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THE DESIGN AND DEMONSTRATION OF A FLUIDIZED BED INCINERATOR FOR THE DESTRUCTION OF HAZARDOUS ORGANIC MATERIALS IN SOILS

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Summary

Many types of thermal oxidation systems in existence today are suitable for the destruction of organic hazardous wastes. Few, however, offer the versatility of fluidized beds. Past research and commercial fluidized bed installations have demonstrated the ability of fluidized beds to successfully destroy organic constituents in a wide assortment of gas, liquid, sludge, and solid wastes. This article describes a further advance: the design and testing of a fluidized bed capable of destroying organic constituents in clay, silt, sands, and gravels. This advance makes fluidized beds suitable for on-site waste cleanup of breached lagoons, dump sites with leached liquids, or spills of liquid chemical wastes.

The soil decontamination program was designed to evaluate the effectiveness of fluidized bed systems for total cleanup of sites contaminated with hazardous organic materials. This paper describes the research program conducted to optimize fluidized bed design for this application, and discusses the lessons learned on material handling. The conclusion is that fluidized bed incineration systems are an effective tool for the cleanup of hazardous organic materials in soil.

Introduction

If one were to try to characterize the thrust of the current hazardous waste regulatory program it would have to be "protect groundwater". The historic use of landfills and lagoons, legal or illegal, has left the U.S.A. with a large number of sites where groundwater is already contaminated or soon will be. Currently, a majority of the identified Superfund sites are landfills, pits, ponds, and lagoons which, by definition, contain contaminated soil. Soils contamination is also common in chemical transportation-related accidents.

To date, most soil cleanup tasks have involved excavating the contaminated soil and moving it to a "secure landfill" where the groundwater is reasonably well protected. Other methods include capping of the site with a water-resistant layer to slow leachate penetration, use of slurry walls in an attempt to contain contaminants, and the use of various pump and flush methods to reduce the site's hydraulic head, slowing the migration

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of contaminants off-site. However, with all these methods the problem contaminants remain.

Although reasonably unknown, fluidized beds have been successfully used for incineration of difficult to combust and nonhazardous wastes for many years. Typical objections to the use of a fluidized bed range from preference to the "old-proven" techniques to myths about fluidized bed shortcomings. At Waste-Tech Services, Inc., fluidized beds have been demonstrated on a large number of unique applications ranging from wood waste to nuclear waste. A development program was successfully undertaken in the early 1980s which demonstrated the use of fluidized beds for the destruction of various chlorinated organic and organophosphate wastes [1]. The success in this program prompted an extension of the work to evaluate fluidized beds for the decontamination of soils.

This paper presents the results and implications of a program designed to evaluate the feasibility of utilizing fluidized beds for the destruction of organic chemicals in soils. The program and its results are presented in the following five sections which are broken into the program description, observations and results, system design considerations, applications and limitations, and conclusions.

Program description

System concept

The concept of decontaminating soils by incineration simply involves bringing the soil to a high temperature in the presence of air and "burning off" the toxic organic compounds. Clearly, toxic inorganic elements such as lead or mercury are not detoxified by the incineration process. Features of good gas/solid contact, good mixing, and a highly abrasive environment all contribute to make fluidized beds very effective in this service.

The concept, schematically depicted in Fig. 1, uses a fluidized bed incineration system for soil decontamination and a conventional wet scrubbing system for particulate removal and acid gas absorption. Energy to heat the soil can be supplied by gas, liquid, or solid fuels. Figure 1 shows fuel oil as the supplemental fuel as it is readily available and easily handled.

The soil, be it sand, silt, or clay, is metered into the fluidized bed at a fixed rate based on the nature of the contaminants. The bed is maintained at a specified temperature by the addition of supplemental fuel. Depending on the size of the soil particles, they either reside in the fluidized bed and become a part of the bed or are elutriated out of the vessel with the combustion gases. Particles that remain in the bed are exposed to the incineration temperature for a substantial time period ranging from a few minutes to a few hours. Smaller particles which are elutriated are exposed to the combustion environment for approximately the same time period as the gases. By experience this is set at approximately two seconds. Particles caught in the bed are eventually removed via the bed drain system

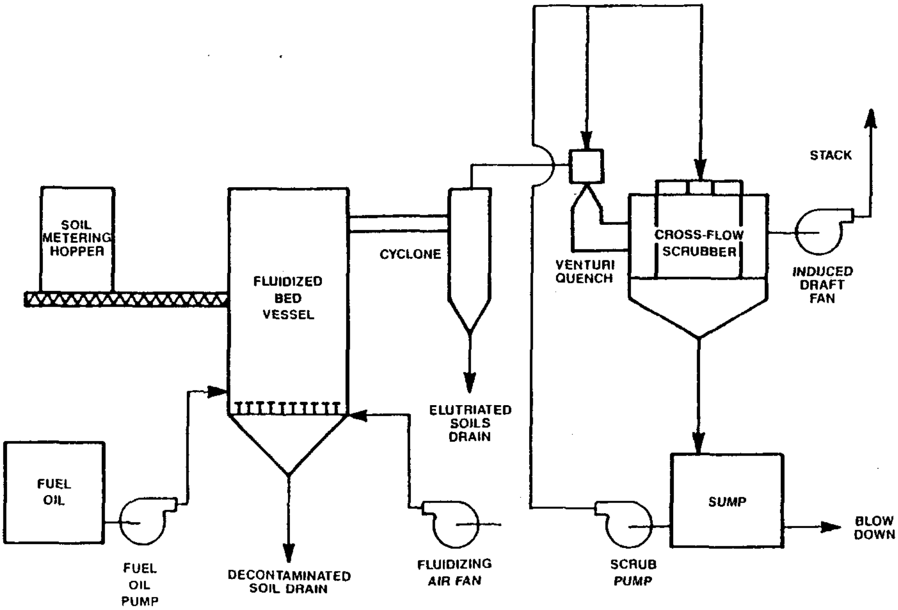

Fig. 1. Fluidized bed soil decontamination system.

which is operated in a fashion that keeps the bed inventory constant. Particles elutriated out of the vessel are captured either in the dry cyclone or in the downstream flue gas scrub system.

Typically, the off-gas cleanup system is a wet scrub system capable of capturing particulate material and neutralizing acidic compounds in the combustion gas. Other off-gas cleanup methods have been considered and are usable, but the conventional wet scrub system is the most flexible for this task.

Before leaving the system concept description, it is appropriate to discuss how the fluidized bed characteristics apply to this waste. Mixing in a fluidized bed (for combustion systems the action is more correctly described as a spouted bed) is very active with bed particles continuously bombarding each other in a very abrasive fashion. The good mixing causes freshly added soil to mix into the bed where it is quickly brought to bed temperature by the bombardment of surrounding hot particles. The abrasive action of the bed actually "sandblasts" organic material from the soil particles and breaks it into small, easily oxidized particles. The bed quickly vaporizes volatile contaminants as the soil particle is actually "floating" on a cushion of hot air.

Test program objectives

The objectives of the program were related to two areas, equipment design and regulatory compliance. From a regulatory compliance viewpoint, the issue of meeting the required Destruction and Removal Efficiency only addresses the stack concentrations of the hazardous organics. An equally important question is what levels of organics can remain in the decontaminated soil while considering it to be nonhazardous. For the purposes of this program, it was decided to operate the system at conditions that would determine reasonably achievable residual levels of organics.

A second objective of the program was the operation of the test facility in a manner that provides design data for future systems. The first feature of this latter objective is simply to make a system that works. Having proven a workable and well instrumented system, the design data objectives then reduce to simply operating the system at numerous operating conditions.

Test program application

The test program was outlined to address various types of contaminants in several types of soil. Two types of soil were readily available: a river bed gravel and local "top soil" which in reality is a fine mixed silicate material with low organic content.

On initial startup of the system, a number of short experiments were carried out using a sand/gravel mixture "contaminated" with laboratory solvents. After developing a successful operating technique with this system, a second phase was undertaken using the top soil (fine sand or silt composition) and reagent carbon tetrachloride as the contaminant. Sodium chloride was added to the feed to evaluate the effect of low melting components. During this phase, numerous destruction efficiency samples were taken to identify the appropriate system operating temperatures. The data from this phase showed general trends in destruction efficiency, but substantial scatter caused a further modification to the feed system as it was the suspected source of the scatter. The last two runs were made by independently metering the soil and organic (90% carbon tetrachloride, 10% dichloroethane) into the feed screw for mixing prior to injection into the system. These last two runs showed excellent reproducibility of destruction efficiency data.

Destruction efficiency samples for the preliminary runs were made using a liquid absorbent analytical method. For these latter two runs, both the liquid absorbent and VOST (volatile organic sampling train) analytical methods were used.

Based on the successful results of the reagent mixture tests, a series of tests was carried out using a soil/sludge mixture which was obtained from a chlorinated solvents manufacturing plant. This mixture contained a large number of chlorinated organics with two through four carbons. Destruction efficiency samples were taken for these runs also.

Description of apparatus

The equipment used is an EPA-permitted fluidized bed incinerator originally designed as a research unit for the development of a fluidized bed liquid destruction system. Modifications for solid waste feeding were minor. The system is shown schematically in Fig. 2.

The fluidized bed vessel is an insulated eight-inch-diameter stainless steel pipe with numerous penetrations for instrumentation and feed input. The overall vessel height is 13 feet. The fluidizing/combustion air is distributed in the bottom of the vessel using a perforated ring manifold. By using a manifold distributor instead of a perforated plate, it is possible to remove excess bed from the bottom of the vessel through a drain valve.

Since experiments were carried out using a 14- to 24-inch-deep fluidized bed, approximately ten feet of empty vessel was available for combustion outside of the bed itself.

The unit is equipped with a propane-fired air preheater system for initial startup. After reaching the ignition temperature, fuel oil is fired directly into the bed. This same fuel oil source is used as the supplementary fuel during contaminated soil operation.

The feed system is a sloped-sided hopper with a variable speed auger in the bottom for metering the waste into the vessel and a vibrator to assist in achieving uniform flow. A manual level indicator is used to determine when the hopper is empty.

The off-gas cleanup system consists of a dry cyclone for particulate removal and a caustic neutralized wet scrub system for HCl removal and additional particulate removal. The sample tap location for stack samples is immediately downstream of the dry cyclone. This location gives an incinerator destruction efficiency and takes no credit for any removal in the scrub system.

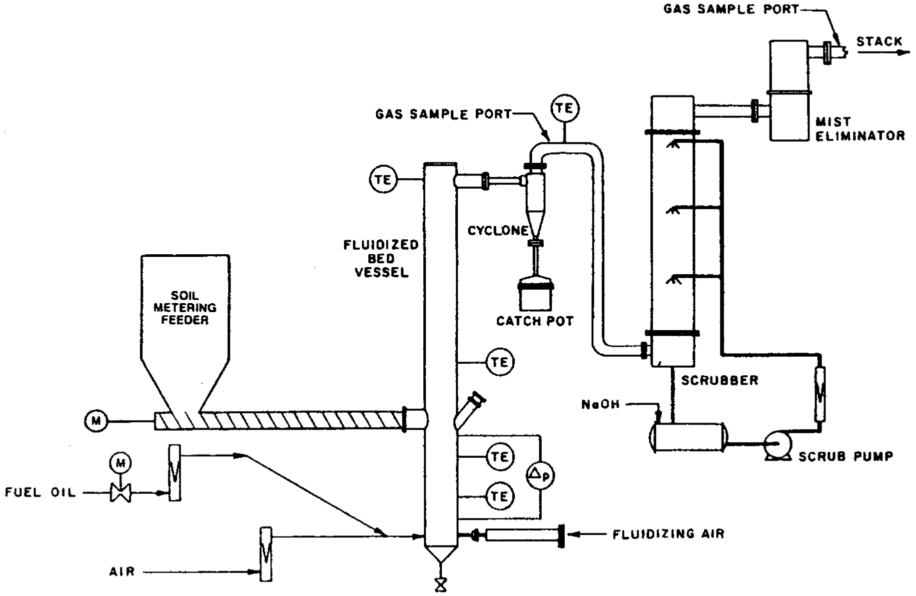

Fig. 2. Eight-inch pilot plant schematic.

Startup of the system was carried out by first using the propane preheater to heat the fluidizing air and subsequently the bed medium (soil). The bed medium first used was inert, but each subsequent run used the bed left from the previous run so the latter runs used a "soil" bed media. When the bed reached 400°C it was possible to turn on the in-bed fuel oil system which completed the preheat to the desired bed temperature, typically 800 to 900°C. When the system temperatures stabilized, the automatic feed cutoffs were set and feed was metered into the bed at the desired rate. An automatic fuel oil control system maintained the bed temperature at the desired value. In the case of gravel feeds, some bed material was periodically removed to maintain a constant bed level. The fine soil essentially all elutriated to the cyclone. An automatic caustic injection system maintained the scrub system pH.

Off-gas analysis procedures

Two different sampling methods were used during this study. Most of the preliminary data was taken using a liquid absorbent technique described below. At the end of the program, stack analyses were taken using a volatile organic sampling train (VOST). The liquid absorbent technique was evaluated by Young and Trejo [2]. The VOST systems was evaluated by Jungclaus et al. [3].

Liquid absorption method

To assure a timely pilot plant development, it was necessary to analyze the off-gas stream several times per day as combustion conditions were varied in an effort to optimize destruction conditions. Therefore, a large number of samples needed to be analyzed in a short time to supply the data necessary to set conditions for subsequent pilot plant runs. Therefore, a liquid absorption method was developed to directly analyze a liquid solution for the principal organic hazardous constituents (POHC) with as short a turnaround as possible.

The use of liquid absorbers was limited to solvents that are soluble in water because water vapor is present in the gas samples analyzed. The water from combustion would form emulsions unless a water-soluble solvent was used. Similarly, if the POHC is not soluble in the absorber, a two-phase system would also develop. These two-phase systems would interfere with the direct analyses of the impinger solution. This limits the absorber to a water-soluble liquid that shows appreciable solubility for organic compounds.

At this point, alcohols were considered. Methanol proved to be too volatile and it is also toxic. Ethanol, butanol, and higher alcohols were too expensive and were not readily available. Isopropanol was found to be inexpensive and is readily available in a pure form, so it was the absorbent of choice.

Bench-scale absorption tests

The liquid absorption system was tested on a bench-scale system to determine the trapping efficiencies for different compounds. Carbon tetrachloride, dichlorobenzene, and hydrochloric acid were placed in a tared flask and heated air was drawn through the compounds, through a heated packed tube, and then into the modified Greenberg—Smith impingers. At the end of the test, the flask was weighed to determine the amount of compound used.

The other compounds tested were phenol, pentachlorophenol, 2,2'-dihydroxybiphenyl, acenaphthylene, biphenyl, and phenanthrene. These compounds had a weighed aliquot placed in a combustion boat. The boat was placed in an oven with a packed bed. The temperature was raised to 400°C over a 35-min period. The trapping efficiencies are listed in Table 1.

TABLE 1

Trapping efficiencies for 2-propanol

Compound	Overall efficiency	% Trapped in impingers			
		1	2	3	4
Carbon tetrachloride	99%	67.2	23.2	7.3	2.2
Dichlorobenzene	97	98.8	1.2	–	–
Phenol	100	100	–	–	–
Pentachlorophenol	99	74	11.5	13.1	1.2
2,2'-Dihydroxybiphenyl	99	76.3	12.4	11.4	–
Acenaphthylene	97	87	12	0.8	–
Biphenyl	90	87	11	1	–
Phenanthrene	90	83	1.5	2	–
Hydrogen chloride	100	97.5	2.3	0.2	–

VOST

The VOST system was developed by the EPA for sampling gas streams for volatile organic compounds. The method and application are described in detail by Jungclaus et al. [3]. The sampling train consists of a condenser followed by an absorption tube containing Tenax GC. The gas then goes into a condensate collection flask before passing through another condenser and into a second absorption tube containing Tenax GC followed by charcoal. The gas then goes through a second condensate collection flask, through a silica gel absorber, through a rotameter, then a dry gas meter, and through a pump. After sampling the gas stream, the POHCs are desorbed in an oven and the gas stream flows through a purge and trap device and into the GC or GC/MS. By selecting the proper conditions and detectors, stack samples can be taken when feed concentrations range from a few ppm to several percent.

Observations and results

During the early operation of the system on the sand/gravel tests, a number of significant qualitative observations were made. As predictable, a high throughput rate of "soil" is possible without influencing bed behavior. A second observation is that the fluidized bed temperature control is very good which avoids "hot spots" and melting problems. The last observation relates to the material balance which indicated that the sand tends to break down into small particles which are elutriated out of the fluidized bed as fines.

The second phase of operation using the silty soil contaminated with carbon tetrachloride was informative in defining the conditions necessary to achieve a minimum destruction efficiency of 99.99%. The system was operated with a gas residence time of 1.3 s and a bed temperature of 850°C. The data showed that it is necessary to control heat losses to keep the incinerator exit temperature greater than 600°C to achieve 99.99%. The silty soil also elutriated from the fluidized bed vessel and did not build up in the bed.

It was mentioned earlier that scatter in the destruction efficiency data limited the value of the results from the first experiments. After careful review of the system, it was determined that the scatter was resulting from a nonuniform feed rate of dirt and organics. With this discovery, the feeder was rebuilt to mix the dirt and organics in the feed screw and two runs were made with the specific purpose of getting good destruction efficiency samples. During this run, a VOST train sampling system was used in parallel with the liquid absorbent train which was used on earlier runs. The run conditions and destruction efficiency results are given in Table 2.

In general, the analytical precision of the multiple samples is good. The liquid absorption sample results were very close to each other ($<15\%$ difference) and the VOST train samples were also acceptable ($<50\%$ difference). The samples showed the incineration conditions to be acceptable to achieve the required destruction.

The second concern was related to bed agglomeration from the presence of low melting materials. To evaluate this effect, sodium chloride was added to the feed for a number of runs and enough salt was added to replace about 30% of the bed media over 32 hours of operation. No detrimental effects were observed. The explanation appears to be related to the high elutriation rate of the soil which carries the salt out of the combustion vessel.

The remaining question deals with the extent of decontamination of the soil. Since the soil was all elutriated, the "residence time" of the soil in the high temperature incinerator is considered to be similar to that of the gas, 1.3 s. The carbon tetrachloride level was found to be less than 0.5 ppm in the cyclone and less than 0.002 ppm in the bed.

With the success of the carbon tetrachloride reagent tests, an experiment was carried out using a sludge taken from a sump in a chloroethylene plant. The sludge was diluted with approximately an equal quantity of sand to give it a "wet dirt" character. A combustion test was carried out with this material using a bed generated in earlier sludge burning tests. Operating conditions were as given in Table 3.

The feed rates of several of the key components are listed in Table 4 along with the destruction efficiency for those components. The destruction efficiencies for three of the four principal components were acceptable. There is currently no explanation for the poor destruction for perchloroethylene as its chemical composition and heat of combustion would predict a destruction efficiency similar to that of carbon tetrachloride. The general conclusion from the run is that satisfactory destruction efficiencies were readily achievable at these conditions.

TABLE 2

Operating conditions for soil decontamination

	Run No.1	Run No.2
Fluidized bed temperature (°C)	850	850
Combustion vessel exit temperature (°C)	650	650
Vessel residence time (s)	1.3	1.3
Feed rate		
Soil (kg/h)	10.5	6.17
Carbon tetrachloride (kg/h)	0.32	0.40
Dichloroethane (kg/h)	0.035	0.044
Destruction efficiency (%)		
Carbon tetrachloride		
by liquid absorbent	99.985	99.993
by VOST	99.998	99.996
Dichloroethane		
by liquid absorbent	>99.7	>99.7
by VOST	99.998	99.997

TABLE 3

Chloroethylene plant sludge combustion test conditions

Fluidized bed temperature	910°C
Combustion vessel exit temperature	794°C
Vessel residence time	2.0 s
Waste feed rate	12.3 kg/h (27.1 lb/h)

TABLE 4

Chloroethylene plant sludge destruction efficiency

Component	Feed composition (%)	Destruction efficiency (%)
Chloroform	0.26	>99.997
Carbon tetrachloride	0.19	>99.995
Trichloroethylene	0.54	>99.998
Perchloroethylene	0.15	99.96

System design considerations

Scale-up of the pilot fluidized bed to commercial scale size involves the solution of a number of problems dealing with solids injection and removal from the reactor, soils sizing, agglomeration considerations, high particulate carryover from the bed, and the proper design for addition of supplemental fuel.

For reasons of simplicity and the ability to achieve a good feed distribution, an over-bed mechanical/pneumatic soils injection system is recommended. Properly screened soils are metered to the feeder which is comparable to a conventional coal stoker feeder. Large particles are mechanically spread across the surface of the bed by a rotating paddle. Fine particles are carried out onto the bed by a pneumatic assist provided along the outer lip of the feeder.

To provide for good distribution and to allow for solids removal from the bed, all rock and soils must be prescreened such that only particles smaller than three inches are admitted to the feed system. Oversize particles may be crushed and recycled to the screens.

Based on decontamination feed rates demonstrated in the pilot tests and calculated system throughputs for various contaminated soils, a soils removal system designed for high letdown rates is required. Because of the diversity of the bed material, typical bed overflow designs are unacceptable. Instead, a system has been developed which utilizes a series of transverse air distribution headers to distribute the air [4] and a "cone-within-a-cone" bed letdown system provided for even bed letdown [5]. This is the same system that has been successfully used on over 30 commercial fluidized beds for combustion of forest products wastes which commonly have a high percentage of rocks and logging-related tramp material associated with it. The system is shown schematically in Fig. 3. The cone-within-a-cone system provides for even bed letdown across the entire cross-sectional area of the bed by means of a series of holes in the inner cone. Each hole creates its own "rathole" within the packed bed region below the bubble caps. Proper sizing and location of the holes provides for even

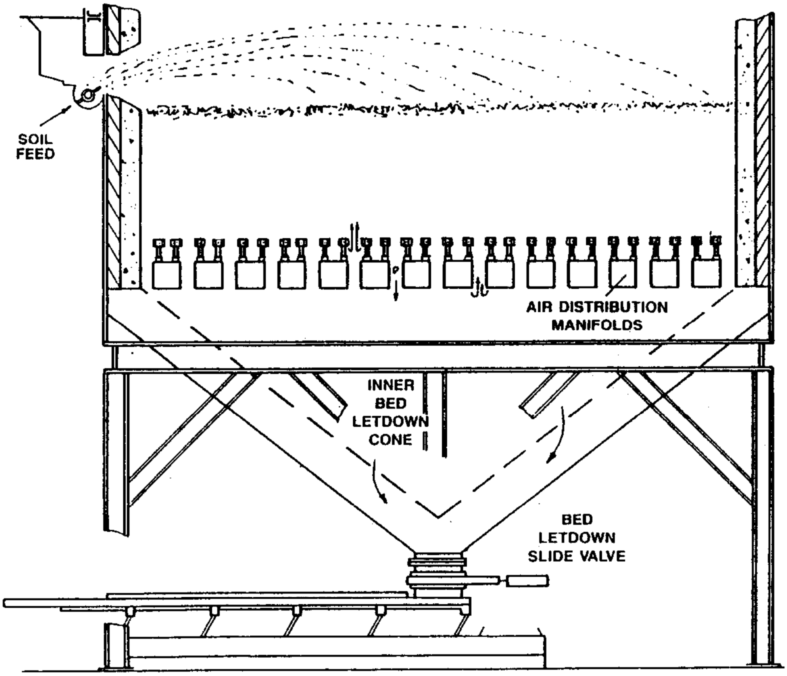

Fig. 3. Proposed soils removal system for high letdown rates utilizing a series of transverse air distribution and a "cone-within-a-cone" bed letdown system.

letdown into the gap between the cones which acts as a slide directing the inert soils toward the discharge at the bottom of the outer hopper. The soils are gradually withdrawn from the hopper by pulsed operation of the withdrawal slide valve. Removal of soils from the letdown port causes soils to be drawn down between the air distribution headers. These soils are cooled and the sensible heat recovered by a small quantity of the fluidizing air which is bled into the vessel along the bottom of the air distribution headers. This air, rising between the headers at a velocity below that required for fluidization is, in effect, preheated before entering the active portion of the bed while at the same time cooling the soils.

Depending on the type of soils processed, a sizable portion of the total feed may become entrained in the gas stream and be carried out of the reactor. To ensure organics destruction in the entrained fines, the system is designed to provide a two-second residence time in the incinerator above the solids injection port at or near the temperature of the bed. One or more hot cyclones is employed at the exit from the fluidized bed vessel to provide for removal of a majority of particulates from the gas stream in a dry form prior to off-gas quenching and final cleanup.

Supplemental fuel, required to achieve temperatures sufficient for breakdown of organics, is added directly into the bed either through the sidewall or, if the system is of sufficient size, through both sidewall and underbed injection ports. The inherent thermal "inertia" of the large mass of solids within the reactor provides a system with low sensitivity to feed heating value perturbations. The resulting long time constants associated with bed temperature easily permit a supplemental fuel feed control system to control temperatures within the reactor to ±5.5°C (10°F).

Applications and limitations

Current trends toward rejection of presently employed "fixes", aimed at containing in-place waste accumulations rather than destroying the wastes and rising resistance to transportation of wastes from one site to another, are resulting in the need for systems that can be temporarily brought on-site to destroy wastes. Such systems must be large enough to economically destroy large quantities of wastes in a reasonable period of time and sufficiently versatile to address the wide variety of contaminated substances typically found at waste sites. Properly designed, bubbling-type fluidized beds fit these criteria.

A modular fluidized bed system designed for over-the-road or rail transportation having a bed area of 4.65 m^2 (50 square ft) with operating conditions comparable to those demonstrated in the tests has the following throughput capacities based on a variety of wastes typical of those found on remedial action sites:

Waste stream	*Throughput* kg/h (lb/h)
Contaminated soil (2% organics, 5% H_2O)	4173 (9200)
Contaminated soil (8% organics, 5% H_2O)	3162 (6750)
Separator sludge and still bottoms (6% organic, 81% H_2O, 13% inerts)	1172 (2583)
Heavy still bottoms (70% organic, 30% inert, 0% H_2O)	611 (1348)

Throughput is primarily a function of the waste composition.

Economics for a system decontaminating soil of a size suitable to create its own bed, containing two percent nonchlorinated organics and five percent moisture, with a decontaminated solid by-product passing EPA's toxicity tests allowing for disposal back into the excavation, will have the following operating costs:

	Hourly cost
Labor (including fringe)	
Crew chief, operator, technician, clerk	$ 77.55

Consumables and utilities	*Hourly cost*
Electricity: 30 kWh $0.08/kWh	26.40
Supplemental fuel: 350 l/h fuel oil $0.26/l	91.00
Water: 1230 l/h $0.0008/l	9.84
Nonlabor	
Equipment depreciation: 5 year, straight line	48.65
Siting costs (based on six months operation)	22.83
Maintenance materials	3.91
Insurance, taxes, and overhead	10.42
Miscellaneous site support costs	20.53
Total hourly cost	$310.53

This results in a cost of $0.074 per kilogram ($0.034 per pound). Additional costs ranging from $0.060 to $0.095 per kilogram ($0.027 to $0.043 per pound) may be incurred for waste excavation, ash replacement, and caustic costs for chlorinated wastes, providing a total cost ranging from $0.134 to $0.169 per kilogram ($0.061 to $0.079 per pound).

Higher costs per kilogram will result for wastes having organic contents greater than that required to sustain operation at temperature without the need for supplemental fuel. Above this point, unit thoughput is limited based on the maximum heat release commensurate with the fluidized bed process design parameters.

Thermal cleanup costs for contaminated soils are comparable to or slightly higher than comparable costs associated with excavation, transportation, and reburial in a permitted landfill. This potentially higher cost for permanent thermal destruction must be weighed against the potential liability of off-site transportation risks and the long-term liability associated with a failure of the secondary landfill.

Wastes recovered in barrels or mixed with inorganics having a dimension larger than three inches will require processing prior to injection to the incinerator to assure a feed size less than three inches. This limiting dimension assures troublefree letdown of bed material between the air distribution headers. A low speed rotating shear has been demonstrated to size reduce typical oversize objects such as barrel parts and rocks.

Salt concentrations in contaminated soils are generally not a consideration in determining the suitability of fluidized beds. The high rate of particulate elutriation typically results in salt carryover at a rate sufficiently high to prevent in-bed salt concentrations which result in bed agglomeration.

Conclusion

The general objective of this program was to develop and operate a pilot system to demonstrate decontamination of various organically contaminated soils. This objective was met. Operation with sand and silt-type soils was carried out continuously and destruction efficiency of the organics in the incinerator meets the EPA requirements. The soil is almost all elutriated from the combustion vessel in the combustion gas stream, and the residual organic contents are very low (< 0.5 ppm).

Based on the pilot studies, a system design and a cost estimate were prepared for a transportable incineration system which could be brought to a site, operated for a limited time period decontaminating a site, and then removed. The economics of soil thermal decontamination are primarily a function of the concentration of organics in the soil. Based on a large transportable system, the cost for thermal decontamination in a fluidized bed is comparable to or slightly higher than that associated with excavation, transportation, and reburial in a "secure" landfill with the advantage that on-site decontamination eliminates liabilities associated with transport and long-term storage.

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