base. The ***ENSCO Corp.,*** Little Rock, Arkansas, has designed and built three modified versions of the EPA model, which include improvements in waste handling and particle removal. One unit was used for cleaning up waste contaminated with chlorinated organics near Tampa, Florida; a second unit is located at El Dorado, Arkansas (also the location of ENSCO's stationary kiln incinerator). The third is not currently in use.

Available ENSCO units are capable of treating 150 gallons of liquid waste and 2 to 6.3 tons of dioxin-contaminated solid waste per hour. Results of tests conducted on an ENSCO unit by the U.S. Air Force at the Naval Construction Battalion Center, Gulfport, Mississippi, indicate that this transportable incinerator could remove and destroy dioxins from contaminated soils at DREs greater than 99.9999 percent.[31]

Another private company that has built mobile incinerators is ***Vesta, Inc.,*** of Ft. Lauderdale, Florida. This firm has three transportable incineration units capable of treating dioxin-contaminated soil at a maximum estimated rate of 5 tons per hour.[32] Treatment of soil, liquid, or sludge is accomplished in a two-stage incineration process (countercurrent rotary kiln; cocurrent secondary combustion cham-

‘Paul E. des Rosiers, “Advances in Dioxin Risk Management and Control Technologies,'' *Chemosphere,* vol. 18, Nos. 1-6, 1989, pp. 45-46.

26U.S. Environmental Protection Agency, op. cit., footnote 17.

27U.S. Environment Protection Agency, op. cit., footnote 1, p. 4.16.

28Ibid., pp. 4.16-4.18; U.S. Environmental Protection Agency, op. cit., footnote 17.

29U.S. Environmental Protection Agency, op. cit., footnote 1, p. 4.16.

30Paul E. des Rosiers, Chairman, Dioxin Disposal Advisory Group, U.S. EPA, personal communication June 10, 1991,

31Fuhr and des Rosiers, op. cit., footnote 9, pp. 29-30; U.S. Environment Protection Agency, op. cit., footnote 1, p. 4.16; and des Rosiers, Op. Cit., footnote 25.

32Phillips, op. Cit., footnote

ber) followed by ahigh-efficiency multistage scrubbing process. Vesta systems can be deployed in about 24 hours; longer setup times are needed when incinerator and prepared stockpiles require covering with inflatable tent-like structures to avoid delays due to inclement weather. Decontamination and demobilization of the entire process maybe accomplished in less than 72 hours. Operations may be conducted by using liquid propane gas, liquid oxygen, fuel oil, or any waste or waste blend considered suitable. Examples of dioxin-contaminated sites at which Vesta's transportable incinerators have been used successfully include American Cross Arms Site (Chehalis, Washington), Fort A.P. Hill (Bowling Green, Virginia),[34] Rocky Boy Post& Pole Site (Rocky Boy, Montana), and Black Feet Post & Pole Site (Browning, Montana).[34]

Cost Estimates for Mobile Rotary Kiln Incineration

Among the factors that must be taken into consideration in developing cost figures for mobile (transportable) incineration are:

- the throughput capacity of the system;
- the caloric content (Btu) and moisture content of the waste because they determine the feed rates that can be maintained;
- the maintenance and consistency of uninterrupted operations; and
- the duration of operation (the longer it is, the higher are the costs).

Setup costs incurred by design requirements and permitting processes also play very important roles; however, they vary from one site to another.[35] One firm reports that mobile incineration operating and maintenance costs can range from $400 to $600 per ton of waste treated.[36]

LIQUID INJECTION INCINERATION TECHNOLOGY

Liquid injection (LI) is not currently available for dioxin treatment, but it has been used aboard ships for ocean-based incineration of Agent Orange. It is also employed in many industrial and manufacturing sectors for treatment of hazardous organic and inorganic wastes. As shown in figure 2-3, the typical LI incinerator consists of a burner, two combustion chambers (primary and secondary), a quench chamber, a scrubber, and a stack. Vertical LI incinerators are preferred for treating liquid waste rich in organics and salts (and therefore ash) because the incinerator unit can be used as its own stack to facilitate the handling of generated ash. Portions of the vertical LI unit can also be used as a secondary combustion chamber. The horizontally shaped LI units are connected to a tall stack and are preferred for treating liquid waste that generates less ash. In both systems, the use of external waste storage and blending tanks helps maintain the waste in a homogeneous form and at a steady flow.[37]

Some of the limitations that must be considered before applying LI incineration to dioxin destruction include the following:

- LI systems are applicable only to combustible low-viscosity liquids and slurries that can be pumped;
- waste must be atomized prior to injection into the combustor; and
- particle size is critical because burners are susceptible to clogging at the nozzles.[38]

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33 At this U.S. Army installation, Vesta successfully treated 189 cubic yards (more than 190 tons) of soil that had been contaminated by corroding storage drums containing the dioxin-bearing herbicides Silvex; 2,4-dichlorophenoxyacetic acid (2,4-D); and 2,4,5-trichlorophenoxyacetic acid (2,4,5-T). Ritu Chaudhari, A.W. Lemmon, and J. Towarnicky, "Dioxin Destruction on a Small Scale-A Success Story," paper presented at the Sixth Annual DOE MODEL Conference, Oak Ridge, TN, Oct. 29 to Nov. 2, 1990; Letter from Dennis J. Wynne, Department of the Army, U.S. Army Toxics and Hazardous Materials Agency, Aberdeen Proving Ground, MD, to Paul E. des Rosiers, U.S. EPA, Office of Research and Development, with enclosure on the U.S. Department of the Army's "Remediation of Contamination at Fort A.P. Hill," dated May 22, 1989. For additional information see Metcalf & Eddy, Inc., *Report on the Remedial Action Fort A.P. Hill Site—Final Report* (Contract No. DAAA15-86-D 0015; Task Order-7), Mar. 16, 1990; prepared for Commander, U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground (Edgewood Area), MD; U.S. Army Training and Doctrine Command, Office of the Command Historian, *The Dioxin Incident at Fort A.P. Hill, 1984-1985 (Fort* Monroe, VA: U.S. Army Training and Doctrine Coremand, July 1987).

34 Vesta Technologies, Ltd., "VESTA 80—Technology Specifications," August 1989; "VESTA 100—Technology Specifications," August 1989; "Vesta Project Profiles," undated, pp. 1, 2-3; "Performance History," undated; "Burning Facts," undated.

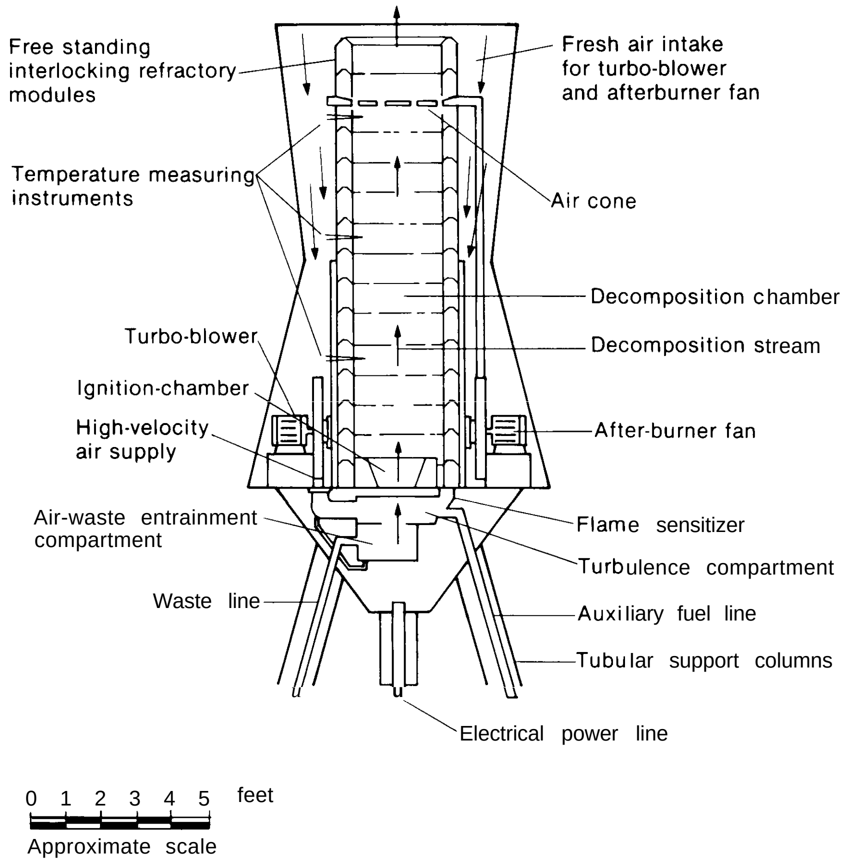
35 U.S. Environmental Protection Agency, op. cit., footnote 1, p. 4.30.

36 Phillips, op. cit., footnote 24.

37 U.S. Environmental Protection Agency, op. cit., footnote 1, p. 4-32.

38 Ibid., pp. 4.32-4.34; see also Timothy E. Oppelt, "Incineration of Hazardous Waste: A Critical Review," *Journal of the Air Pollution Control Association* (JAPCA), vol. 37, No. 5, pp. 558-586.

Figure 2-3-Vertically Oriented Liquid Injection Incinerator



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

The only documented use of liquid injection technology in the United States for dioxin destruction comes from the burns that took place aboard the ocean incinerator M/T ***Vulcanus* in the summ**er of 1977. This facility consisted of:

- a modified LI system;
- two LI incinerators at the stern;
- a combustion chamber and a stack for each incinerator;
- electrical pumps for sending the waste to the combustion chamber; and
- a blending device for mixing and reducing solids to a pumpable slurry.[39]

Although land-based LI facilities must install scrubbers to remove acid gases (particularly hydrogen chloride), the M/T ***Vulcanus*** was not required to on the assumption that acidic gases resulting from combustion would be absorbed and neutralized by the ocean. Some operating parameters included: 1) a flame temperature of 1,375 to 1,610 'C, 2) a furnace wall temperature of 1,100 to 1,200 'C, and 3) a residence time of 1 to 2 seconds. Results of the EPA-sponsored trial burns indicated that the ocean incinerator's destruction of dioxin averaged more than 99.93 percent DRE. A subsequent EPA-sponsored trial burn of PCBs in August 1982

[39]U.S. Environmental Protection Agency, op. cit., footnote 1, pp. 4.32-4.34. See also T.A. Wastler, C.K. Offutt, C.K. Fitzsimmons, and P.E. des Rosiers, ***Disposal of Organochlorine Wastes at Sea*, *EPA-43019-75-014*,** July 1975; D.D. Ackerman et al., ***At-Sea Incineration of Herbicide Orange Onboard the MIT Vulcanus*, *EPA-60012-78-086*,** April 1978.

revealed no TCDDs in the stack gas (based on a 2- to 22-ppb detection limit).[40 41]

No data exist on the burning of dioxins at land-based liquid injection incinerators. Existing LI units that may be able to burn dioxins most effectively (i.e., with a 99.9999 percent DRE) include General Electric's thermal oxidizer (in Pittsfield, Massachusetts) and LI incinerator (in Waterford, New York) permitted to burn PCBs, and Occidental Chemical's LI unit currently employed for burning hazardous leachate from the Hyde Park Superfund site in New York.[42]

Cost Estimates for Liquid Injection Incineration

As for most incineration methods, the cost of liquid injection depends on the type of waste to be treated. Aqueous, low-Btu waste costs more to incinerate because of increased heat energy or fuel requirements; highly halogenated waste also costs more to incinerate because a scrubber is required to remove acid gases formed during combustion. In 1986, EPA reported that the typical cost for the treatment of halogenated solvents containing more than 50 percent waste was $200 per metric ton. In the same report, EPA indicated that LI treatment of PCB-contaminated oil would cost more than $500 per metric ton because of the "six-nines" DRE requirement and suggested that, because of similar performance requirements, treatment costs of incinerating liquid dioxin waste would be approximately the same.[43] More recent estimates indicate that the cost of LI treatment for dioxin-contaminated liquid waste could be much higher than for PCB - containing waste.[44]

FLUIDIZED-BED INCINERATION

Traditionally, fluidized-bed combustion systems (FBCs) were employed for the treatment of sludge produced by municipal waste treatment plants and waste generated from oil refineries, pulp and paper mills, and the pharmaceutical industry. Today, about 25 FBCs are operating in the United States and Europe; only a few of them are used commercially to treat hazardous waste. None are available for dioxin treatment, but with certain design improvements, some experts believe they have the potential for this application.

The FBC system consists of a vertical refractory-lined vessel holding a perforated metal plate on which abed of granular material (preferably sand) is located. Bed particles are fluidized by forcing hot air up through the medium to create a highly turbulent zone that ensures the mixing of waste materials with bed particles and combustion air. Startup temperatures are reached by use of a burner located above the bed; once heated, the bed material causes the waste to combust. Solid noncombustible materials in the waste become suspended and exit into a cyclone for particle removal; exhaust gases flow into the after-burner for additional combustion.[45] Particular attention must be paid to the type and size of materials to be incinerated because variations in gravity and density could be deleterious to the process.[%]

The fluidized-bed incinerator system has been modified on several occasions; the two systems with the highest potential for dioxin treatment (one designed by Waste-Tech Services and the other by General Atomics Technologies[47]) are discussed below.

Waste-Tech Services System

In August 1985, Waste-Tech Services, Inc.,[48] of Golden, Colorado, designed and built its modified fluidized-bed incineration unit, which uses a granular bed composed of a mixture of combustion

40U.S. Environment protection Agency, op. cit., footnote 1, pp. 432,4.34-4.37.

41 For additional information on the formation and destruction of dioxins at ~/T *Vulcanus*, see: N.C.A. Weerasinghe, J.L. Meehan, M.L. Gross, and R.L. Harless, "The Analysis of Tetrachlorodibenzo-*p*-dioxins and Tetrachlorodibenzofurans in Chemical Waste and in the Emissions From Its Combustion." L.H. Keith, C. Rappe, and G. Choudhary, *Chlorinated Dioxins & Dibenzofurans in the Total Environment* (Stoneham, MA: Butterworth Publishers, 1983), pp. 425-437.

42U.S. Environmental Protection Agency, op. cit., footnote1, pp. 4.38-4.40.

43U.S. Environmental Protection Agency, op. cit., footnote 1., p. 4.38.

*ales Rosiers, op. cit., footnote30.

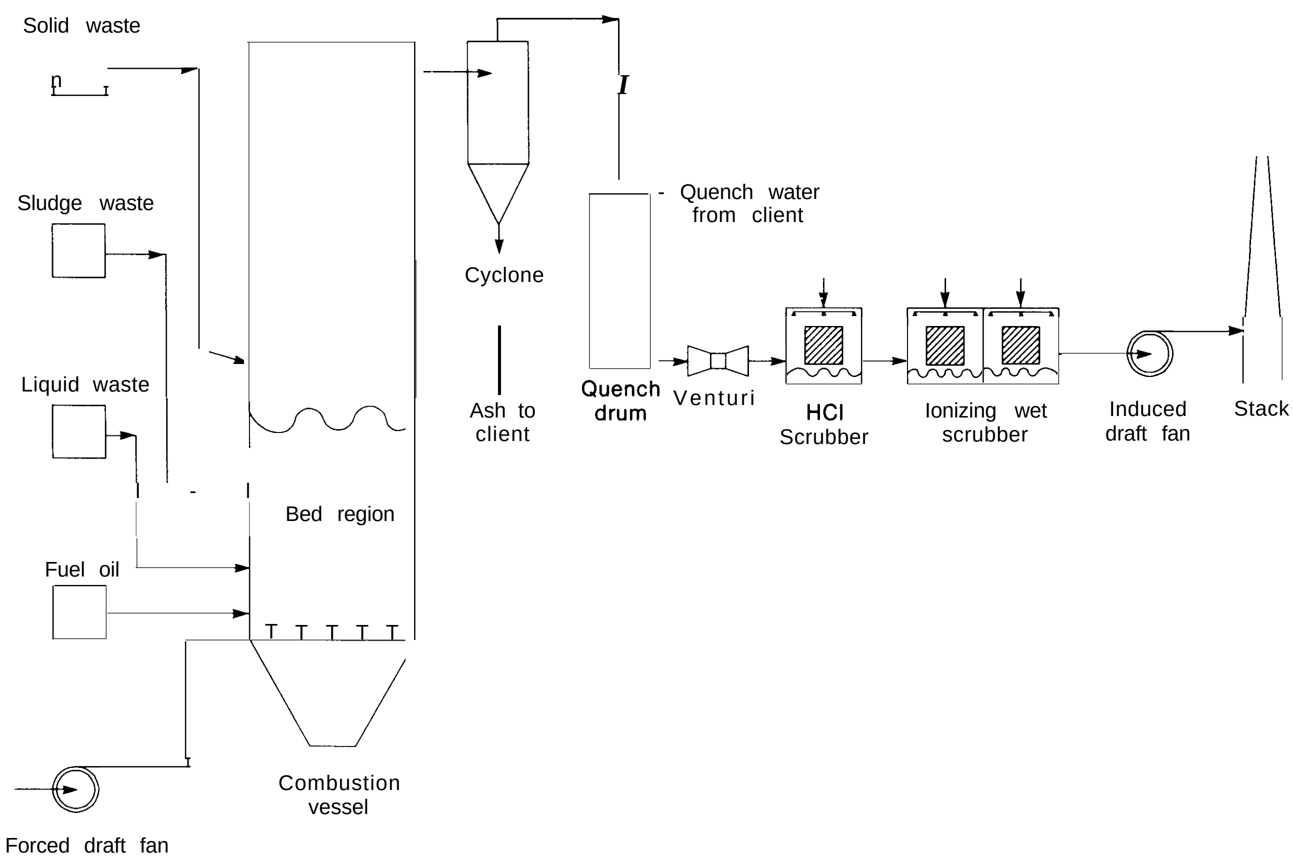
45U.S. Environmental Protection Agency, op. cit., footnote1, p. 4.41.

46Phillips, op. cit., footnote 24.

47This system is marketed by Ogden Environmental Services, San Diego, CA.

48Waste-Tech Services, Inc., is an affiliate of the AmocoOil Holding Co.

Figure 2-4-Schematic Diagram of the Waste-Tech Incineration Process



SOURCE: Charles D. Bartholomew and R.W. Benedict, Waste-Tech Services, Inc., "Performance of a Fluidized Bed Hazardous Waste Thermal Oxidation System," paper presented at the 81st Annual Meeting of the Air Pollution Control Association, Dallas, TX, June 19-24, 1988,

catalyst and limestone rather than sand. This unit is presently located at a plant that manufactures chlorinated chemicals in Lake Charles, Louisiana.[49] With a thermal rating of 22 million Btu per hour,[50] the Waste-Tech unit is composed of multiple feed systems, a fluidized bed,[51] secondary combustion chambers, air pollution control equipment, and ancillary support equipment for removing cyclone ash, fugitive emissions in storage tank area, and scrubber blow-down water.[52] Figure 2-4 is a schematic of the Waste-Tech incineration process.

A feature that makes this treatment technology highly attractive is its ability to sustain continuous addition of limestone and extraction of bed material during operations; this, in turn, allows the system to operate at lower temperature, thus reducing fuel consumption.[53]

During a RCRA Part B trial burn conducted in October 1987, to demonstrate its operability, the Waste-Tech unit was tested under varying operating conditions (e.g., temperature, feed rate, chlorine

[49] Charles D. Bartholomew and R.W. Benedict, Waste-Tech Services, Inc., "Performance of a Fluidized Bed Hazardous Waste Thermal Oxidation System," paper presented at the 81st Annual Meeting of the Air Pollution Control Association, Dallas, TX, June 19-24, 1988.

[50] Letter from Francis M. Ferraro, Manager Technology Applications, Waste-Tech Services, Inc., to German Reyes, Office of Technology Assessment, Feb. 11, 1991.

[51] The bed is approximately 3 feet deep, with fluidizing velocities ranging between 6 to 8 feet per second.

[52] Bartholomew and Benedict, op. cit., footnote 49, P. 2.

[53] U.S. Environmental Protection Agency, op. cit., footnote 1., P. 4.41.

loading, and particulate loading) with chlorinated waste containing carbon tetrachloride, tetrachloroethane, and p-dichlorobenzene. Dioxins and furans were also tested. With one exception, all bed ash tests showed no measurable amount of any of the chlorinated pollutants treated. No 2,3,7,8 -TCDD was detected in any of the four samples tested.[54]

On the basis of the results obtained during the trial burn, company officials feel that the "fluidized bed combustion system is a viable technology for the destruction of hazardous wastes.' '[55] Currently, Waste-Tech is concentrating its efforts on obtaining a TSCA operating permit for treating PCBs and PCB-contaminated material.[56]

Ogden's Circulating-Bed Combustor (CBC) [57]

The second modification of the fluidized-bed system with good potential for dioxin destruction is the circulating-bed combustor (CBC), designed and built by General Atomics Technologies, Inc. (G.A. Technologies, Inc.) and now the property of Ogden Environmental Services, Inc., San Diego, California. Some unique characteristics of this system (shown in figure 2-5) include its high-velocity combustion medium and, more significantly, the utilization of contaminated soil as bed material. In 1986, EPA referred to the Ogden system as "[appearing] to have significant potential for future use in the destruction of hazardous wastes"[58] today, Ogden holds an operating permit from EPA (under TSCA)[59]

The high-velocity air flow of the system (three to five times higher than conventional fluidized-bed systems) suspends the bed solids, creating a high-turbulence zone (800 to 1,100 'C) into which solid or liquid waste is poured for treatment. Rapid movement of the bed particles and waste materials in turn promotes more efficient combustion at lower temperature, without the need for an afterburner. Residence times are generally 2 seconds for gases and 30 minutes for solids.[60]

The major components of Ogden's CBC incineration system axe:

- a startup combustor burner, which uses natural gas and is off after waste ignition;
- a combustor consisting of a refractory-lined carbon steel tube;
- a cyclone, which is a carbon steel and refractory-lined device responsible for both filtering and recirculating uncombusted bed materials in the suspended gases;
- a flue gas cooler for cooling the off-gases; and
- a baghouse filter that collects the suspended particulate matter of incomplete combustion.[61]

All parts making up the Ogden CBC system can be transported in 17 flatbed trucks; requiring only 2,500 square feet of space to operate and approximately 3 weeks to set up. Ogden Environmental Services currently offers CBC treatment units in a variety of sizes, the smallest being its 16-inch-diameter combustor with a thermal rating of 2 million Btu per hour. Construction of a 36-inch-diameter combustor is now being planned.[62]

Advantages of the Ogden units include the following:

- the absence of moving parts in the combustor to ensure greater reliability;
- simpler operation demanding smaller crews;
- no requirement for scrubbers;
- low-temperature operation that reduces fuel consumption and eliminates the need for an afterburner; and

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[54] Bartholomew and Benedict, op. cit., footnote 49, p. 5-6.

[55] Ibid., p. 9.

[56] Francis M. Ferraro, Waste-Tech Services, Inc., Lakewood, CO, personal communication, Feb. 24, 1991.

[57] See also: H.H. Yip and H.R. Diot, "Circulating Bed Incineration," Hazardous Materials Management Conference, Toronto, Ontario, September 1987; H.R. Diet and H.H. Yip, "Transportable Circulating Bed Combustor for Thermal Treatment of Hazardous Liquids, Sludges, and Soils," Ogden Environmental Services, Inc., September 1987; U.S. Environmental Protection Agency, Office of Research and Development *The Superfund Innovative Technology Evaluation Program: Technology Profiles,* EPA 540/5-90/006 (Washington DC: EPA, November 1990), pp. 64-65.

[58] U.S. Environmental Protection Agency, op. cit., footnote 1., P. 449.

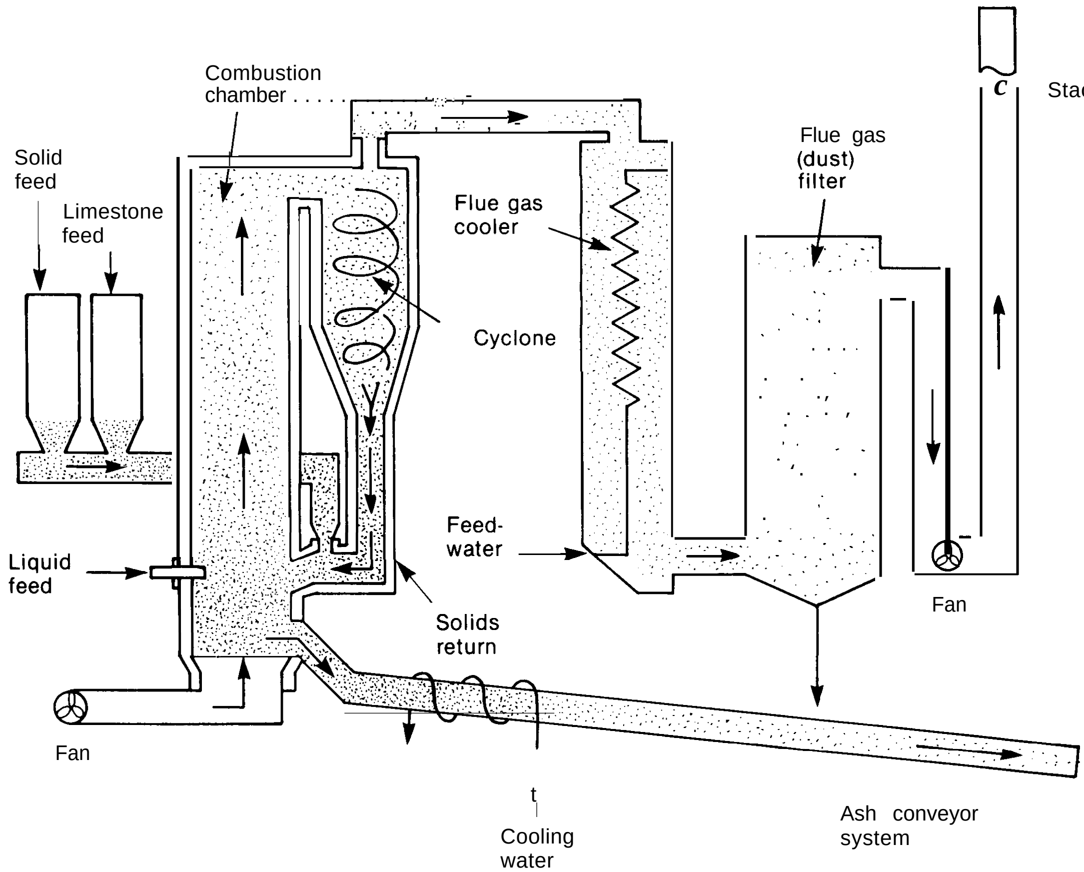
[59] Ogden Environmental Services, Inc., "Circulating Bed Combustion+' undated.

@ales Rosiers, op. cit., footnote 25, P. 47.

[61] U.S. Environmental Protection Agency, op. cit., footnote 1, pp. 4.43,4.49.

[62] Ben Warner, "Ogden' 's Successful 'New Image' Combustor,'' *WasteAlternatives,* December 1989; and, OgdenEnvironmental Services, Inc., "Site Remediation. . . PCB Contaminated soil," undated.

Figure 2-5—Circulating-Bed Combustion System Offered by Ogden Environmental Services, San Diego, CA



SOURCE: Ogden Environmental Services, Inc., "Circulating Bed Combustion," undated.

- the ability to treat dioxin-containing liquid, soil, or sludge waste.[63]

The Ogden CBC system uses high-velocity air to fluidize the bed particles and create a highly turbulent combustion loop. Solids are introduced at a point between the cyclone and the combustion chamber and are immediately swept to the bottom of the combustion chamber. Liquids are injected directly into the combustion zone. The increasing circulating flow of hot air and hot suspended particles around the loop formed by the combustion chamber, cyclone, and return leg maintains a high temperature throughout, thus eliminating the need for an afterburner (see figure 2-5).[64]

Bottom ash is removed from the system on a continuous basis, cooled in a water-cooled screw conveyor, and solidified or packed in drums for final disposition.[65] Hot exhaust gases from the cyclone are passed through the flue gas cooler; once cooled, they are filtered in the baghouse before exiting through the stack. DREs of 99.9999 percent have been achieved with soil containing about 12,000 parts per million (ppm) PCBs.[66]

[63]Ogden Environmental Services, Inc., op. cit., footnote 59.

[64]Fuhr and des Rosiers, op. Cit., footnote 9, p. 35.

[65]U.S. Environmental Protection Agency, op. cit., footnote 1, pp. 4.43, 4.49; des Rosiers, op. cit., footnote 25, p. 47; and Ogden Environmental Services, Inc., op. cit., footnote 59.

[66]des Rosiers, op. cit., footnote 25, p. 47; U.S. Environmental Protection Agency, op. cit., footnote 57, p. 64.

Testing and Availability of Ogden's CBC Technology

Prior to its incorporation into Ogden Environmental Services, G.A. Technologies conducted three trial bums on its stationary pilot-scale unit using soil contaminated with PCBs at levels ranging from 9,800 to 12,000 ppm. Test results demonstrated the ability of the system to meet the destruction and removal standard of 99.9999 percent for incinerating chlorinated waste.[67]

Under Ogden's ownership, CBC technology was tested in 1988 at the Swanson River oil field, Kanai Peninsula, Alaska. The successful achievement of DREs greater than "six nines" was primarily responsible for issuance of a national permit by EPA under TSCA in June 1989.[68]

Ogden has five separate National, State, and local permits; the national permit is one of seven granted by EPA to incinerator facilities in the United States for PCB burning.[69] A summary of existing and planned portable CBC units offered by Ogden is presented below:

- One unit, located in Stockton, California, is part of a soil remediation project involving the cleanup of soil contaminated with fuel oil. A total of 80 to 100 tons of soil is treated and disposed of daily.
- Another unit is operating at Alaska's Swanson River oil field (Kanai Peninsula) to remove and treat about 75,000 tons of PCB-contaminated soil. Completion of the Swanson River project is scheduled for the end of 1991.
- Two additional transportable units are now being built (one of which will be dealing with a coal tar remediation project in California).
- Ogden is also planning to build smaller systems for permanent onsite application, particularly the treatment of waste streams at chemical and petroleum plants.[70]

Cost Estimates for Fluidized-Bed Incineration

Although costs for conventional fluidized-bed systems depend largely on factors such as fuel requirements, scale of equipment, and site conditions, they are for the most part comparable to those of rotary kiln incineration.

The cost of circulating-bed combustion treatment, on the other hand, is considered by EPA to depend more on the size of the incinerating unit and the waste types requiring treatment.[71] For example, installing a 25-million-Btu-per-hour unit costs $1.8 to $2.0 million, with an annual operating cost of $0.25 million for chlorinated organic sludge, $0.35 million for wet sludge, and $0.35 million for contaminated soil. Circulating bed incineration treatment costs per ton of material treated are therefore $60, $32, and $27 respectively.[72] Costs for PCB-contaminated soil, such as that being treated at Swanson River, Alaska, are estimated to range between $100 and $300 per ton.[73] The costs of dioxin treatment are not available. According to a company official, the cost of processing more than 20,000 tons of soil in 1991 is approximately $250 per ton; this price includes site preparation.[74]

HIGH-TEMPERATURE FLUID WALL DESTRUCTION—ADVANCED ELECTRIC REACTOR (AER)

Advanced electric reactor (AER) technology is not available commercially, but R&D shows that it may have potential for dioxin treatment. A typical system consists of a porous tube (primarily graphite) or reactor enclosed in a hollow cylinder. To radiate heat to the waste, the reactor uses radiant energy provided by heated carbon electrodes. Waste is prevented from coming in contact with the reactor core by a blanket of nitrogen flowing countercur-

[67] Ogden Environmental Services, Inc., op. Cit., footnote 59.

[68] Ogden Environmental Service, Inc., op. cit., footnote 59; and Harold R. Diot, Ogden Environmental Services, "Circulating Fluidized Bed Incinerators for Site Remediation: An Update on Ogden's Successes," March 1990.

[69] Warner, op. cit., footnote 62; U.S. Environmental Protection Agency, op. cit., footnote 59, pp. 64-65.

[70] Warner, op. cit., footnote 62.

[71] U.S. Environment Protection Agency, op. cit., footnote 1, p. 4.49.

[72] Ibid., p. 4.51.

[73] Brenda M. Anderson and Robert G. Wilbourn, Ogden Environmental Services, "Contaminated Soil Remediation by Circulating Bed Combustion: Demonstration Test Results,' November 1989, p. 7.

[74] Sharin Sexton, Ogden Environmental Services, Inc., San Diego, CA, personal communication, Jan. 25, 1991.

rently upward through the porous core walls.[75] Although originally designed by Thagard Research (Costa Mesa, California), this technology is known as the Huber process because of proprietary modifications incorporated into the original design by J.M. Huber Corp. (Huber, Texas). Figure 2-6 shows the major components of AER technology.

During processing, liquid or solid waste is poured through an airtight feed bin or nozzle located at the top of the reactor. After passage through the heated reactor (about 4,500 ‘F), pyrolyzed waste products and gases are sent to two post-treatment chambers. Whereas the first chamber is designed to provide additional combustion heat (about 2,000 ‘F), the second cools the off-gases.

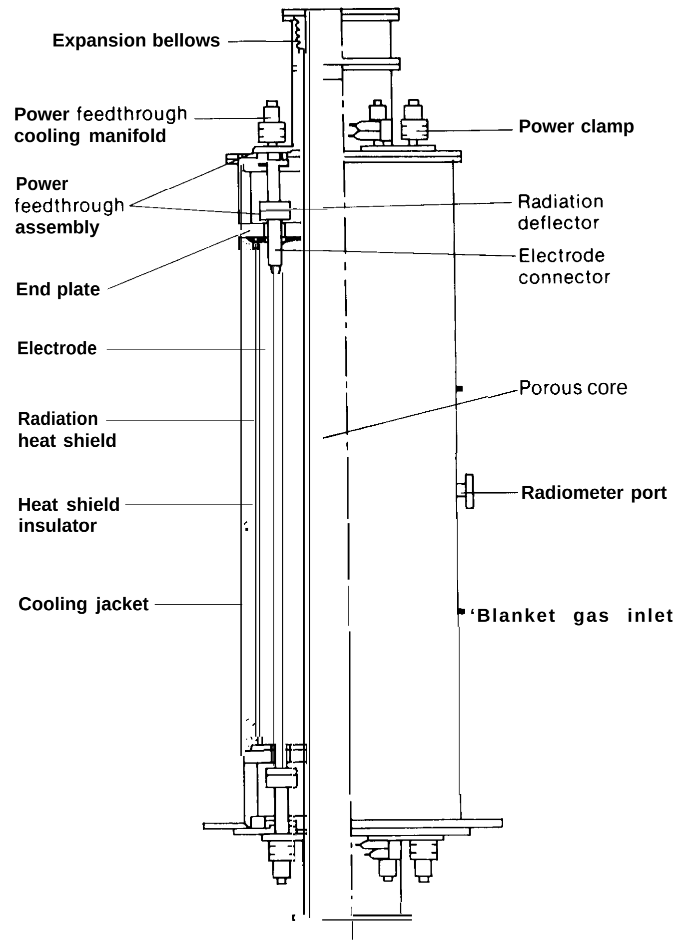
Once cooled, gases are passed through a pollution control system composed of four major devices: a cyclone for collecting particles that did not fall into the solids bin, a bag filter for removing fine particles, an aqueous caustic scrubber for removing acid gases and free chlorine, and an activated carbon bed. In AER technology, activated carbon beds are used primarily to remove trace residues of chlorine and organic compounds.[76]

Some of the advantages of AER considered relevant to dioxin treatment include the following: 1) waste is destroyed by pyrolysis rather than by oxidation as in rotary kiln incinerators; and 2) the extremely lower gas flow rates[77] and the absence of oxygen allow longer residence times, which in turn reduces the production of toxic gases. This results in the emission of much cleaner off-gases through the stack.[78]

Several limitations have also been identified in AER thermal technology. The following limitations are most relevant to the treatment of dioxin-contaminated material:

- the system is unable to treat solids and liquids simultaneously;
- the system treats only free-flowing nonagglomerating solids no larger than 0.0059 inch in size, hence shredding and drying are required prior to treatment; and

Figure 2-6--Major Components of the AER Treatment Process



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

[75] H.M. Freeman, U.S. Environmental Protection Agency, Hazardous Waste Engineering Research Laboratory, “Update on New Alternative Hazardous Waste Treatment Processes,” pp. 8-9. Paper prepared for presentation at conference on Performance and Costs of Alternatives to Land Disposal of Hazardous Waste of the Air Pollution Control Association New Orleans, LA, Dec. 8-12, 1986; H.M. Freeman and R.A. Olexsey, “AReview of Treatment Alternatives for Dioxin Wastes,” *Journal of the Air Pollution Control Association,* vol. 36, No. 1, January 1986, p. 70.

[76] U.S. Environmental protection Agency, op. cit., footnote 1, pp. 4.52-4.55.

[77] Gas flow rates in AER technology differ from those of rotary kiln incinerators by an order of magnitude (350 cubic feet per minute compared to 10,000 cubic feet per minute).

[78] Jim Boyd, J.M. Huber Corp., personal communication, July 16, 1991; H.M. Freeman, op. cit., footnote 75, pp. 8-10; Freeman, “Innovative Thermal Processes for the Destruction of Hazardous Wastes,” *Pollution Equipment News,* April 1988, pp. 108-109; U.S. Environmental Protection Agency, op. cit., footnote 1, p. 4.55.

- the system lacks supplementary fuel sources making it less competitive with conventional incineration techniques (e.g., rotary kilns) for treating waste with high-Btu content.[79]

Cost Estimates for AER Incineration

Treatment costs for AER incineration depend on several factors, including quantity and characteristics of the materials to be incinerated.[80] Although never proven, typical costs for a 100,000-ton cleanup have been said to range from $365 to $565 per ton. J.M. Huber has not used this technology since 1987, opting to invest in other treatment processes with greater market potential. One company official points out that a national research and development program with a focus on dioxin treatment would help to further test and develop this promising technology.[81]

INFRARED INCINERATION

Another technology with dioxin treatment potential but with no current commercial use in the United States is infrared incineration. An infrared incineration mobile pilot unit was developed in 1985 by Shirco Infrared Systems, Inc., Dallas, Texas. It consists of a waste feed system, two combustion chambers (primary and secondary) made of carbon steel, a venturi scrubber system, a blower and heat control system, and a monitoring and pollution control system. The entire unit could be transported in a 45-foot trailer and set up in a few hours for the treatment of PCBs, pesticides, dioxins, and furans.[82]

The primary chamber contains electrically heated silicon carbide elements for radiating incoming waste.[83] Depending on chemicals present in the waste, the elements can be heated to 1,850 °C for 10 minutes to 3 hours. After infrared radiation treatment in the primary combustion chamber has been completed, the partially combusted particulate and exhaust gases are passed into the secondary chamber for complete combustion.[84] The combusted material or ash is then conveyed to the end of the furnace where, after passage through a chute, it is deposited in an enclosed hopper.[85]

Combustion in the secondary chamber is accomplished by using electrical elements in combination with a propane burner; air from the blower system helps maintain the turbulence necessary for complete combustion. Exhaust gases from the secondary chamber are released into the atmosphere after being passed through the wet scrubber for particle removal and cooling.[86]

Testing and Availability of Infrared Incineration Technology

2,3,7,8-TCDD-contaminated (156 to 227 ppb) soil from Times Beach, Missouri was collected and treated by the Shirco pilot-scale technology during a 2-day experimental test in June 1985. Results showed that the Shirco system was successful in treating dioxin, with DRE values exceeding 99.999996 percent. Relatively insignificant levels of dioxin were found in the off-gas. The DRE for gases was calculated and found to exceed 99.999989 percent.[87]

Larger Shirco units have been tested by EPA at several contaminated sites with varying degree of success. Tests of a full-scale unit at the Peak Oil site, Florida and a pilot-scale unit at Township-Demode Road, Michigan, for example, yielded positive results. However, the full-scale unit tested under EPA's Superfund Innovative Technology Evaluation (SITE) Program, has not produced comparable results.

Although infrared incineration has also been employed in remediation of the Florida Steel Corp. Superfund site, Florida and the LaSalle Electric Superfund site, Illinois, much of the success associ-

[79] U.S. Environmental Protection Agency, op. cit., footnote 1, P. 4.55.

[80] Typical energy requirement for treating normal soil is 800 to 1,000 kilowatt-hours per ton.

[81] Jim Boyd, J.M. Huber Corp., Texas, personal communication, Jan. 25, 1991.

[82] Fuhr and des Rosiers, op. cit., footnote 9, p. 32; U.S. Environmental Protection Agency, op. cit., footnote 1, p. 4-61; Freeman, Op. cit., footnote 75, pp. 6-7.

[83] The external dimensions of the primary chamber are 2.5 feet wide, 9 feet tall, and 7 feet deep; with a weight of approximately 3,000 pounds.

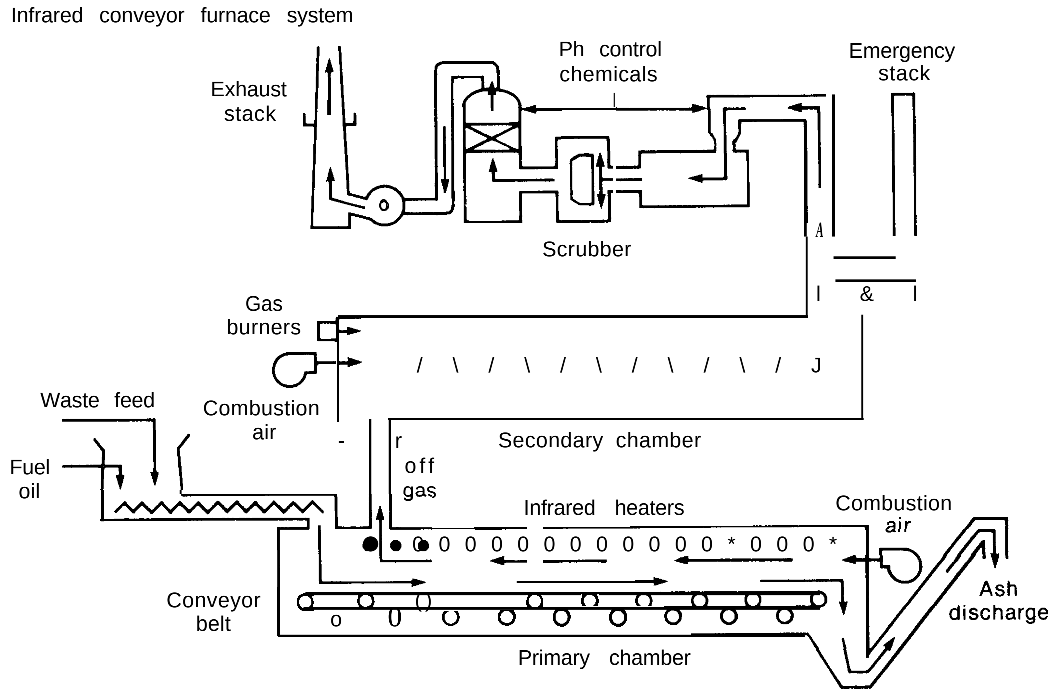
[84] The much lighter secondary chamber (1,500 pounds) is 3 feet wide, 9 feet tall, and 3 feet deep.

[85] U.S. Environmental Protection Agency, op. cit., footnote 1, p. 4.61; U.S. Environmental Protection Agency, op. cit., footnote 57, p. 84.

[86] U.S. Environmental Protection Agency, op. cit., fOOtnote 1, pp. 4.61-4.62.

[87] des Rosiers, op. cit., footnote 25, p. 46; U.S. Environmental Protection Agency, op. cit., footnote 1, pp. 4.62-4.64; and Freeman and Olexsey, op. cit., footnote 75, pp. 70-71.

Figure 2-7—Infrared Incineration Process Offered by Westinghouse Environmental Services, Pittsburgh, PA



SOURCE: Westinghouse Environmental Services, 'Thermal Destruction—Infrared Conveyor Furnace System," undated.

ated with infrared technology has been achieved in Europe.[88] In Hamburg, for example, DEKONTA, a C.H. Boehringer-Ingelheim subsidiary, has completely redesigned the basic unit to the point where it no longer employs the Shirco process.[89]

To date, Shirco Infrared Systems, now known as ECOVA,[90] has built three small pilot units capable of treating 20 to 100 pounds of waste per hour. Each unit can be housed in a 42-foot-long trailer truck for shipment to treatment sites. The Westinghouse Environmental Services Division in Pittsburgh currently offers a full-scale system (shown in figure 2-7) that uses the Shirco process. Westinghouse claims that this unit is able to treat 100 to 175 tons per day.[91]

Cost Estimates for Infrared Incineration Technology

Information on treatment costs for infrared incineration is limited. However, preliminary estimates by EPA indicate that operation and maintenance of the Shirco technology could cost at least $200 per ton of treated waste.[92]

PLASMA ARC PYROLYSIS INCINERATION

Plasma arc pyrolysis (PAP) is a technology currently in the R&D stage, with features that could make it a candidate for dioxin treatment in the future. In PAP, the chemical substances that make up the waste are dissociated into their atomic elements by

88U.S. Environmental Protection Agency, op. cit., footnote 57, p. 85; Fuhr and des Rosiers, op. cit., footnote 9, p. 32; Paul E. des Rosiers, Chairman, Dioxin Disposal Advisory Group, U.S. EPA, personal communication, Dec. 6, 1990.

89des Rosiers, op. cit., footnote 30.

90ECOVA of Richland, WA purchased Shirco Infrared Systems in the late 1980s. An ECOVA subsidiary in Dallas, TX is currently responsible fOr commercializing the Shirco system.

91C. Keith Paulson, Technology, Regulations and Compliance, Westinghouse Environmental Systems and Services Division, Pittsburgh, PA, personal communication, Feb. 11, 1991.

92Ibid. U.S. Environmental Protection Agency, op. cit., footnote 1, p. 4.64.

passage through a thermal plasma field. The thermal plasma field is created by directing an electric current through a low-pressure air stream; plasma fields can reach 5 to 15,000 'C. This system can process nearly 10 pounds per minute of solid or 55 gallons per hour of liquid waste.[93]

The central component of the PAP system is a cylindrical pyrolysis reactor or chamber, which consists of a plasma device, a wet scrubber, a flare stack, a process monitoring system, and a laboratory. These components, plus transformers and switching equipment, can be mounted on a 45-foot-long tractor-trailer bed.

Immediately after waste has been injected or atomized into the plasma device of the pyrolysis chamber, the resulting elements are passed to the second portion of the chamber and allowed to recombine to form hydrogen, carbon monoxide, and hydrochloric acid. The typical residence time in the second portion of the pyrolysis chamber (' 'recombinant zone' is about 1 second, and temperatures are between 900 and 1,200 'C.

Recombined gases are then passed through a wet caustic scrubber for removal of particulate matter and hydrochloric acid. The remaining gases, 'a high percent of which are combustible, are drawn by an induction fan to the flare stack where they are electrically ignited. '[94] Although no supporting data were submitted to OTA, Westinghouse claims that because hydrogen, carbon monoxide, and nitrogen are produced, the gas 'burns with a clean flame after being ignited," which indicates that most toxic constituents have been destroyed.[95]

Some of the theoretical advantages of PAP technology relevant to dioxin treatment include:

- the ease of transport from one site to another;
- the ability to incinerate chlorinated liquid wastes, such as those found at the Love Canal and Hyde Park Superfund sites;[96] and
- the ability to use organic effluents as fuel to run a generator.[97]

The most significant limitation of PAP treatment is that only liquids can be treated. Contaminated soil and viscous sludge thicker than 30- to 40-weight motor oil cannot be processed by the system.[98]

Testing and Availability of PAP Incineration Technology

Westinghouse is currently developing PAP incineration technology (see figure 2-8) but has not specifically tested the system with dioxins. Nonetheless, tests in which PCBs containing dioxins, furans, and other chlorinated pollutants were treated in a bench-scale PAP unit showed dioxin levels in scrubber water and stack gases in the part-per-trillion range. DREs in the test ranged from six to eight nines .99

SUPERCRITICAL WATER OXIDATION

A technology receiving recent R&D effort, with some promise for dioxin treatment, is supercritical water oxidation (SCWO). A system developed by MODAR, lnc., Natick, Massachusetts, is based on the oxidizing effect of water on organic and inorganic substances at 350 to 450 'C and more than 218 atmospheres (pressure)-or a supercritical state. Under supercritical conditions, the behavior of water changes, and organic compounds become extremely soluble whereas inorganic salts become "sparingly' soluble and tend to precipitate.[100]

93Westinghouse Environmental Services, ''Thermal Destruction—Pyroplasma,'' July 1988, p. 2.

94U.S. Environmental Protection Agency, op. cit., footnote 1, p. 4-67.

95Ibid.; Westinghouse Environmental Services, op. Cit., footnote 93.

96Ibid.

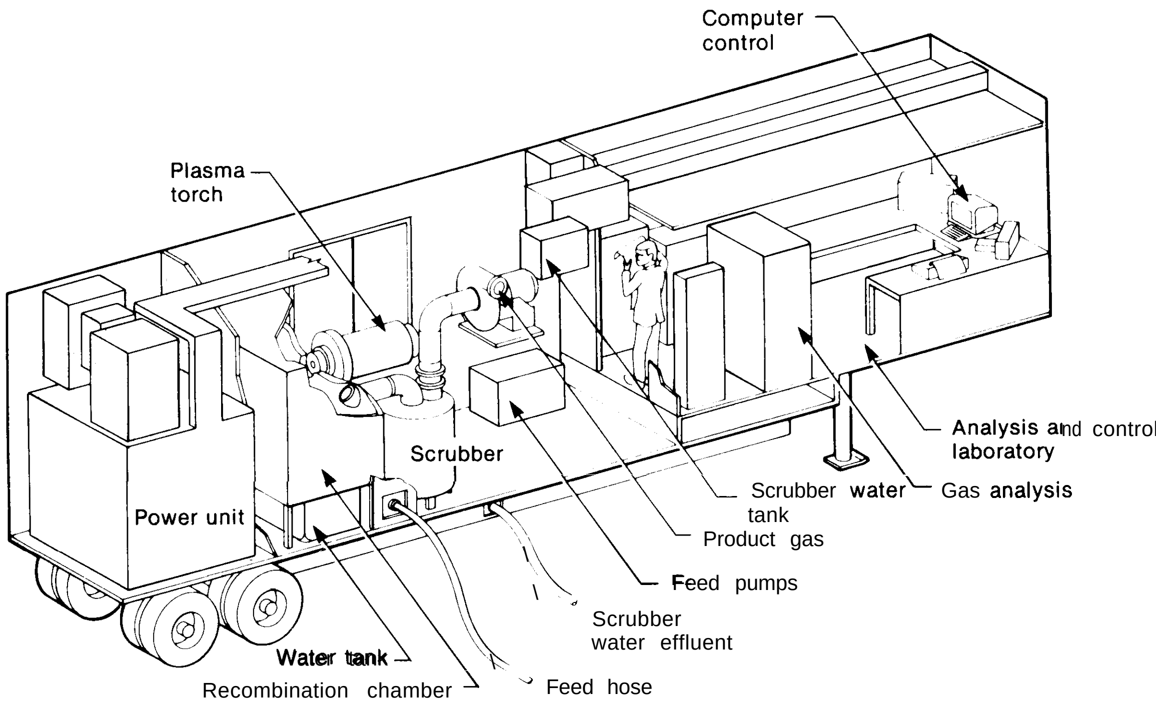
97U.S. Environment Protection Agency, op. cit., footnote 1, pp. 4.68,4.72.

98Ibid., p. 4.67.

99U.S. Environmental Protection Agency, op. cit., footnote 1, pp. 4.68-4.71; des Rosiers, op. cit., footnote 25, p. 48; Fuhr and des Rosiers, op. cit., footnote 9, p. 37; Nicholas P. Kolak et al., "Trial Burns-Plasma Arc Technology,'' paper presented at the U.S. EPA Twelfth Annual Research Symposium on Land Disposal, Remedial Action, Incineration and Treatment of Hazardous Waste, Cincinnati, OH, Apr. 21-23, 1986; Freeman and Olexsey, op. cit., footnote 75, pp. 4-5.

100U.S. Environment Protection Agency, op. cit., footnote 1, pp. 4.80-4.82; Terry B. Thomason et al., "The MODAR Supercritical Water Oxidation Process," paper submitted for publication to *Innovative Hazardous Waste Treatment Technology Series*, Nov. 3, 1988, p. 3. This paper was found in MODAR, Inc., *MODAR Information, an* undated company report; K.C. Swallow et al., "Behavior of Metal Compounds in the Supercritical Water Oxidation Process," paper presented at the 20th Intersociety Conference on Environmental Systems of the Engineering Society for Advancing Mobility, Land, Sea, Air, and Space; Williamsburg, VA, July 9-12, 1990; Freeman and Olexsey, op. cit., footnote 75, pp. 7-8.

Figure 2-8—Westinghouse Environmental Services' Pyroplasma Waste Destruction Unit



SOURCE: Westinghouse Environmental Services, 'Thermal DestructionPyroplasma," July 1988.

The process is designed to convert the intricate arrangements of carbon and hydrogen that make up organic compounds into their most basic forms, carbon dioxide and water. Treatment of contaminated liquid waste results in two effluents-a solid composed primarily of precipitated salts containing metals and elements such as chlorine, and a liquid consisting of purified water.[101] The typical low temperature found during SCWO treatment helps prevent the formation of the primary pollutants sulfur dioxide and nitrogen oxides.[102] Figure 2-9 represents a flow diagram of this technology.

Although SCWO can treat contaminated materials with up to 100 percent organic content, most R&D has focused on aqueous waste containing 20 percent organics or less. In this range, SCWO technology is said to be highly competitive and cost-effective with other available alternative treatment technologies.[103] SCWO can be used to treat organic solids; slurries and sludge may also be treated with the addition of high-pressure pumping systems. The evaluation of SCWO on dioxin-contaminated soil, although successful, has been limited to bench-scale tests.[104]

MODAR's SCWO process involves pumping contaminated materials into a highly pressurized reactor vessel; liquid oxygen and air are also pumped alternatively into the reactor vessel. The optimum heat content of the mixture (1,800 Btu per pound) is maintained either by adding water to reduce the heat content or by adding organic materials or fuels, such as natural gas or fuel oil, to increase it. Caustic may also be added to the supercritical reactor to neutralize the acid produced when organic and inorganic contaminants in the soil or waste are oxidized. Normally, part of the effluent is recycled by mixture with the waste stream being fed into the reactor to maintain proper operating temperatures, as well as rapid and effective destruc-

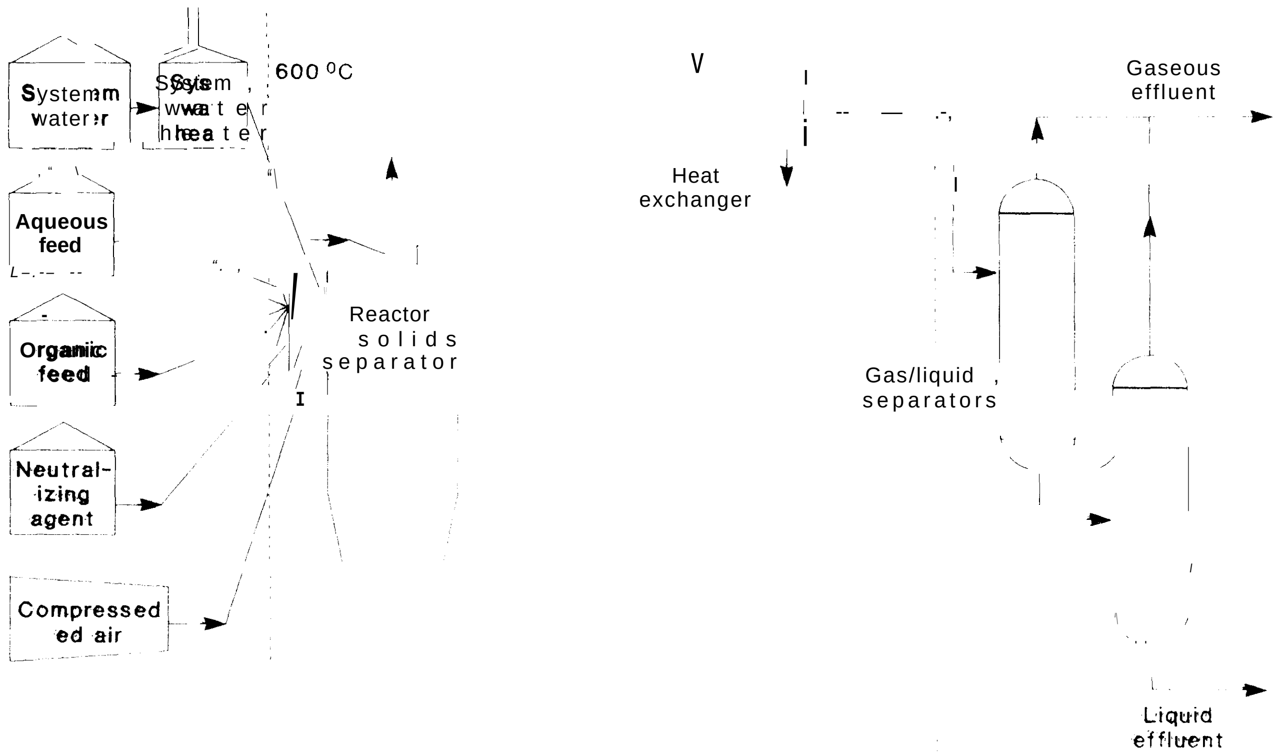
[101] U.S. Environmental Protection Agency, op. cit., footnote 1, p. 4-82.

[102] Thomason et al., op. cit., footnote 100, p. 4.

[103] Ibid., p. 5.

[104] Ibid., pp. 4,5; Ralph Morgan, MODAR, Inc., personal communication, Mar. 28, 1991.

Figure 2-9—Supercritical Water Oxidation Treatment



Feeds are pumped to 23 MPa* operating pressure. System water is heated to 600°C. Compressed air is sent to the reactor with materials to be treated.

*M Pa • megapascal

Organics are oxidized to carbon dioxide (CO_2) and water. Inorganic solids and salts from **neutralized acids are precipated in** the reactor Remaining liquids exit through the top of the reactor into the heat exchanger unit

Fluid from reactor **is** cooled to ambient temperature, and forms a two-phase system

Two phases are separated in gas/liquid separator. Gaseous effluents are **combined** for **sampling.** Liquid effluents are sampled and collected.

SOURCE: K.C. Swallow et al., "Behavior of Metal Compounds **in the Supercritical Water Oxidation Process " paper presented at the 20th Intersociety conference on Environmental Systems of the Engineering Society for Advancing Mobility, Land, Sea. Air, and Space; Williamsburg, VA, July 9-12, 1990.**

tion of pollutants; heat from the effluent can also be used to generate power for running pumps, compressing oxygen, and other uses,[105] According to claims in an undated MODAR report,[106] the SCWO technology has "sufficient instrumentation for operation and automatic control by a distributed computer control system" that includes process monitoring and control, automated start-up/shutdown procedures, and emergency shutoff and response systems.

During SCWO treatment, organic compounds are oxidized rapidly into their most basic chemical components; inorganic chemicals (salts, halogens, metals) become insoluble in the supercritical envi-

[105] Thomason et al., op. cit., footnote 100, pp. 6-7; Carl N. Staszak et al., MODAR, Inc., 'The Pilot-Scale Demonstration of the MODAR Oxidation Process for the Destruction of Hazardous organic **Waste Materials,** ' *Environmental Progress, vol. 6, No. 1, February* 1987, p. 40; and Michael Lawson and Kenneth Brooks, "New Technology Tackles Dilute Waste:, ' *Chemical Week*, Oct 1 1986, p. 40.

[106] '**The MODAR Oxidation Process.** Process Flow Diagram Representative Mass and Energy Balance System Economics,' MODAR, Inc., Nov. 15, 1988. This **paper** was found in MOD. AR, Inc., *MODAR Information*, **an** undated company report,

ronment and descend to the bottom of the reactor where they are removed as salt or cool brine; and hot aqueous and gaseous reaction products are recycled or released to the atmosphere after cooling.[107] Although brine may be disposed of in a deep well, salts-especially if they contain heavy metals—must be disposed of in a secure landfill after proper solidification.[108] The discharged effluents consist of clean water and off-gases (carbon dioxide, oxygen, nitrogen).[109]

The advantages of SCWO technology (if developed as proposed) most relevant to dioxin treatment include the following:

- the reduction of contaminants to their most basic chemical form and the harmless effluents produced eliminate the need to dispose of treated effluents;
- compounds that are difficult to dispose of are reduced to their most basic, nonhazardous forms in a process that can be adapted to a wide range of waste streams or scale of operations;[110]
- all chemical reactions occur in a totally enclosed and self-scrubbing system, thus allowing complete physical control of the waste and facilitating the monitoring of reactions throughout the process; and
- MODAR's SCWO technique can also be applied to condensates produced from the use of soil washing technologies.

The firm marketing this technology claims that it can be cost-effective when compared to incineration, particularly in treating waste with an organic content of less than 20 percent.[111]

SCWO systems are limited by their ability to treat dioxin-contamin ated waste in liquid form. Often, organic waste must be diluted with benzene[112] prior to treatment (to at least 20 percent by weight). Use of the MODAR system for treating waste with higher heat content is not cost-effective.[113] Because SCWO's particle size limitation is 200 microns, it has been suggested that one way to remediate contaminated sites such as Times Beach may be by grinding and pulverizing the soil to make a slurry that can then be oxidized.[114] This practice, however, is yet to be demonstrated and, if proved feasible, may be prohibitively high in cost.

Testing and Availability of SCWO Technology

Since 1984 when SCWO was permitted by EPA as a research treatment facility, the MODAR process has been tested at various locations and on different scales to destroy waste contaminated with substances, such as chlorinated organics and dioxins.[115] Laboratory analysis of the effluents after testing showed no detectable dioxin in the residues.[116] Laboratory-scale tests using waste feed containing a mixture of synthetic dioxin and trichlorobenzene (about 100-ppm concentration) demonstrate a DRE for dioxin in liquid organic waste exceeding the EPA standard of 99.9999 percent. On this occasion, lab tests showed that 110 ppb of 2,3,7,8 -TCDD present in waste was reduced to less than 0.23 ppb.[117]

Bench-scale tests have been conducted on different organic chemicals, including chlorinated solvents, PCBs, and pesticides. Efforts to detect dioxins in treated effluents have been unsuccessful. Similar results were obtained in field demonstrations conducted by MODAR in New York and Pennsylvania. In one test, for example, SCWO treatment of dioxin-contaminated methyl ethyl ketone achieved

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107 Thomason et al., op. cit., footnote 100, Pp.6-7.

108 MODAR, Inc., op. cit., footnote 106.

109 Thomason et al., op. cit., footnote 100, Pp. 6-7, 10.

110 Ibid., pp. 8-10; Terry B. Thomason and Michael Modell, "Supercritical Water Destruction of Aqueous Wastes," *Hazardous Waste, vol. 1, No. 4, 1984, p. 465.*

111 Brian G. Evans, Development Manager, ABB Lummus Crest, Inc., personal communication, Apr. 2, 1991.

112 A known cancer-causing solvent.

113 U.S. Environment@ Protection Agency, op. cit., footnote 1, pp. 4.80-4.82.

114 Evans, op. cit., footnote 111.

115 ABB Lummus Crest, "The MODAR Technology: Supercritical Water Oxidation Process, " a technical profile, undated; Thomason et al., op. cit., footnote 100, pp. 14-15.

116 U.S. Environmental Protection Agency, op. cit., footnote 1, p. 4.83.

117 Fuhr and des Rosiers, op. cit., footnote 9, p.34.

DREs ranging from 99.99994 to 99.999991 percent.[118] MODAR has tested its SCWO process on more than 50 different types of organic waste.[119]

Bench-scale studies of the MODAR technology have also shown that when treated, organic pollutants (e.g., PCBs and dioxins) are oxidized completely to carbon dioxide, water, nitrogen, and inorganic salts with DREs of 99.9999 percent or higher. After oxidation under supercritical conditions, the chlorine present in PCB and dioxin. molecules is converted to inorganic chloride.[120]

Plans for commercialization of this technology began in 1989 as a joint venture between MODAR, Inc. (Natick, Massachusetts), and ABB Lummus Crest, Inc. (Houston, Texas). To date, ABB Lummus Crest, the only worldwide SCWO licenser, offers two engineering packages for small (5,000 gallons per day) and medium-sized (20,000 gallons per day) plants. R&D work is underway with the U.S. Department of Energy at the Savannah River site to treat radioactive organic waste.[121] The National Aeronautics and Space Administration has also shown considerable interest in SCWO because of its ability to treat human waste and recycle water simultaneously.[122]

Cost Estimates for SCWO Treatment

No experience with full-scale operation of this technology is available, and the only cost estimates have been made by private firms marketing these systems. According to ABB Lummus Crest, Inc., costs for dioxin treatment are expected to be higher than liquid incineration but significantly lower than those for rotary kiln incineration--this, however, has yet to be demonstrated. Expenses incurred from permitting and other factors would increase these costs.[123]

IN SITU VITRIFICATION

In situ vitrification (ISV) is a technology developed to thermally treat waste in place and to solidify all material not volatilized or destroyed. It may have application to special types of dioxin contamination if current developments can be successfully tested. ISV was developed in 1980 by Pacific Northwest Laboratories (PNL), a division of Battelle Memorial Institute, under the primary sponsorship of the U.S. Department of Energy (DOE). PNL has also received financial support for vitrification research from the U.S. Environmental Protection Agency and the Electric Power Research Institute. Battelle holds exclusive rights for the application of this technology at DOE sites, whereas the Geosafe Corp., sublicensed by Battelle, is responsible for carrying out the development and application of ISV in the private sector.[124]

Vitrification involves placing four electrodes at specified depths and distances on the surface of the contaminated soil to be treated. Space between the electrodes is covered with a layer of graphite and glass frit to make up for the typically low conductivity of soil. Soil treatment areas may range from 100 to 900 square feet, with a maximum depth of 30 feet per setting. At this depth, its developers expect ISV to be able to treat 800 to 1,000 tons of contaminated soil at rate of 4 to 6 tons per hour. The electrodes and the layer of conductive materials are covered by an octagon-shaped hood to collect off-gases rising from the melting zone and surrounding soil.[125]

As electricity is applied to the electrodes, current flows through the graphite/glass layer, heating it to 1,000 to 2,000°C. Once the top soil layer has been melted, it becomes electrically conducting and facilitates the transfer of heat and current to deeper

[118] Thomason et al., op. cit., footnote 100, pp. 13-14, 15.

[119] Fuhr and des Rosiers, op. cit., footnote 9. p. 34.

[120] Staszak et al., op. cit., footnote 105, p. 42; Terry B. Thomason et al., op. cit., footnote 100, p. 20.

[121] Evans, op. cit., footnote 111.

[122] Glenn T. Hong et al., MODAR, Inc., "Supercritical Water Oxidation: Treatment of Human Waste and System Configuration Tradeoff Study," paper presented at the Space 88 Conference sponsored by the American Society of Civil Engineers, , Albuquerque, NM, Aug. 29-31, 1988.

[123] Evans, op. cit., footnote 111.

[124] 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. 1-2; Geosafe Corp., "Geosafe Corporation Comments on Claims by Larry Penberthy, President of PEI, Inc., Against In Situ Vitrification Technology, Nov. 22, 1990; and James E. Hansen et al., "Status of In Situ Vitrification Technology: A Treatment Process for Destruction and/or Permanent Immobilization," paper presented at the 8th Annual Hazardous Materials Conference, Atlantic City, NJ, June 5-7, 1990.

[125] Geosafe Corp., "Application and Evaluation Considerations for In Situ Vitrification Technology: A Treatment Process for Destruction and/or Permanent Immobilization of Hazardous Materials," op. cit., footnote 124, pp 4,5,6.8

portions of the soil block. The transferred heat and electricity in turn mix or blend different materials and contaminants found in the melting zone.

During melting, solids and contaminants in the soil undergo physical and chemical changes, including:

- thermal decomposition of chlorinated organic pollutants into simpler compounds of carbon, hydrogen, and chlorine;
- breakdown of nitrates into nitrogen and oxygen; and
- thermal decomposition of inorganic soil components into oxides such as silica and alumina.

The latter products are responsible for the crystalline, glasslike appearance that characterizes vitrified soil.[126]

On completion of treatment, electrodes are left in place until the soil cools; once cooled, the electrodes are removed, reused, or recycled. Off-gases escaping the melting zone are trapped within the hood and sent to the gas treatment system, which consists of a quencher, scrubber, dewatering or mist-elimination system, heating system (for temperature and dew point control), and filtration and activated carbon adsorption systems. According to Geosafe officials, only 1 percent of the off-gases treated by the pollution control system originates at the melt itself.[127]

Testing and Availability of ISV Technology

ISV has been tested in the United States and Canada on several different soil types containing heavy metals (lead, cadmium, mercury), liquid organics (dioxin, PCBs, toluene), solid organics (wood, polyvinyl chloride, DDT), and radioactive materials (plutonium, radium, uranium). Although considerable differences were said to exist among tested soils (e.g., permeability, density, water content), the developers claim that they had no adverse effects on the process.[128] The developers, however, caution that when fully saturated soils are being treated, water reduction or extraction should be employed in advance to minimize overall treatment costs, because the removal of 1 pound of water consumes as much energy as the removal of 1 pound of soil.

ISV treatment of soil contaminated with pentachlorophenol (PCP) and PCBs has been subject to concern because of the potential to produce dioxins as well. Dioxins were detected in the off-gas during testing of ISV at the U.S. Navy's PCB-contaminated Superfund site on Guam in 1990. However, no dioxins were detected in most other cases involving pilot testing of ISV on PCB-contaminated soil.[129] In early 1987, a bench-scale ISV test on soil from the Jacksonville, Arkansas Superfund site containing nearly 10 ppb of dioxins, resulted in DRE values of 99.9999 percent; treatment of off-gases would, according to a company report, have resulted in even higher DREs.[130] Figure 2-10 is a flow diagram of the bench-scale unit tested at the Jacksonville, Arkansas site.

Support by DOE and its contractors have been essential for the development and application of ISV, particularly at the nuclear weapons complex. *31 Following the work by DOE, ISV was selected under EPA's Superfund Innovative Technology Evaluation (SITE) program. EPA has since sup-

126 Geosafe Corp., ''Theoretical Basis of process Operation for Volatile Components-Appendix B,'' *Pilot Test Report for Application of In Situ Vitrification Technology to Soils and Ash Contaminated With Dioxin, PCBs, and Heavy Metals at the Franklin Burns Site #1,* vol. 2. GSC 1005, Geosafe Corp., Kirkland, WA, June 27, 1990, p. 8; Geosafe Corp. ''Apphctttlon and Evaluation Consideration for In Situ Vitrification Technology: A Treatment Process for Destruction and/or Permanent Immobilization of Hazardous Materials,'' op. cit., footnote 124, p. 12; and Fuhr and des Rosiers, op. cit., footnote 9, p. 17.

127 Geosafe Corp., "Application and Evaluation Considerations for In Situ Vitrification Technology: A Treatment Process for Destruction and/or Permanent Immobilization of Hazardous Materials,'' op. cit., footnote 124, pp 2-3, 5.

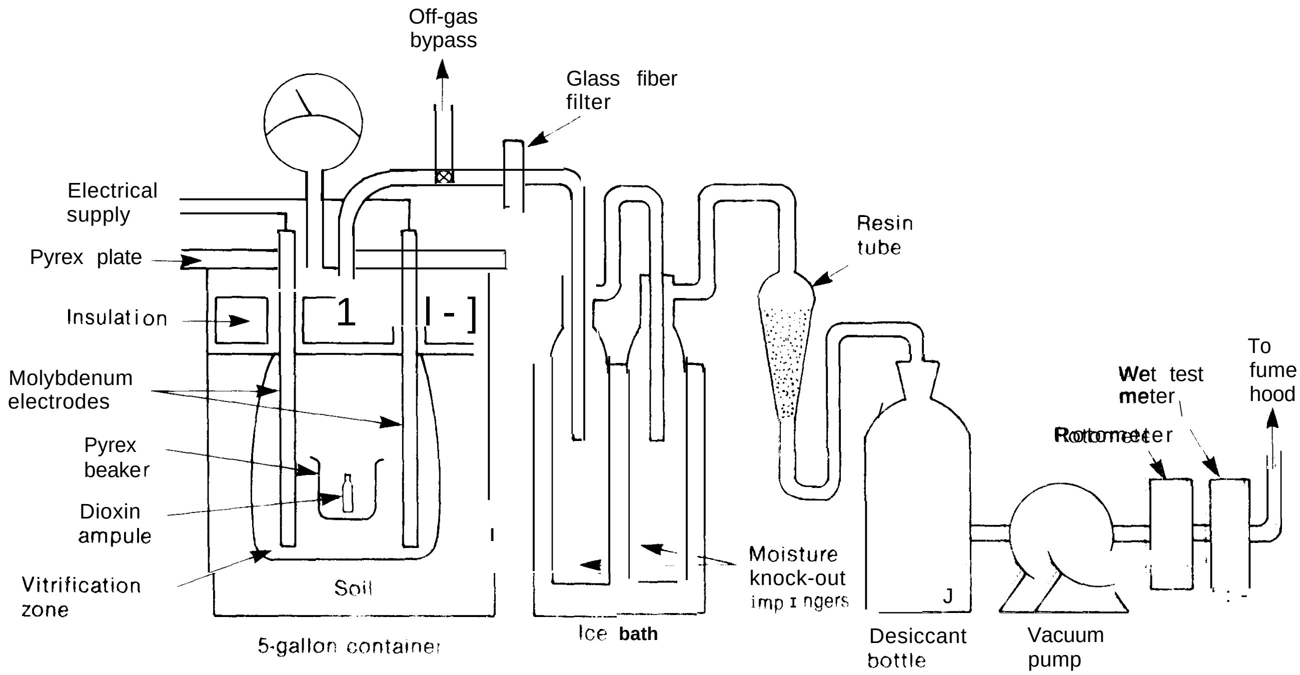
128 Ibid., pp. 13-15.

129 Geosafe Corp., ''Geosafe Corporation Comments on Claims by Larry Penberthy, President of PEI, Inc., Against In Situ Vitrification Technology,'' Nov. 22, 1990; James E. Hansen et al., op. cit., footnote 124; Naval Civil Engineering Laboratory, Engineering Evaluation/Cost Analysis (EE/CA) for the Removal and Treatment of PCB-Contaminated Soils at Building 3009 Site, Naval Civil Engineering Laboratory, Port Hueneme, CA, July 3, 1990, p. 9.

130 S.J. Mitchell, Battelle Pacific Northwest Laboratories, Richland, WA, ''In Situ Vitrification for Dioxin-Contaminated Soils,'' report prepared for American Fuel & Power Corp., Panama City, FL, April 1987, pp 2, 18.

131 For information regarding the status of ISV at DOE weapons Sites, see Office of Technology Assessment, *Long-Lived Legacy: Managing High-Level and Transuranic Waste at the DOE Nuclear Weapons Complex---Background Paper, OTA-BP-O-83* (Washington, DC: U.S. Government Printing Office, May 1991).

Figure 2-10—Bench-Scale ISV Unit Tested With Dioxin-Contaminated Soil From the Jacksonville, AR Superfund Site in February 1987



SOURCE: S.J. Mitchell, Battelle Pacific Northwest Laboratories, Richland, WA, "In Situ Vitrification for Dioxin-Contaminated Soils," report prepared for American Fuel & Power Corp., Panama City, FL, April 1987

ported the testing of this technology at highly contaminated sites.

Thus far, in-situ vitrification has been developed on four different scales: bench (5 to 10 pounds), engineering (50 to 150 pounds), pilot (1O to 50 tons), and large (500 to 1,000 tons). Current plans call for additional tests to gather- the data needed to understand the behavior of large-scale systems in deeper soil, particularly because ISV has not been very successful at depths of more than 16 feet.

According to reports of most bench-scale tests performed, ISV technology has exceeded EPA's efficiency requirement for the destruction and removal of dioxins from soil (9.9999 percent).[132] Additional research, however, is still needed particularly on pilot- and large-scale levels, to demonstrate the effectiveness of ISV.

Cost Estimate for ISV Technology

Cost data for ISV treatment of soil contaminated with dioxins do not exist at this time. Like most innovative technologies discussed in this paper, ISV costs would depend heavily on site-specific factors such as the amount of site preparation required; the properties of the soil to be treated, including volume and the amount of glass-forming material present; treatment depth (the deeper, the less costly because more soil can be treated); moisture content; unit price of electricity: and season of year.[133]

[132] Geosafe Corp., "Application and Evaluation Considerations for In Situ Vitrification Technology ,4 Treatment Process for Destruction and/or Permanent Immobilization of Hazardous Materials, ' op cit., footnote 124, pp 17, 32

[133] Ibid., pp. 13, 28-29.