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Technology Assessment of the Vertical Well Chemical Reactor

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TECHNOLOGY ASSESSMENT OF THE VERTICAL WELL CHEMICAL REACTOR

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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communications link between the researcher and the user community.

This report assesses a promising new technology which utilizes the well known wet combustion process to treat high strength organic wastes. Because of its unique configuration, the technology labeled the vertical well chemical reactor (VWCR) has the potential to oxidize these wastes more safely and more economically. The report describes how the VWCR works, analyzes its development to date, evaluates the technology it uses and makes preliminary cost and energy estimates. The report also compares the VWCR to equivalent technologies and makes an assessment of its potential national impact.

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ABSTRACT

The vertical well chemical reactor (VWCR) is designed to oxidize high strength organic wastes using wet combustion principles. The reactor vessel consists of two stainless steel concentric tubes suspended in a well and surrounded by a heat exchange jacket. Provisions for air injection to support combustion are included.

VWCR concentric tube configuration uses little space compared to above ground wet oxidation vessels and promotes efficient heat exchange. Waste pressurization from the weight of the liquid above results in safer and more economical operation. Full-size reactors are expected to descend as much as 6000 feet and operate at temperature and pressures exceeding 650°F and 2200 psi respectively. An important potential benefit from VWCR operation is energy recovery from autothermal oxidation of the high strength wastes.

Bench scale COD reduction experience using a batch laboratory reactor has been similar to that obtained from the pilot plant, supporting the use of bench scale treatability studies to model expected COD reduction rates. COD reductions of waste sludges have approached 50 percent on pilot scale. As much as 80 percent COD reduction is expected for full-scale where higher temperature and pressures can be attained. The poorly understood interacting effects of metal solubility, adsorption and desorption has not permitted a definitive explanation about the fate of metals in the VWCR. More work needs to be done in this area. In other independent but related work, detoxification of specific organic compounds by wet oxidation suggests the VWCR is a viable method for treatment of toxic wastes.

Much of the pilot scale effort has concentrated on solving structural, mechanical, and other operational problems. Construction is expected to begin in late 1981 on a full-scale demonstration plant at Longmont, Colorado. Design and operation of this plant will address the major problems encountered during pilot scale operation. Important among these are pit corrosion, scale formation, and leaking joints.

In summary, the VWCR is a potentially desirable treatment process for stabilization of organic wastes when significant sludge volume reduction is required, where stringent requirements for sludge disposal exist, when destruction of toxic materials or pathogenic organisms is necessary, or where potential energy recovery from high strength wastes is good. A major goal remaining is to demonstrate VWCR steady-state operation at full-scale. This experience will not only produce operational information and characterize certain process variables, but will better define actual operating costs for various strength wastes so they can be more realistically compared to competing processes.

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SECTION 1

TECHNOLOGY DESCRIPTION

INTRODUCTION

The Vertical Well Chemical Reactor (VWCR) is designed to oxidize high strength wastewaters and sludges utilizing wet combustion principles. If sufficient air (oxygen), temperature, and pressure are present, organic substances can be oxidized in a liquid state. The oxidation reaction proceeds exothermically and if organic content of the material is high enough and heat losses are controlled, combustion may be thermally self-sufficient. Autothermal oxidation is a desirable although not required benefit of the VWCR process. Sludge, with its concentrated organics and therefore higher heating value, is the preferred wet oxidation medium but wastewaters containing organic materials with high oxygen demands may also be considered.

Configuration of the VWCR is unique for its purpose. Wastewater flows down the center tube of two concentric vertical tubes and returns in the annular space. Use of this vertical tube configuration has multiple purposes. Tube diameter and length are designed so that sufficient reaction time and pressure desired during fluid waste oxidation can be attained. Pressure is developed naturally by the hydrostatic liquid head above the waste flowing down the tube. Heat resulting from the exothermic combustion reaction maintains much if not all of the downhole temperature required to sustain the reaction. Any required heat is input by a fluid heat exchanger. Conversely, excess heat can be recovered to the ground surface for use as an additional energy source.

The VWCR configuration utilizes little space and can be placed in existing well shafts when feasible. Its concentric configuration minimizes reactor heat losses. As the surrounding earth approaches equilibrium with a continuously operating VWCR, operation will be less affected by waste quality changes or outside (climate) influences because the surrounding earth will act as a thermal buffer. Heat loss to the surrounding rock for a rock conductivity of 0.4 BTU/ft-hr-^{o}F is estimated to decrease by 66% after one year (1). With the exception of the high pressure pumping requirements needed for the heat exchange fluid and moderate pressure requirements for air compressors, the natural hydrostatic head in the well eliminates high pressure pumps or fluid containment vessels and their associated pressure controls. Natural pressurization is fixed at any point however and depends on the weight of liquid above it. VWCR's vertical configuration and compactness make downhole accessibility difficult should temperature and pressure measuring devices or other well components need to be unplugged, inspected, or replaced. Thus mechanical reliability and maintenance of the VWCR system is an important consideration.

DETAILED TECHNICAL DESCRIPTION (1)

Figure 1 is a process flow diagram showing a vertical section of the VWCR. Figure 2 shows a cross section of the reactor. Neither is to scale. These figures are from the first full-scale design which will extend approximately 6000 feet into the ground.

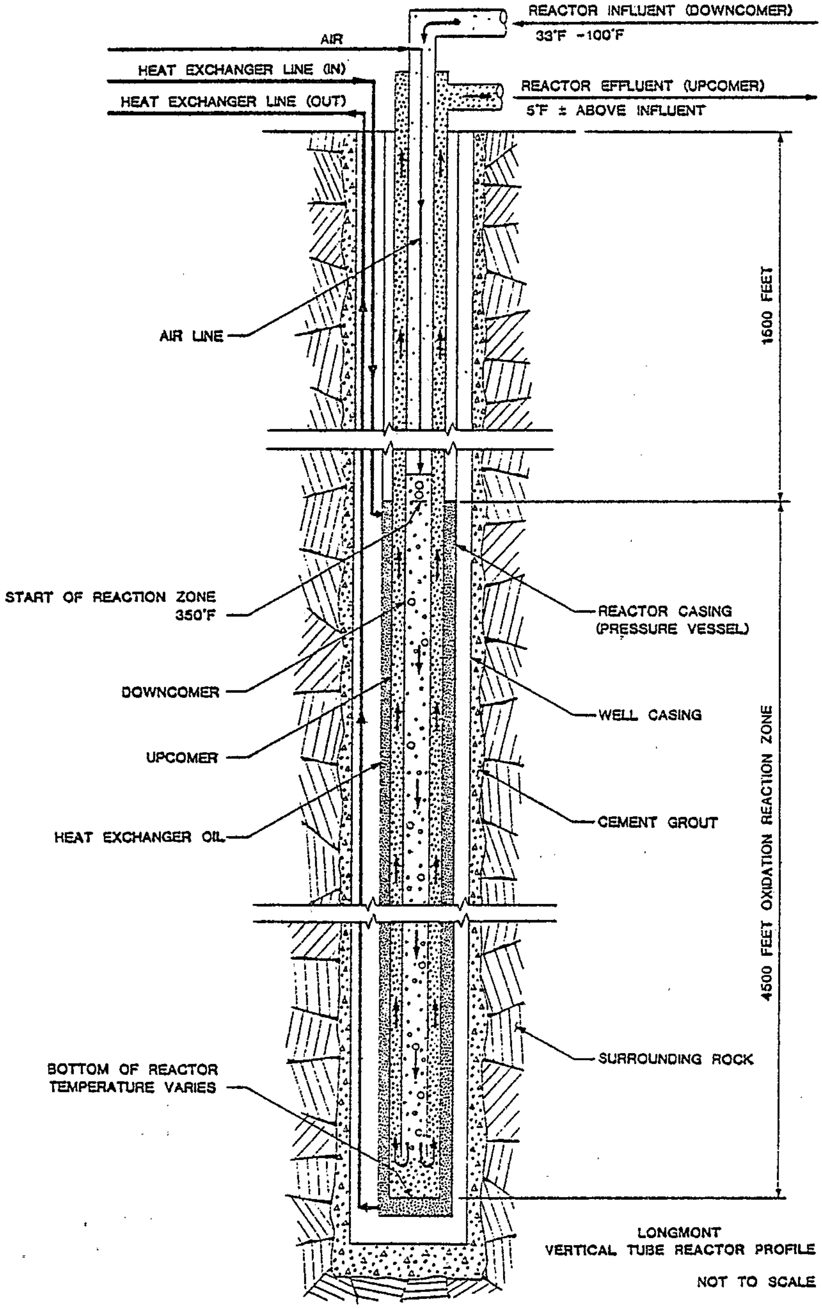

Figure 1. Typical vertical well chemical reactor profile.

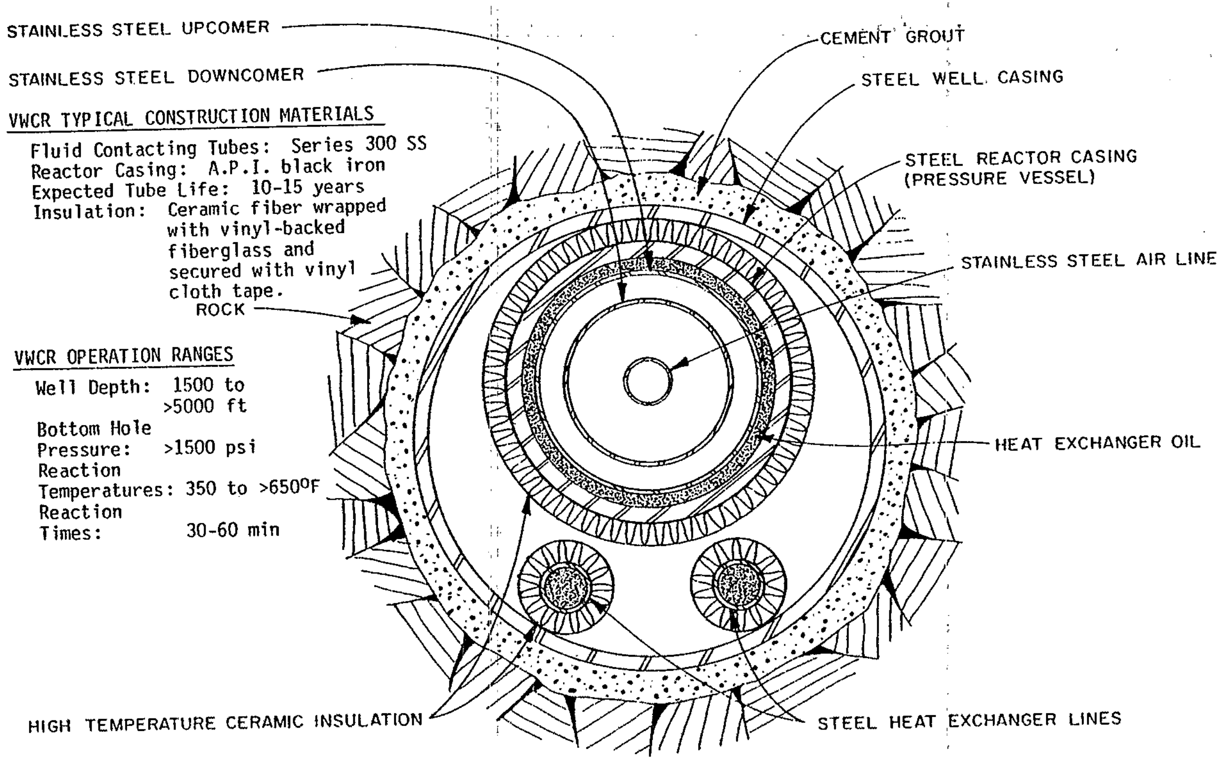

Figure 2. Typical vertical well chemical reactor cross section.

The VWCR system can be placed into a conventionally cased oil or gas well. Two concentric tubes serve as the reactor vessel and are constructed from 300 series stainless steel. The reactor tubes are surrounded by a heat exchange jacket containing a liquid which independently adds or removes heat as needed to maintain the required reaction temperature range. Air is injected at several downcomer locations along the waste fluid path at depths ranging from 150 to 800 feet depending on influent COD. The multiple air injection depths are used to accommodate varying influent waste strengths. A maximum air compressor pressure of 500 psig is recommended. Air assists fluid flow through the reactor and provides the oxygen needed for combustion. When waste strength oxygen demand (COD) exceeds air supply capability, the waste is diluted with effluent or other low COD strength wastes. Insulation to minimize heat losses from the VWCR to the surrounding earth completes the basic VWCR reactor design. Typical projected VWCR operation ranges and common construction materials are also summarized in Figures 1 and 2.

Waste fluid is injected into the downcomer tube at the earth's surface. Air is injected at several points down the reactor. As the waste stream and air flow down the tube, they undergo natural pressurization due to the hydrostatic head above. Thus fluid pumps need to be primarily designed to overcome surface friction and pressure head at their influent or injection point. They do not need to develop the high pressure actually experienced at the bottom of the reactor. At some depth (typically 1500 to 2000 feet) temperature of the waste fluid increases to 350° due to heat transfer from the upcomer effluent to the downcomer influent and wet oxidation effectively begins. Temperature increases with depth however it can never be allowed to exceed the boiling temperature at any point or the fluid will flash into a vapor. Maximum allowable temperature varies with pressure existing at any point and approximately follows the saturated vapor curve for water. The fluid flows down the center tube and up the annulus and oxidation proceeds until either the organic material or dissolved oxygen are depleted or until hydrostatic pressure and temperature decrease below those necessary to support combustion. Upflowing oxidized waste is gradually cooled as it transfers heat to the downflowing fresh waste. Any excess heat which may result from the exothermic oxidation reactions is removed from the reaction zone by the exchange jacket. Excess heat is thus available for use at the ground surface. The heat exchange jacket can also supply heat when necessary, for example, during startup. Effluent fluid temperature is generally within 5°F of the influent temperature. A temperature profile for a typical reactor as a function of detention time is shown in Figure 3.

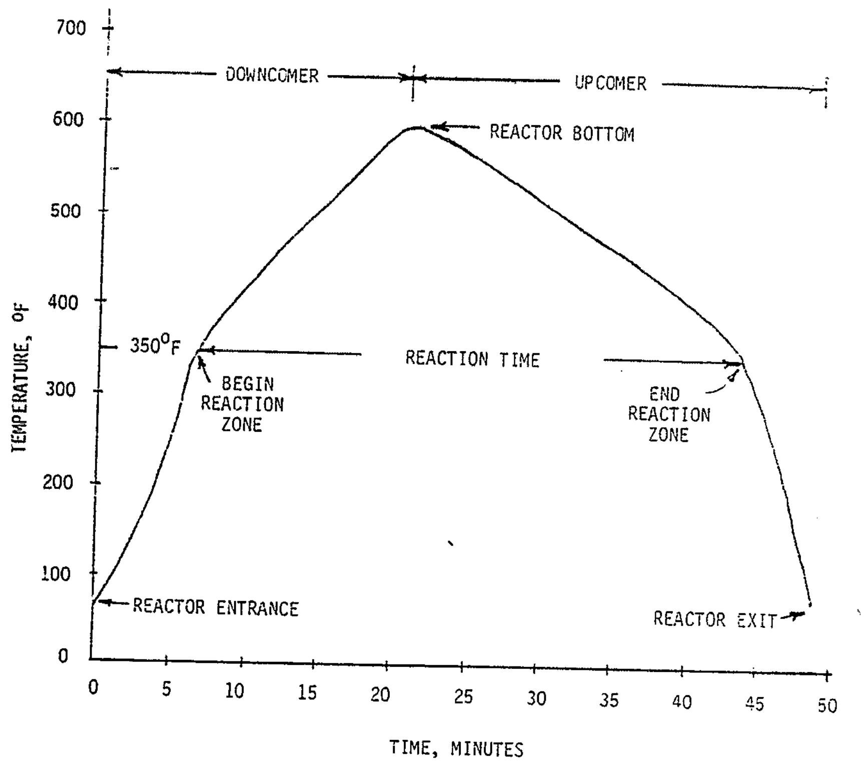

Figure 3. Temperature versus detention time for a typical VWCR reactor.

The VWCR is designed with no moving parts below the ground surface and needs no high pressure vessels above ground like those used for conventional wet oxidation methods. Its components below the surface are the tubes containing the waste, heat exchange fluids and air, and the associated temperature thermistors and pressure measuring devices. The tubes are subject to potential scaling and corrosion characteristic of high pressure, high temperature combustion reactions. VWCR operation efficiency, in addition to design and waste composition considerations, is dependent on the reliability and accuracy of downhole measuring equipment and on the efficiency of heat exchange between the fresh and oxidized waste.

SECTION 2

DEVELOPMENT STATUS

GENERAL

The Vertical Well Chemical Reactor process is being developed and tested by the Vertical Tube Reactor Corporation, Englewood, Colorado. Their research on oxidation of municipal wastewater sludge has been partially sponsored by EPA's Municipal Environmental Research Laboratory (MERL) (2). The study forms part of MERL's municipal sludge conversion research effort. In particular, this process, while maintaining all the advantages of wet oxidation, appears to be more cost effective than conventional wet oxidation methods because expensive high pressure equipment is minimized (high pressure vessels, pumps, and compressors).

BENCH AND LABORATORY SCALE RESEARCH

Research on the development of the VWCR process began in 1973 with the design and fabrication of a 2.7 liter stainless steel laboratory batch reactor. The laboratory reactor employs the same thermodynamic principles upon which a full-scale VWCR process is based and is designed to oxidize organic materials over a wide range of COD concentrations, temperatures, pressures and reaction times.

Under EPA/MERL sponsored research since July 1979, raw primary and digested secondary sludges from several municipal wastewater treatment plants have been oxidized in the laboratory batch reactor (2). Sludge used in the laboratory tests has usually been diluted to collect basic treatability data on various strength wastes. The laboratory reactor is also limited with respect to the amount of oxygen it can supply to satisfy waste oxygen demand. For a typical laboratory run, 1.3 liters of the sample material is placed inside the reactor cylinder. Compressed air is used to pressurize the vessel and satisfy sample COD requirements.

Batch reactor tests using municipal wastewater have primarily been run on wastewater from Montrose, Colorado. Montrose wastewater is made up of a candy factory wastewater portion (which presently contributes about 21 percent of its total organic load) and a domestic wastewater portion. Based on a 0.6 BOD/COD ratio (COD was measured), the BOD of the industrial wastewater averages about 740 mg/l (1240 mg/l COD) and ranges from 120-1500 mg/l (200-2500 mg/l COD). The BOD of the municipal wastewater presently averages 320 mg/l and ranges 166-482 mg/l (3).

For organic wastes without a significant COD refractory component, it has been found that the extent of COD reduction is a function of operating conditions rather than specific waste make-up. Figure 4 summarizes general COD removal experience using the laboratory reactor oxidizing both wastewater and sludge (3). Figure 5 summarizes average solids reduction of five municipal wastewater sludges collected in the Denver metropolitan area and treated in the laboratory reactor (1). Solids and BOD reduction experience has been more sporadic than COD reduction experience. One possibility which may affect BOD reduction results is that BOD refractory compounds which initially do not exert a BOD demand may be partially oxidized to non-refractory compounds which do exert a demand, thus effectively masking true BOD reduction percentages.

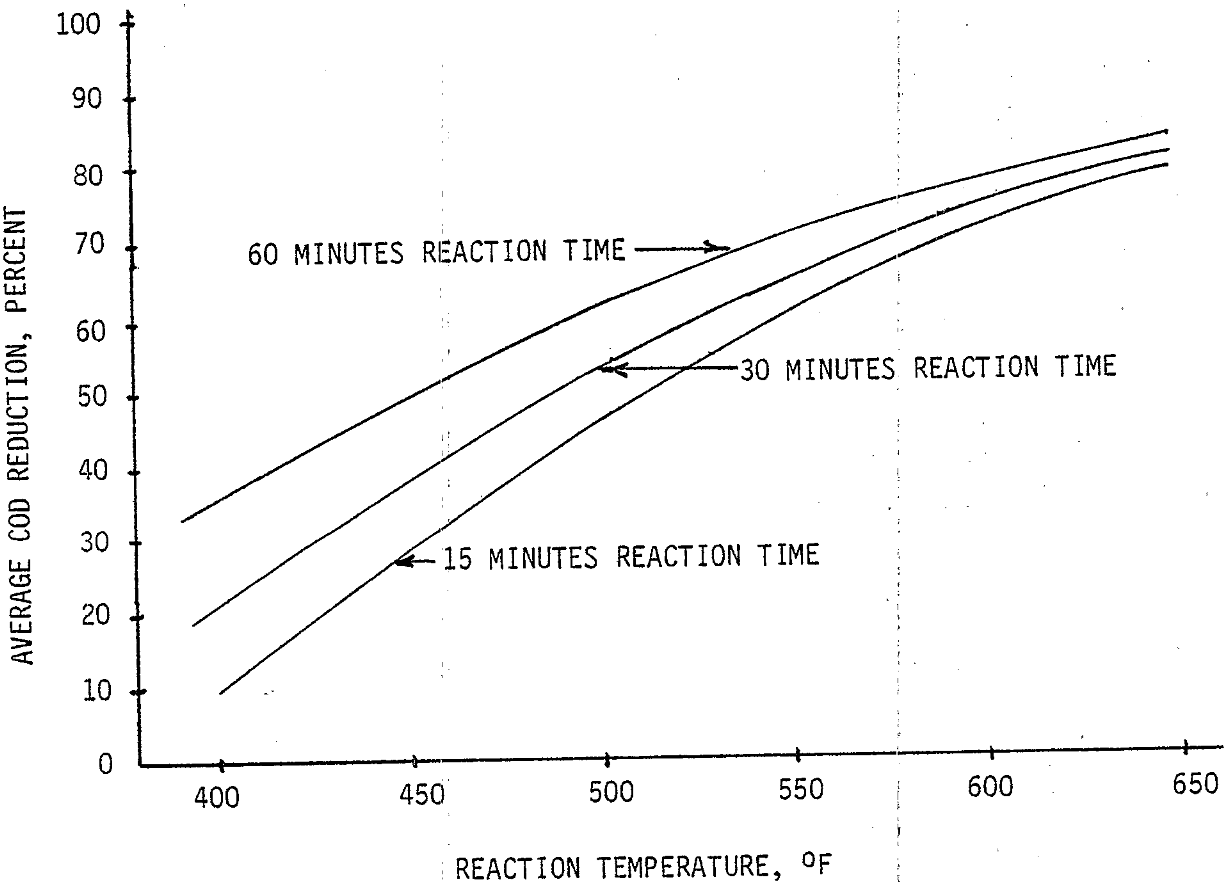

Figure 4. Typical COD reduction versus reaction temperature and time using laboratory reactor data.

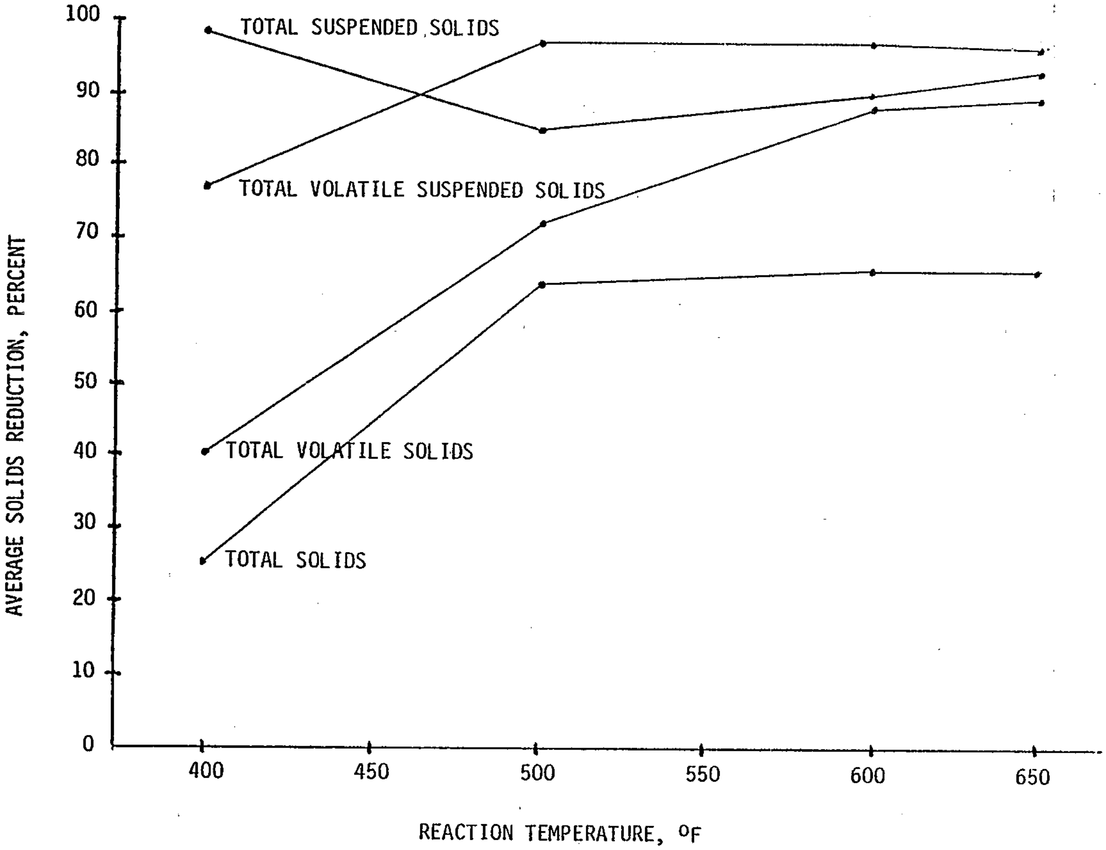

Figure 5. Effect of reaction temperature on average solids reduction for five sludges after 60 minutes using laboratory reactor data.

General trends about COD and BOD reduction via wet oxidation using the laboratory batch reactor are summarized in Table 1. These trends generally agree with those reported by Hurwitz et al., at the Metropolitan Sanitary District of Greater Chicago in 1965 using conventional wet oxidation above-ground pressure vessels (4). Hurwitz made pilot plant and full-scale studies of wet air oxidation of several sewage sludges for various degrees of oxidation as measured by COD, volatile solids, and BOD removal.

TABLE 1. WASTE STABILIZATION TRENDS USING LABORATORY REACTOR DATA

- The extent of COD reduction significantly increases with temperature up to at least 600°F.
- Increasing batch reaction time from 1/2 to one hour effects about 10 percent greater COD removal at 400°F and approaches no difference at 650°F.
- The particulate (ash) COD decreases to almost zero about 600°F confirming expectations of an inert ash.
- The portion of effluent BOD remaining (as a fraction of total COD) increases with reaction temperature indicating the refractory reactor effluent is mostly biodegradable for the wastes tested.

Selected metal analyses have been made on laboratory reactor effluents to determine whether the metals remain in the soluble or particulate fractions. Preliminary results suggest that it varies among the metals tested. Figure 6 summarizes the results of metal transformations for five sludges in a 30-minute and one hour run at 650°F in the laboratory reactor (1). The metals are reported as the percent of total effluent metal concentration within the effluent solids. The poorly understood interacting effects of metal complexing, solubility, absorption and desorption at high temperatures does not permit a definitive explanation of metal transformations within the reactor at this time. It is possible that some metals may at times be plating out on the reactor walls and at other times be redissolved into solution.

In earlier work, Sommers and Curtis studied the effect of wet oxidation on selected nutrients and metal concentration levels in the particulate fraction of primary and waste activated sludges (5). In general, they concluded that wet oxidation decreased total nitrogen content of the sludge solids but had no effect or increased the phosphorus and metals content. Copper, zinc, nickel, cadmium and lead were measured. They discussed the desirability of land application of sludge if nitrogen is reduced and metal content remains the same or increases. They also discussed the desirability of recycling if nutrient or metal build-up causes removal or operational problems.

PILOT SCALE RESEARCH

A VWCR pilot plant has operated intermittently since 1977 at Lowry Bombing Range, approximately 20 miles east of Denver, Colorado. The pilot plant reactor consists of a 1-3/4 inch diameter downcomer and a 2-inch diameter upcomer, both of 304 L stainless steel encased in a 2-1/2 inch reactor casing of schedule 40 American Petroleum Institute (API) pipe. The reactor, air line, heat exchanger lines and insulation are all suspended in a 5-inch diameter standard API well casing. The pilot VWCR extends to a depth of 1500 feet below the ground surface (1). Raw or digested sludge for oxidation in the VWCR has been obtained from nearby Aurora and Englewood wastewater treatment plants. The sludge is hauled to the pilot plant site in 1500 gallon loads. A 6000 gallon sludge storage tank receives the sludge. Well water is mixed with the sludge to obtain the desired COD concentration for a day's run.

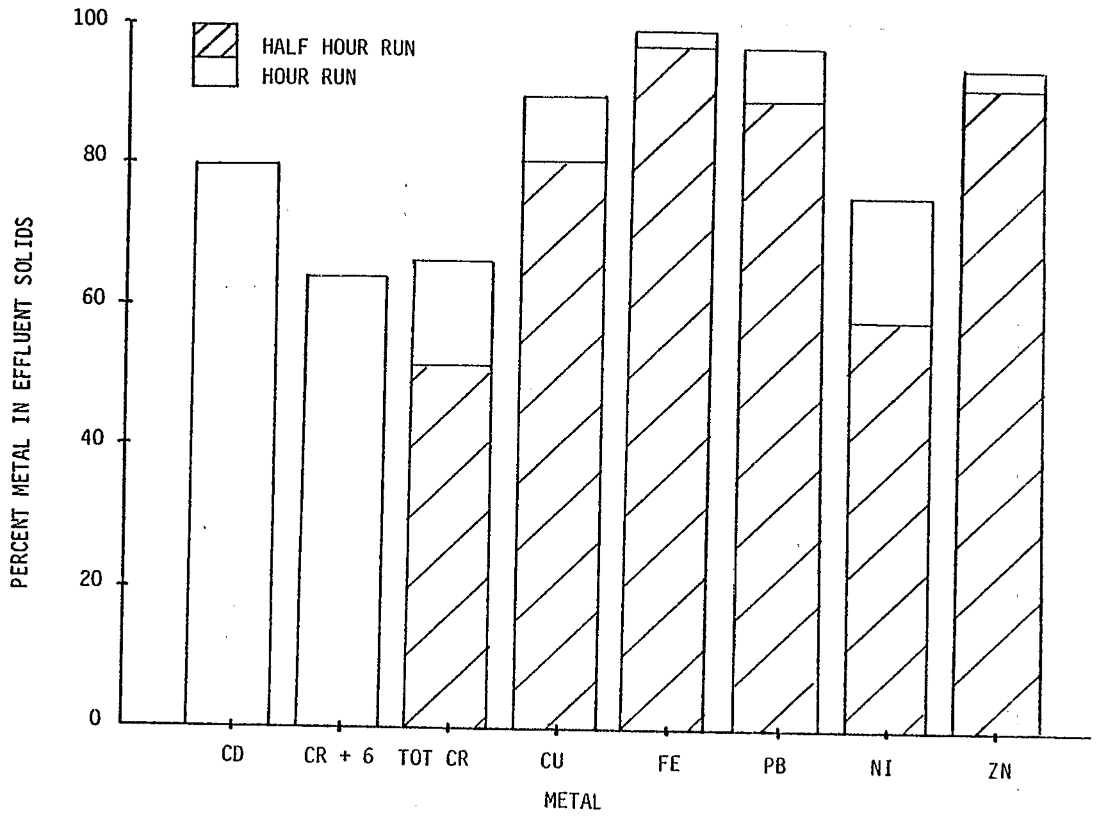

Figure 6. Average percent of various metals in the effluent solids from five municipal sludges.

Most of the pilot scale effort has concentrated on solving structural, mechanical, and other operational problems (2). Of the many engineering problems encountered, four major ones have resulted in proposed changes or additions for future reactors. The problems are pit corrosion and a scale formation, heat exchange line plugging, reactor-heat exchange interface, and leaking joints. These subjects are discussed in the Technology Evaluation section.

The pilot VWCR reactor was last reinstalled in the ground in June 1980. Because of its small size and limited depth, it has not been possible to achieve reaction temperatures above 510°F or demonstrate autogenous oxidation with respect to outside heat requirements. To date the pilot plant has operated at two distinct heat-pressure regimes oxidizing municipal sludges. The first was during July-December 1980, at 400-440°F with reactor maximum pressures at 250-380 psi. A second test condition was in March 1981, at 500-510°F with a 680-750 psi reactor maximum pressure.

Table 2 presents a summary of sludge COD reduction data from various pilot plant tests and compares them to batch laboratory reactor removals experienced under similar operating conditions. Table 3 presents a total solids and total volatile solids removed data for two composite sludges oxidized in the pilot plant in March 1981. Table 4 presents the results of a settleability test made on a pilot plant sludge effluent sample in March 1981.

TABLE 2. A COMPARISON OF VWCR PILOT PLANT AND LABORATORY BATCH REACTOR COD REDUCTION DATA (1)

Date	Flow gal/min	Reaction Time min	Max Temp °F	Inf. COD mg/l	Eff. COD mg/l	P.P. COD Reduction %	Lab COD Reduction %
7/24-25 1980	4.0	30	440	350	248	29	28
9/11-22 1980	4.1	25	400	100	73	27	18
11/06-21 1980	4.2	25	420	740	548	26	24
12/07-16 1980	4.5	20	440	600	468	22	22
12/20-23 1980	4.5	20	420	880	695	21	22
3/19-23 1981	4.5	28	500	1,424	784	45	51
3/20/81	4.5	28	500	1,118	657	41	-
3/23/81	4.5	28	510	1,063	567	47	51

*Estimated time that sludge was above 350°F while flowing through pilot plant.

TABLE 3. VWCR PILOT PLANT SOLIDS REMOVAL DATA (1)

Test Dates	Total Solids*			Total Vol. Solids*			Total Sus. Solids*			Total Vol. Sus. Solids		
	Inf.	Eff.	% Rem.	Inf.	Eff.	% Rem.	Inf.	Eff.	% Rem.	Inf.	Eff.	% Rem.
3/19/81	2070	958	54	1140	661	42	1630	488	70	790	452	43
3/20/81	2000	736	64	1040	-	-	1180	300	75	950	-	-

*Influent and effluent concentrations are in mg/l.

TABLE 4. VWCR PILOT PLANT SOLIDS SETTLEABILITY DATA (1)*

	Total Solids mg/l	Total Vol. Solids mg/l	Total Sus. Solids mg/l	Total Vol. Sus. Solids mg/l
Effluent	1480	681	600	166
Settled Effluent	878	502	141	52
% Removed	41	26	74	69

*Results from one grab sample of VWCR reactor effluent which was placed into a 2.0 liter graduated cylinder and allowed to settle for 2 hours. The decant from this cylinder was then poured out carefully and analyzed for solids determination. An additional 1.0 liter of reactor effluent was also placed into a 1.0 liter Imhoff cone. After 2 hours the settled solids had compacted to 2.5 percent of the cone volume.

Table 5 presents results of the metal analyses from VWCR pilot plant samples of municipal sludge. Pilot plant reaction was 20 minutes and bottom reactor temperature was 400-440°F. Table 5 indicates that most of the iron, total chromium and lead effluent metal concentration is in the ash and copper is approximately 30% soluble. Chromium VI, cadmium and nickel concentrations were too near or below detection limits to make any conclusions about their fate. There is a slight reduction in both iron and lead which suggests they might be tied up in downhole scale formation.

Shown in Table 6 are the results from a reactor effluent off-gas sample taken December 23, 1980. Gas samples were analyzed by combined gas chromatograph/mass spectrometer analysis. No organic components were detected at the detection limit of 5 ppm.

In summary pilot plant performance with respect to COD reduction, solids removal, metal concentrations and off-gas make-up are reportedly as expected considering the reaction time, pressure, and temperature limitations of the pilot reactor. COD reduction experience using the batch laboratory reactor has been close to that obtained from the pilot plant under similar operating conditions, supporting the use of batch reactor to model pilot plant treatability expectations.

FULL-SCALE FACILITIES

EPA's Office of Research and Development has recently received a pre-application for federal assistance from the City of Longmont, Colorado to build and evaluate a full-scale demonstration VWCR (1). The facility proposed consists of a VWCR system complete with all downhole and above ground equipment needed to treat raw sludge from the Longmont wastewater treatment plant and selected industrial sludges from the surrounding area.

TABLE 5. VWCR PILOT PLANT METAL CONCENTRATION DATA (1)

Metal	12-15-80 In mg/l	12-15-80 Out mg/l	Soluble Out mg/l	12-10-80 In mg/l	12-10-80 Out mg/l	Soluble Out mg/l	12-21-80 In mg/l	12-21-80 Out mg/l	Soluble Out mg/l
Fe	7.9	6.5	<0.02	6.4	5.6	<0.02	7.0	6.1	<0.02
Total Cr	0.33	0.32	0.03	0.29	0.26	0.03	0.30	0.27	0.03
Cr^{+6}	<0.01	<0.01	<0.01	0.01	0.01	<0.01	<0.01	<0.01	<0.01
Cd	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Pb	0.130	0.086	0.007	0.073	0.061	0.005	0.091	0.062	0.005
Cu	0.70	0.56	0.23	0.69	0.60	0.22	0.66	0.56	0.25
Ni	0.09	0.05	<0.05	0.50	0.05	0.05	0.10	0.06	<0.05

TABLE 6. VWCR PILOT PLANT OFF-GAS ANALYSIS (1)

	Percent by Volume
Nitrogen	79.2
Oxygen	17.9
Argon	0.9
Carbon Dioxide	2.1
	100.1

The Longmont wastewater treatment plant (WWTP) is a secondary, biological process with flow equalization and two stage anaerobic sludge digestion. The treatment process includes mechanical screening and shredding, aerated grit removal, primary sedimentation, redwood media roughing filters, rotating biological contactors, secondary clarification and chlorination. Longmont WWTP flow is expected to average 7.5 mgd in 1982.

Treated plant effluent is discharged to the St. Vrain River which is a tributary to the South Platte River. Anaerobically stabilized sludge is spread on agricultural lands in the vicinity of the WWTP.

Solids handling facilities at the Longmont WWTP are nearing design capacity. The 201 Facilities Plan is presently being reviewed and updated with particular emphasis on expanding sludge handling capacity. The VWCR process for sludge treatment is considered a reasonable alternative solution to Longmont's sludge disposal problem.

The proposed VWCR system at Longmont includes an 8-inch nominal diameter reactor 6,000 feet deep which will allow for operation of the process over the full range of temperatures from 500°F to 650°F with influent sludge strengths of 5,000 mg/l to 10,000 mg/l COD and reaction times from 25 to 100 minutes. Sludge from the Longmont plant will be diluted to achieve this relatively low sludge COD strength. Design is based on a 1985 diluted sludge flow volume of 150,000 gallons per day into the VWCR at an average COD concentration of 10,000 mg/l. This results in 12,500 lbs COD processed each day. Oxidation efficiency is expected to be about 75 percent giving an estimated 9400 lbs. of COD oxidized each day. Figure 7 gives the process flow schematic for the VWCR demonstration plant proposed for Longmont, Colorado (1).

The overall objective of the Longmont program is to demonstrate technical and economic feasibility of a full-scale VWCR for combustion of municipal sludge and selected industrial wastes (1). The program involves three basic phases which will last at least two years.

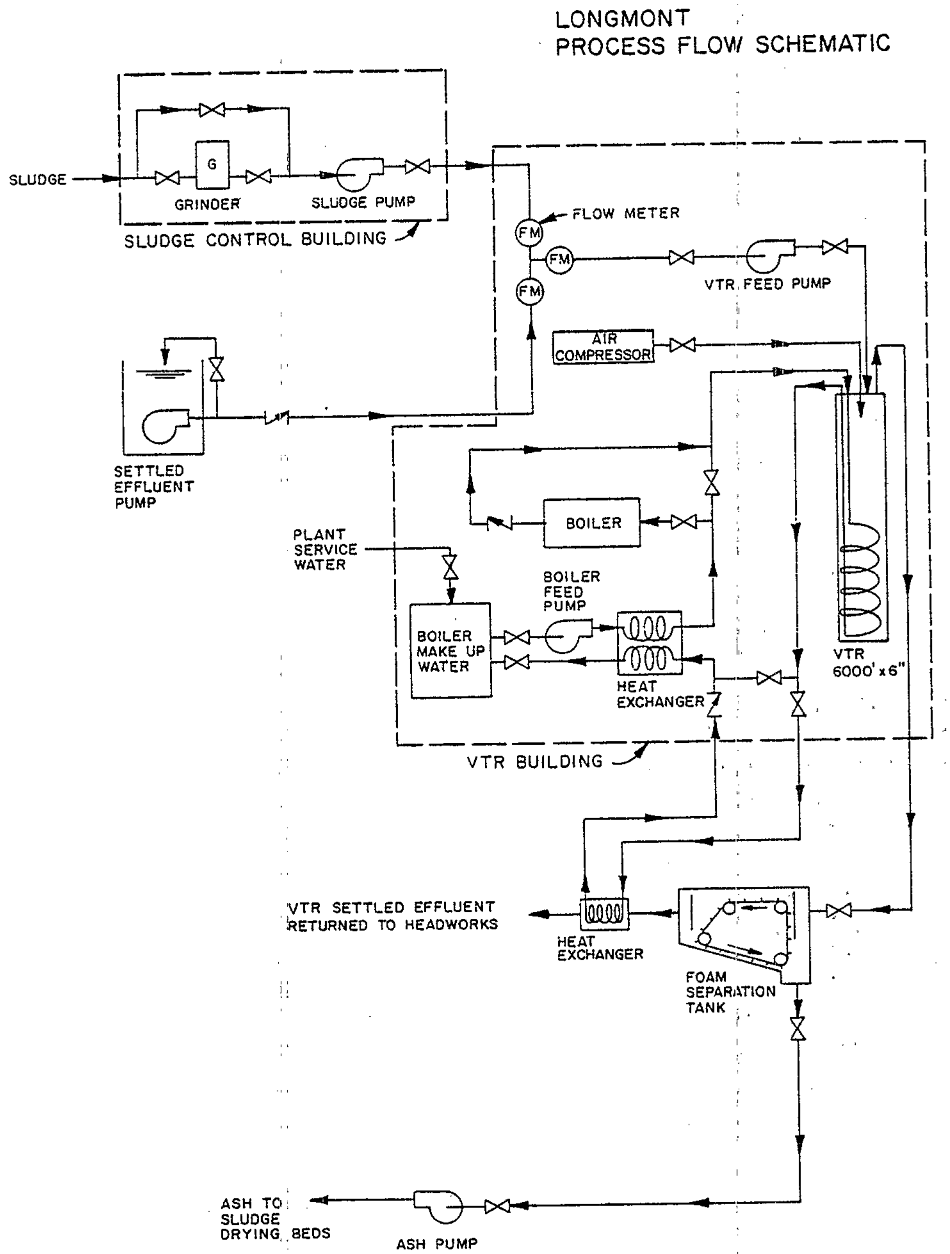

Figure 7. Proposed Longmont VWCR process flow schematic.

Phase I, the construction phase, includes design, construction and initial operation of the VWCR at Longmont. In particular, sludge and air flow, plumbing, heat control and instrumentation will all be checked out to insure they meet design criteria.

Phase II, the operation and evaluation phase, is designed to provide longterm reliability and operative information in processing municipal sludge and to evaluate the impact of VWCR operation on Longmont wastewater treatment plant operations. Full-scale treatability results will be compared to those predicted in the laboratory; computer model thermodynamic predictions will be verified or reevaluated, optimum operating conditions for processing Longmont municipal sludge will be established. Optimum operating conditions are those which effect the desired COD reduction, a minimum COD recycle load, and net positive heat production. In general, important engineering and operational data will be developed that was not possible at pilot scale due to size and design limitations. Evaluating the extent and subsequent control methods for reactor scaling and corrosion using nitric acid is an important task to be done. The biological treatability of VWCR effluent will also be studied using bench scale aerobic and anaerobic treatment units.

Phase III will investigate treatment and disposal of complex organic industrial wastes. In addition, an energy recovery system will be sized in order that excess combustion heat from the wet oxidation process can be covnerted to electricity for treatment facility use. During all phases, system components will be monitored for energy efficiency, operation and maintenance characteristics, and material durability. An extensive sampling program will monitor oxidation efficiency as well as the fate of selected metals and complex industrial organics as appropriate. The preapplication is under review as of this writing. Grant award and initial construction is anticipated during the fall of 1981.

In general, full-scale facilities for VWCR plants must consider the following major unit operations or equipment:

- Preliminary treatment: to protect pumps, remove large objects, measure flow and pretreat as necessary.
- Equalization Basin: to allow a constant pumping rate to the VWCR, to receive recycle flow and to act as a buffer against large variations in wastewater quality and quantity.
- Vertical Well Chemical Reactor: for wet oxidation.
- Heat Exchange Unit and Boiler: to maintain required temperatures for wet oxidation or to remove excess heat for productive use (includes water conditioners, high pressure pumps and boiler make-up requirements if heat exchange fluid is water).
- Acid Wash System: to protect the stainless steel reactor tubes against the effects of corrosion and deposition.

- Air Compressors: to provide air required for waste transport and oxidation, and pressure for air injection into the reactor.

- Foam Separation Tank: to allow both solids and gas separation from the VWCR effluent (a surge gas stand pipe may proceed the tank).

- Final Biological or Chemical Polishing Operations: to meet permit requirements of wastewater effluent or to treat sludge supernatant (which may be recirculated back to the head of the plant).

- Solids Dewatering Facilities: to prepare the VWCR solids for final disposal.

- Air Treatment Equipment: if needed to scrub odorous off-gases.

A hypothetical waste treatment plant flow sheet is shown in Figure 8. Unit operations before and after the VWCR will be a function of the incoming waste characteristics (sludge or wastewater) and disposal requirements.

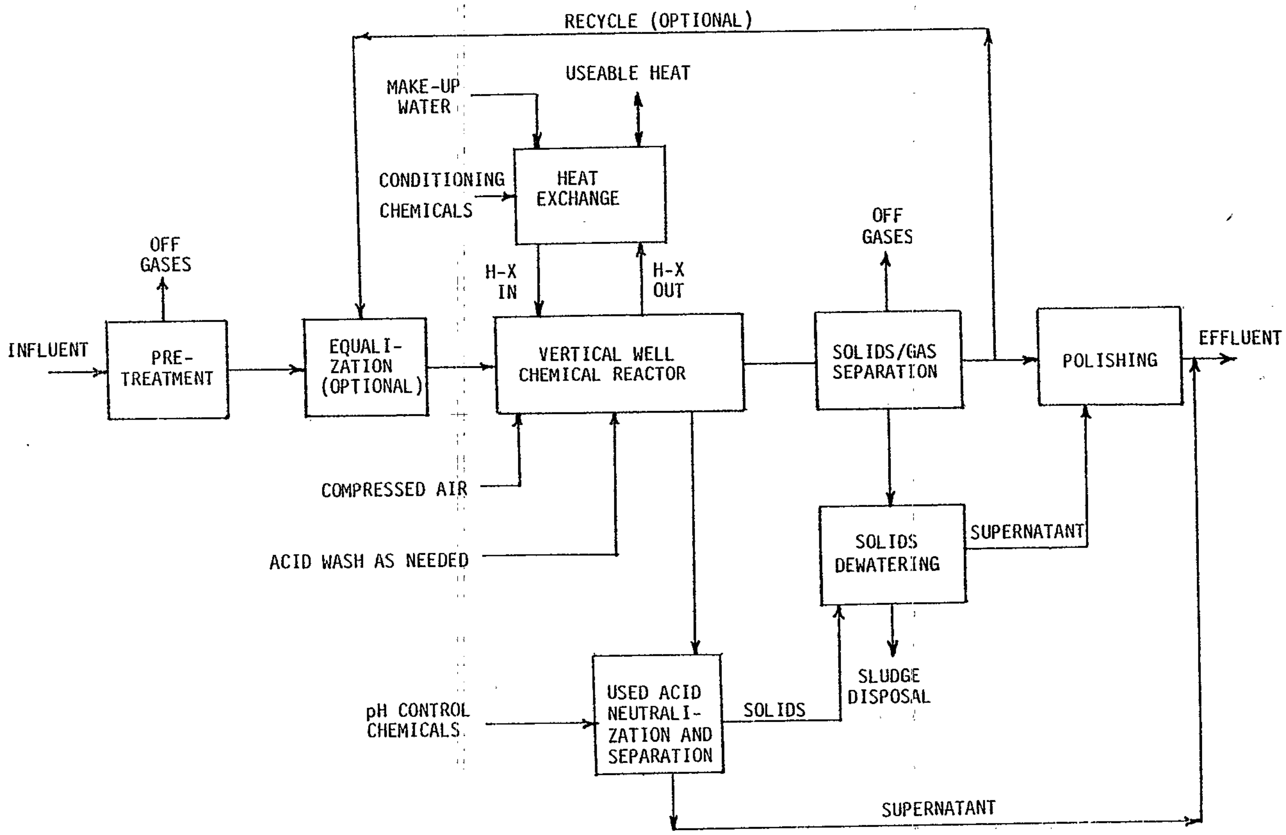

Figure 8. Hypothetical waste treatment plant flowsheet using the VWCR.

While no full-scale facilities exist, the 201 Facility Plan for the city of Montrose, Colorado recently included consideration of a wastewater treatment plant design utilizing VWCR/aerobic fluid bed filter (AFBF) unit operations (3). Montrose wastewater is primarily domestic, supplemented with an organic loading (10-20%) from a candy factory discharge. During the facility planning process, four final wastewater treatment alternatives were considered for a design flow of 2.88 mgd. These were activated sludge with anaerobic sludge digestion and landfill disposal of sludge; use of an oxidation ditch; use of the VWCR/AFBF; and use of a deep well biological reactor with aerobic sludge digestion and disposal. The list of major equipment and unit operations for the VWCR/AFBF alternative is outlined in Table 7. The schematic process flow diagram and preliminary pilot plant for this alternative are shown in Figures 9 and 10.

Details of the VWCR design for Montrose, along with the expected influent and effluent quality of the reactor are summarized in Table 8. Although the VWCR/AFBF process was selected by the consultant and approved by the city as the most cost effective innovative design, failure of Montrose to obtain full innovative funding at 85% and lack of assurance from the State of Colorado that the city would be eligible for 100% payback funding should the process fail precluded choice of the process in the final selection.

TABLE 7. MAJOR EQUIPMENT AND UNIT OPERATIONS PROPOSED FOR THE WASTEWATER TREATMENT PLANT AT MONTROSE, COLORADO (3)

	Number (each)
Pretreatment Facilities	
a. Bar Screens	2
b. Grit Chambers	2
c. Influent Flow Meter	1
d. Return Flow Meter	1
Equalization Tank/Wet Well	
a. Equalization Tank	1
b. Wet Well	1
c. VWCR Feed Pumps	4
Vertical well Chemical Reactor	
a. Feed Pumps	see above
b. Air Compressors	3
c. Reactors	2
d. Heat Exchangers	included as part of reactor
e. External Boiler	1
f. Discharge Standpipe	1
g. Flow Meters	2
h. Acid Cleaning Facilities	included as part of reactor
Anaerobic Fluid Bed Filter	
a. Filters	4
b. Flow Meters	4
c. Effluent Pump	1
d. Recycle Pumps	3
Ash Ponds	2
Prechlorinated Facilities	
a. Mixing Compartment	Part of equalization tank
b. Mixing Pump	1
c. Chlorinator	2
Wastewater Monitoring	
a. Composite Samplers	2 (influent/effluent)
b. pH Recorder	1
c. Parshall Flume	1
d. Flow Recorder-Totalizer	1
Other Facilities	
a. Control building	1
b. Standby Power Generator	1
c. Fence	1
d. Outfall Sewer	1

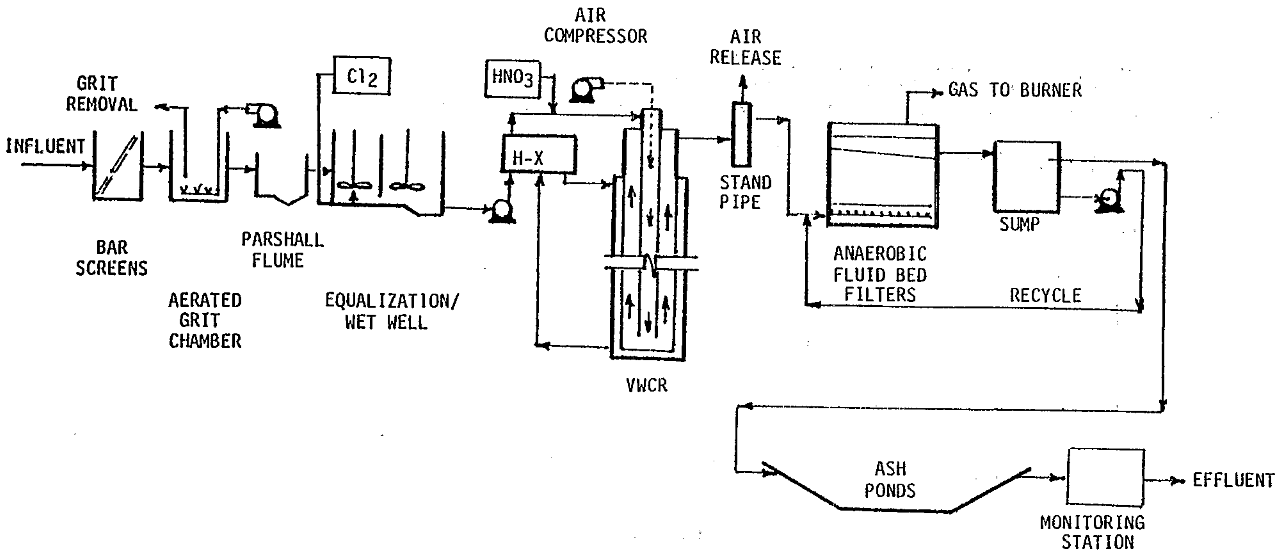

Figure 9. Schematic process flow diagram of the treatment train proposed for Montrose, Colorado.

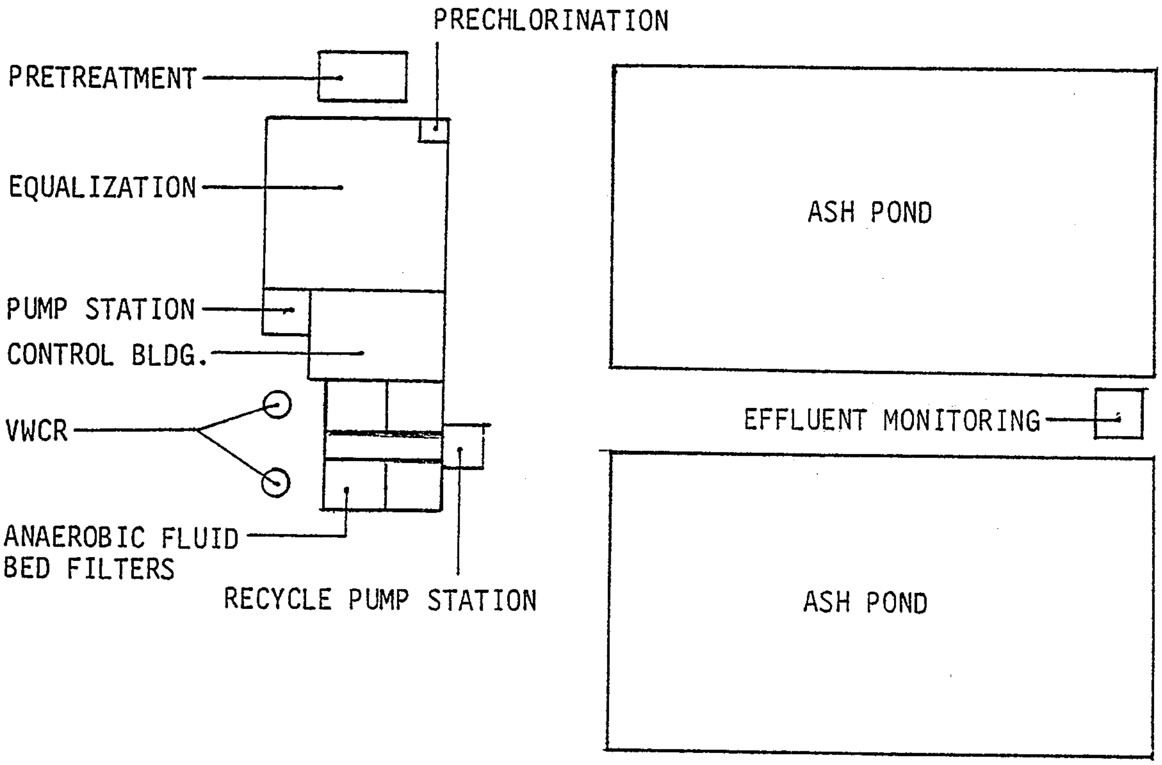

Figure 10. Preliminary plot plan of the treatment train proposed for Montrose, Colorado.

TABLE 8. DETAILS OF THE MONTROSE, COLORADO VWCR DESIGN (3, 6)

1. Expected Wastewater Characteristics around the reactor:

a. Design Flow: 2.88 mgd

b. Influent:	BOD range	100 - 600	mg/l
	BOD av.	245	mg/l
	COD range	150 - 1000	mg/l
	COD av.	590	mg/l
	NH_3-N av.	27	mg/l
	TKN av.	46	mg/l
c. Effluent*:	BOD range	50 - 300	mg/l
	BOD av.	123	mg/l
	COD range	54 - 360	mg/l
	COD av.	212	mg/l
	NH_3-N av.	33	mg/l
	TKN av	37	mg/l

*Effluent estimates are based on a maximum 625°F downhole temperature and 34-minutes reaction time as well as influent wastewater characteristics.

2. VWCR and Auxiliary Facilities:

a. Feed Pumps	Two 1400 gpm at 52 psig, 120' TDH (60 - 75 HP ea.)
	Two 1400 gpm at 25' TDH (15 HP ea.)
b. Air Compressors	Three 500 scfm at 112 psig (25 HP ea.)
c. VTR Reactors	Two 18" diam. x 4500' deep
d. Heat Exchangers	Included with reactors
e. External Boiler	5×10^6 BTU/hr
f. Discharge Standpipe	24" diam. x 25' high
g. Flow Meters	Two each
h. Acid (HNO_3) Cleaning Facilities	Included with reactors

SECTION 3

TECHNOLOGY EVALUATION

PROCESS THEORY (7, 8, 9, 10, 11)

The VWCR process is a unique application of wet air oxidation. It makes use of the fact that any burnable substance can be oxidized in the presence of water at sufficiently high temperatures (flameless combustion) and resulting high pressure. Oxygen to support the combustion is often supplied by air.

Wet oxidation is the result of three types of chemical reactions. Initially, the destruction of solid organic waste is predominantly the result of heterogeneous (two-phase) oxidation due to direct contact and ensuing reaction between adsorbed oxygen gas and organic solids. At elevated temperatures, these solids are quickly reduced to simpler organic colloids which are solubilized by hydrolysis. Hydrolysis splits the organic polymers from both colloidal and soluble organic matter into smaller units but will not destroy them. The only remaining path for ultimate destruction of the organic matter is liquid phase oxidation, i.e., wet combustion, following the individual collisions and interactions of dissolved oxygen with solute elements or compounds in solution.

In wet air oxidation, organic matter can be potentially stabilized to carbon dioxide and water. Organic nitrogen is converted to ammonia and sulfur to sulfates. One of the last residual compounds prior to complete oxidation is acetate. The oxidation reactions are exothermic and release energy as heat. The amount of heat released is dependent on the make-up of the waste. If the heating value of the waste is high enough, the temperature required for oxidation can be supported by the oxidation itself.

Pressure down hole in the VWCR at any point is a function of the weight of the liquid above it. Maximum allowable temperature is just below the boiling point of the liquid. Maximum temperature is a function of the pressure of the liquid and roughly follows the saturated vapor temperature-pressure curve for water. Detention time is dependent on the depth and diameter of the VWCR and the velocity of the mixture flowing through it.

For sufficient conditions of temperature and pressure, wet oxidation proceeds until the organic removal rate decreases to zero and percent organics removed remains constant. The organics remaining at this point are termed refractory organics. At low temperatures of 212 to 400° F, this plateau or equilibrium is not reached for hours. Above 575° F, it is reached in a matter of minutes. The rate of oxidation will increase up to the critical point of water (705°F) above which it cannot exist as a liquid regardless of pressure. The height of the plateau also increases with increasing temperature. Thus, the extent and rate at which a material is oxidized is significantly influenced by reactor temperature with very little oxidation occurring below approximately 300°F. Temperatures of 430°F or more are required for 80% COD removal.

Oxygen must be added to the wet combustion system in stoichiometric proportions at a rate that will not impede combustion. Oxygen in excess of stoichiometric requirements does not accelerate the process and is economically undesirable because of air compression costs. In practice, excess quantities of air above stoichiometric requirements may be necessary to account for differences between ideal and actual combustion conditions. The COD of the influent material is normally used as a convenient parameter of oxygen requirements. It is roughly equal to the oxygen utilized in the combustion process.

In summary, four important parameters control the performance of wet oxidation units: feed solids concentration, pressure, temperature, and air supply. The COD test is normally used as a measure of process efficiency. The average wet oxidation efficiency is 70-90 percent as COD reduction. Some organic matter in the form of low molecular weight compounds such as organic acids, aldehydes and acetates will be observed in the effluent. Final oxidation products are highly dependent on the degree of oxidation and the composition of the waste.

PROCESS CAPABILITIES AND LIMITATIONS

Basic Process (12)

Waste treatment by a VWCR is basically a combustion process utilizing high temperature/high pressure wet-air oxidation to produce an easily dewatered ash plus some stabilization of the supernatant. Because it is not necessary to supply energy for the latent heat of vaporization (since oxidation must occur in the presence of a liquid) wet air oxidation is particularly applicable for materials like organic sludges which are combustible but cannot be separated readily from water and which can supply some or all of the heat required for reaction. While most combustion processes require dewatered sludge to achieve thermal self sufficiency, considerably less concentration of the organic matter is adequate for wet air oxidation. As an extreme, wet air oxidation can be used for sludge conditioning which results in improved sludge solids separation characteristics but leaves a high strength supernatant.

Corrosion and scale formation in the reactor and heat exchange tubes are inherent problems of the process. High temperature, pressure and the presence of oxygen are all conducive to corrosion. Calcium, magnesium and sulfate ions in the waste can cause deposition problems. Stainless steel depends on a very thin surface layer of chromium oxide for its stainless properties. Scale (such as calcium carbonate or calcium chloride deposits) formed on this surface may deprive the surface of sufficient oxygen to maintain its protective passive layer properties. When the scale breaks off, it may also remove the protective layer of chromium oxide. Pit corrosion can result, leading to stress corrosion cracking failures (13). Measures can be taken to minimize corrosion and deposition such as repassivation. They are discussed under Design Considerations. The degree of scaling and corrosion which can be expected in a full scale VWCR has yet to be characterized.

Configurations

Configuration of the VWCR is claimed to be an important advantage of the process. As indicated earlier, the VWCR takes little space. It is estimated that the land area required to treat sludge from a 40 mgd wastewater treatment plant is one-half acre. The concentric tubes are conducive to good heat transfer because of their proximity. Once the surrounding earth reaches equilibrium, it may act as a heat envelope and buffer to external temperature variations. The vertical tube also allows natural pressurization because of the weight of the fluid column, eliminating the need for high pressure surface vessels and controls.

The depth of the column of waste in the vertical tube sets downhole pressure. Maximum allowable temperature (that temperature just below the flashing point) and pressure can be considered related according to the saturation vaporization curve of water. Thus maximum allowable temperature in the reactor at any given depth is set and in this respect the VWCR is less flexible than above ground pressure vessels which can mechanically increase pressure and therefore increase their maximum allowable temperature. Within certain limits there are trade-offs which can mitigate this situation. They include heat exchange (removal), dilution of waste, and increasing effective reaction time in the reactor (Figure 4) via recirculation or lower flow velocities (while still maintaining adequate velocities to avoid grit deposition). In addition, much of the oxidation may occur at less than maximum allowable temperatures. The point to be stressed is that preliminary treatability studies on the waste to be oxidized must be made at several operating conditions so that alternative reactor dimensions and plant flow schemes can be evaluated in the planning phase. The degree and rate of waste wet oxidation are significantly influenced by temperature, pressure, and oxygen supply.

The compactness of the VWCR makes downhole maintenance difficult. Delays in pilot operation to date have come from difficulties in replacing components which for various reasons had to be changed or redesigned (2). Considerations about VWCR maintenance and accessibility are discussed under Design Considerations.

Water Composition

As indicated previously, the VWCR is especially applicable to wastes which are difficult to dewater or which have sufficiently high organic content to maintain a thermally self-sustaining (autogenous) reaction. Solids content greater than 20 percent may create problems with mixing and consequent mass transfer of the oxygen needed for combustion. Municipal wastewater sludges, however, normally contain only 2-10 percent solids.

Oxidation using the VWCR may provide a good approach to treatment of toxic and hazardous wastes, landfill leachates in particular. Wet oxidation using moderate (527°F) and high (608°F) temperatures has been demonstrated to be an excellent method to destroy and detoxify certain organic compounds including various phenols, acrolein, dinitrotoluene and diphenylhydrazine (14). Destruction of 99.8 + percent of the starting materials was achieved by wet oxidation at 608°F for 1 hour. Oxidation at 527°F for 1 hour produced over 99 percent destruction of most compounds. In other work, laboratory tests have shown that organic substances can be completely solubilized and broken down ("reformed") to low to medium molecular weight compounds in supercritical water (SCW) (i.e., above 705°C and 220 atm) (15). This discovery is the basis of a U.S. Patent assigned to the Massachusetts Institute of Technology (M.I.T.) (15) and from which O'Donnell and Rich Enterprises, Inc., of Natick, MA have devised a new process to treat toxic and hazardous wastes. The MODAR process, initially developed at M.I.T. for coal degasification, involves catalytic oxidation of the products of SCW reforming while still under supercritical conditions. The major advantages claimed for operating in the supercritical region are:

- enhanced solubility of air and oxygen in water (essentially 100%), which eliminates two-phase flow;
- rapid oxidation of organics approaching adiabatic combustion and allowing short residence times;
- complete oxidation of organics;
- removal of inorganics which precipitate out rapidly when the temperature is 450-500°C because of the extremely low solubility of inorganic salts at these temperatures.

Unlike the reformation step which has been demonstrated to work, oxidation of the reformed products is just beginning to be tested with SCW. The Incineration Research Branch of the U.S. EPA's Industrial Environmental Research Laboratory is currently co-sponsoring research to establish operating parameters for the extraction/destruction of PCB's and 2,4-dinitrotoluene using conventional above ground high pressure/temperature equipment (17). The fluid which exists under these supercritical conditions has a density of 0.2-0.5 g/cm^3. Thus some of the natural hydrostatic pressure head advantage of a VWCR would be lost when operating in the supercritical regime (only reactor contents near the bottom would be at supercritical temperature and pressure). The reactor would have to be pressurized.

External Treatment

Preliminary treatment to remove large refuse and inorganic solids is required. Thickening may be desirable to concentrate the waste so it has a higher heating value. Equalization to act as a buffer and provide uniform flow to the VWCR is necessary for certain applications.

Odors, especially in the case of sludge treatment, may result from pretreatment thickening, or as off-gases from the VWCR system itself. Future pilot operation should answer some of these questions. Pilot plant operation to date has not resulted in objectionable odors from the VWCR system. Odor level is dependent to a high degree on the total hydrocarbon content of the waste. Air pollution control must be addressed when comparing alternatives.

Although effluent solids from the VWCR are sterile and small in volume, the concentration of metals or other suspected toxic materials in the sludge, as well as their leachability, must be determined so that proper disposal can be made. This is especially of concern when treating industrial wastes and requires pilot plant or laboratory reactor study. Figure 8 shows inputs, effluent, and residual streams for a hypothetical waste treatment plant for either wastewater or sludge treatment.

DESIGN CONSIDERATIONS

Several mathematical models have been developed to assist in designing full scale Vertical Well Chemical Reactor plants. Verification of model predictions should come from demonstration plant operation and later from full-scale experience. Parameters addressed in model development represent important design considerations and are summarized below (1, 18).

Hydrodynamic Analysis

Using output from this model and laboratory treatability data for the given waste at similar reaction times and pressures, various VWCR size and depth options are considered. Operating air and water horsepower requirements can be determined for specific cases. Options may be ranked according to estimated costs and/or desirability.

Inputs--

- Waste COD treatability data
- Plant site ambient conditions
- Waste flow rate
- VWCR physical dimensions including reactor depth, size, roughness, and heat exchange properties
- Oxidation reaction zone boundaries
- Desired reaction temperatures at various depths (controlled by the heat exchanger)
- Air injection point location and characteristics
- Air compressor characteristics

Outputs--

- Flow velocities, pressures, and temperatures at downhole locations along the reactor. Flow velocities allow determination of reaction time.

Heat Flow Analysis

Output from the model is used when evaluating the energy deficiency or surplus for a given waste and VWCR reactor in order to establish heat exchanger design criteria.

Inputs--

- Reactor physical dimensions
- Operating temperatures
- Insulation thickness and thermal conductivity
- Earth thermal conductivity and temperature profile
- Initial reactor temperature profiles

Outputs--

- Heat loss to earth surrounding the reactor system as a function of time and reactor insulation.

Heat Exchanger Analysis

Output from this model allows calculation of the net energy surplus expected from (or energy input required to) the heat exchanger fluid serving the VWCR system. External boiler capacity can then be determined and potential energy credits estimated.

Inputs--

- Heat flow losses to the earth for various operating conditions
- Reaction enthalpy production rates

Outputs--

- Heat flow losses from the heat exchanger lines as a function of reactor physical dimensions, flow rate, temperature, and line insulation thickness and thermal properties.

Note that when considering the feasibility of a VWCR, a subsurface geological investigation is necessary both to consider well drilling costs and to estimate the surrounding earth's thermal and structural properties. Important parameters which should be addressed include: 1) depth to bedrock; 2) thickness of bedrock; 3) dip of sedimentary rock; 4) identification of aquifers in the area; and 5) identification of geological structures in the area. A geophysical survey of available sources of data, including geological maps and cross sections, water, oil or gas well logs may contain most or all of the information necessary (19).

As indicated previously, precautions must be taken to minimize the effects of corrosion and deposition in the reactor. A weekly nitric acid passivation operation (10-20% aqueous nitric acid for 20 to 30 minutes through the reactor) has been recommended to mitigate the effects of both corrosion and scaling (13). The success of this approach in a full-scale reactor, the influence of temperature, and the effect of acid addition operations on wastewater treatment efficiency is not known at this time. The procedure for acid addition over long-term operation will be developed during demonstration plant operation. A related problem discovered during pilot plant testing is leaking joints in the reactor case. This leaking problem is expected to be corrected by welding all joints in the reactor case in future full-scale reactors (20).

Corrosion and deposition tendencies of impurities in the heat exchange fluid must also be addressed. If it is water, chemical stabilizers or corrosive inhibitors commonly used for high pressure boiler water control can be employed. If scale deposits are allowed to accumulate or if the heat exchange jacket annulus is too small, heat exchange efficiency in the reactor will decrease and heat exchange fluid pumping head and costs will increase. The heat exchange jacket annulus has been increased and redesigned to enable it to be pulled independently to minimize plugging problems.

ENERGY CONSIDERATIONS

The most important energy consideration is the heating value of the waste. Table 9 gives the heating value of a number of waste materials, fuels, and pure substances. Ideal combustion reactions for carbon and hydrogen are:

$$C + O_2 = CO_2 + 14{,}100 \text{ BTU/lb. C}$$

$$2H_2 + O_2 = 2\,H_2O + 61{,}000 \text{ BTU/lb. } H_2$$

In the absence of other data, a value of 6000 BTU/lb. COD oxidized can be used to estimate the heat value of the waste. This value correlates with observed heat generation levels of 1200-1400 BTU/lb. air required for oxidation of most waste materials (8). How it is used is illustrated in the discussion below which calculates minimum COD for a thermally self-sufficient sludge:

Consider a 10 mgd plant producing 10 tons per day of dry sludge solids.

Assuming the wet sludge consists of 5 percent solids, then:

$$10 \text{ tons} \times \frac{2000 \text{ lb.}}{\text{ton}} \times \frac{1}{.05} = 4 \times 10^5 \text{ lbs. wet sludge}$$

are produced daily.

Assuming further that the wet sludge has the specific heat properties of water, then to raise one pound of it one degree Fahrenheit requires 1 BTU.

TABLE 9. HEATING VALUES OF VARIOUS MATERIALS AND FUELS

A. Heating Value and Heat Delivered Per Pound of Air Consumed in Oxidation (10)

Material	BTU Per Lb. Material	Lbs. O_2 Per Lb. Material	Lbs. Air Per Lb. Material	BTU Per Lb. of Air
Ethylene	21,460	3.42	14.8	1,450
Carbon	14,093	2.66	11.53	1,220
Acetic Acid	6,270	1.07	4.6	1,365
Oxalic Acid	1,203	0.178	0.77	1,565
Pyridine	14,950	2.53	10.9	1,370
Fuel Oil	19,376	3.26	14.0	1,380
Lactose	7,100	1.13	4.87	1,455
Casein	10,550	1.75	7.55	1,395
Waste Sulfite Liquor Solids	7,900	1.32	5.70	1,385
Semi-Chemical Solids	5,812	.955	4.13	1,410
Sewage Sludge Primary	7,820	1.334	5.75	1,365
Sewage Sludge Activated	6,540	1.191	5.14	1,270

B. Heating Value of Typical Sewage Treatment Residuals (21)

Waste Materials	Dry Solids Combustibles (%)	BTU/lb. of Combustibles
Grease & Scum	88.5	16,750
Raw Sewage Solids	74.0	10,285
Fine Screenings	84.4	8,990
Digested Sludge	59.6	5,290
Grit	33.2	4,000

C. Comparative Heating Values of Pertinent Fuels (21)

Fuel	Heating Value (BTU/lb of fuel)
No. 2 Oil	19,600
No. 6 Oil	17,500
Natural Gas	22,800
Bituminous Coal	13,600
Wood (air dried)	5,500
Grease & Scum	16,700
Sludge (dry solids)	10,000
Anaerobic Digester Solids	5,300
Anaerobic Digester Gas	15,400
Municipal Refuse (70% moisture)	4,900

D. Heat Released on Combustion of Sewage Sludge (21)

Material	Range (BTU/lb of Material)
Raw Sludge (primary & activated dry solids)	6,500 - 9.500
Digester Sludge (from anaerobic digester, dry solids)	2,500 - 5,500

In the VWCR, heat loss from the VWCR system to the surrounding earth effectively reduces the heat available to heat the sludge. Assume 20% of the heat produced is loss to the surrounding earth. Then,

effective heat value of the waste = 6000 x (1.0-0.2) = 4800 BTU/lb. COD oxidized.

Influent and effluent temperatures are generally within 5^oF during steady-state operation (1). Assuming a loss of 5^oF has to be made up then the heat required to make this up for 4×10^5 lbs. of wet sludge is ($Q = MC\Delta T$):

$$4 \times 10^5 \text{ lbs.} \times \frac{1 \text{ BTU}}{\text{lb.-}^oF} \times 5^oF = 20 \times 10^5 \text{ BTU}$$

The COD required to be oxidized to make up this heat loss (taking into account heat losses to the earth) is:

$$\frac{20 \times 10^5 \text{ BTU}}{4800 \text{ BTU/lb. COD oxidized}} = 416.7 \text{ lb. COD oxidized.}$$

Not all of the sludge COD is satisfied in the VWCR. Assume 75% is reduced. Then the COD of the sludge which has enough heating value to make up for the heat losses and oxidation efficiencies is:

$$\frac{416.7 \text{ lb. COD}}{0.75 \text{ oxidation efficiency}} = 555.6 \text{ lb. COD}$$

Thus for steady-state conditions where heat losses just equal heat production through the VWCR, the COD must be at least:

$$\frac{555.6 \text{ lbs. COD}}{4 \times 10^5 \text{ lbs. wet sludge}} = 1389 \text{ ppm or mg/l to maintain thermal}$$

self-sufficiency.

The example illustrates how several variables can affect calculations estimating the thermal self-sufficiency of the oxidized waste. Note that the example assumed that sludge had the specific heat of water, that influent and effluent temperatures were within 5^oF, that 20% of the heat was lost to the earth, that only 75 percent of the volatiles were oxidized, and that the wet sludge was composed of 5 percent solids. If the difference between influent and effluent waste temperatures was only 2^oF, the mg/l COD required for thermal self-sufficiency would have been only 556 mg/l. Influent-effluent temperature differential plays a large part in establishing thermal self-sufficiency boundry conditions. Figure 11 shows how waste strength (as COD) required for thermal self-sufficiency varies with temperature differential (washout heat) and heat transfer efficiency.

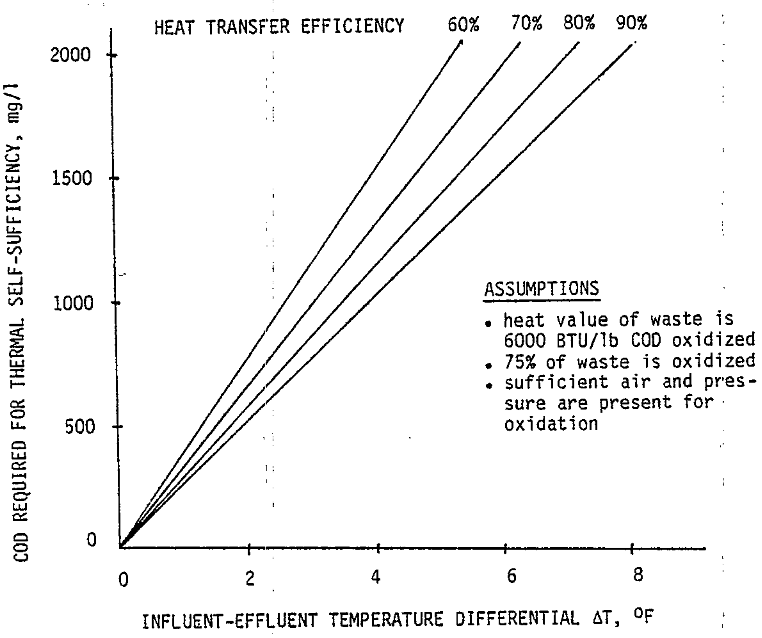

Figure 11. Waste strength required for thermal self-sufficiency under certain conditions.

Figure 12 gives the projected energy balance for conditions inside the VWCR proposed for Longmont, Colorado. Washout heat for an influent-effluent temperature differential of $5^{o}F$ is 260,000 BTU/hr (150,000 gal/day X 8.34 lb./gal X day/24 hr X 1 BTU/lb.-^{o}F X $5^{o}F$). Heat loss to the surrounding rock for the particular conditions existing at Longmont is projected to be about 430,000 BTU/hr at steady-state conditions. Heat of reaction is 2,350,000 BTU/hr (9400 lbs. COD/day X 6000 BTU/lb. COD X day/24 hr). Net heat production is thus 1.66 X 10^{6} (2.35-0.43-0.26) BTU/hr.

At Longmont, heat loss to the surrounding earth is expected to be about 18% (0.43/2.35 X 100). In other words, heat transfer in the reactor is expected to be about 82 percent efficient. From Figure 11, for a wash-out heat loss due to a temperature differential of $5^{o}F$, and heat transfer efficiency of 82 percent, minimum mg/l COD required for thermal self-sufficiency is about 1370 mg/l COD. Longmont expects COD of the waste to be 5,000-10,000 mg/l COD so that exothermic conditions should exist.

It is important to keep in mind that these energy examples assume that sufficient conditions exist in the reactor for oxidation to proceed. That is, initial start-up heat to bring the reactor up to the temperature required for oxidation has been supplied; there is sufficient air for oxidation; and there is sufficient pressure to keep water in liquid phase at the reaction temperature. An important task in demonstration plant operation will be to gain

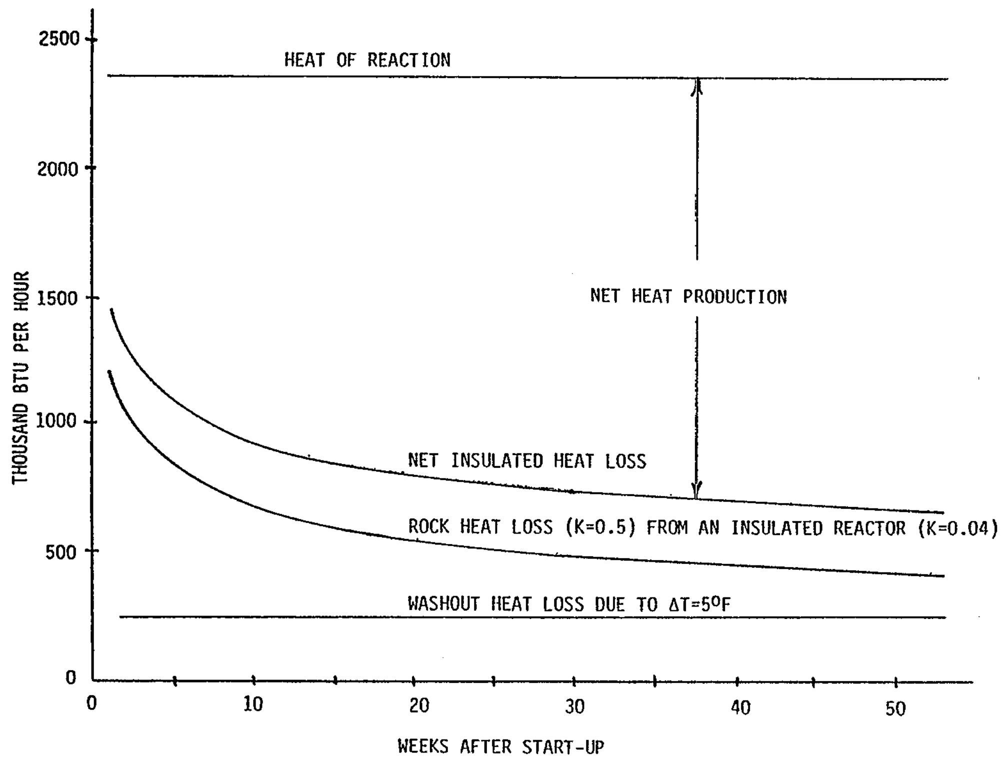

Figure 12. Net heat production expected for the Longmont VWCR.

confidence in such assumptions made when designing full-scale facilities for a particular waste. In any reactor design the thermally self-sufficient COD concentration will be a function of the specific design, the waste characteristics and the thermal conductivity of the surrounding earth.

Other energy requirements for the VWCR are for feed pumps, air compressors, heat exchange fluid pumps, and miscellaneous smaller requirements, such as from acid wash and recirculation pumps. Sidestream energy requirements are in addition to these. For the Longmont, Colorado VWCR, which is designed to treat sludge generated by a 7.5 mgd wastewater flow, the operating horsepower requirements are estimated to be 135 hp total: 20 hp VWCR feed pump; 100 hp air compressor; 5 hp heat exchange pump; and 10 hp for other miscellaneous pumping requirements.

During start-up, there will be an initial large energy (fuel) input into the heat exchange boiler to bring the reactor up to operating temperature. Just how much fuel will be needed will be determined from the demonstration plant studies at Longmont. It is expected that the oxidation reactions will quickly (within a few days) generate enough heat for oxidation to proceed autogenously and that net heat production will increase until steady-state conditions are attained (in about 40 weeks for Longmont--see Figure 12).

OPERATION AND MAINTENANCE REQUIREMENTS (22, 23)

Operation and maintenance requirements for the full-size plant at Longmont have been estimated based on pilot plant experience. See Figure 3 for the unit operations comprising the VWCR system. Major daily labor expenditures are for pump and valve maintenance, coarse screen cleaning, and sludge disposal to the drying beds. For the particular case at Longmont, it is estimated that the 7.5 mgd wastewater flow will result in 7,000 lbs. of dry suspended solids each day coming from the primary clarifier to the VTR. These will be reduced 90 percent in the VWCR to 700 lbs. of dry solids. It is estimated that 80 percent of these solids will be settled in the foam separator/clarifier giving 560 lbs. of dry solids in a 10 percent concentrated sludge (or "ash"). This works out to be approximately 3.3 yd^3 of thickened sludge to the drying beds each day (560/[0.1 X 62.4 X 27]) from the 7.5 mgd plant.

Structures and reactor casings are estimated to have a 40 year life including air and heat exchange lines; mechanical/electrical equipment 15 years. The stainless steel upcomer and downcomers of the VWCR are conservatively estimated to have a 10 year life and will have to be replaced over a normal 20 year life cycle period.

Nitric acid quantities and indeed acid wash operation have yet to be determined. This is one of the important areas to be investigated at the Longmont VWCR demonstration plant. The range of high temperatures and pressures occuring in the reactor and the unknown buffering capacity of the wastewater which influences pH complicate the estimation of free CO_2 which can be expected to be in solution. This in turn makes estimates about bicarbonate and carbonate quantities difficult. Hardness as calcium bicarbonate is soluble. Calcium carbonate is not and may precipitate out or adhere to the sides of the reactor. At this writing, best estimate of the amount of nitric acid needed for Longmont is based on the reaction:

$$CaCO_3 + 2HNO_3 \longrightarrow H_2CO_3 + Ca(NO_3)_2$$

The 150,000 gpd of sludge (40,000 gpd) plus dilution water or recycled VWCR supernatant (110,000 gpd) entering the Longmont VWCR is expected to contain a total of 350 lbs. of calcium. From the stoichiometry, for every 40 lbs. of calcium, 126 lbs. of nitric acid is needed. Thus about 1110 lbs (126/40 X 350) of nitric acid is needed each day to react with the potential calcium carbonate which may form. Considering that equilibrium CO_2 increases with temperature (and thus less bicarbonates decompose to carbonates) and that not all calcium carbonate will necessarily adhere to the reactor piping, about 800 lbs. of nitric acid is estimated to be needed for Longmont. This figure must be considered a best guess. Nitric acid available on the market is at 67 percent concentration and has a specific gravity of 1.3. Thus 110 gallons of 67 percent concentrated nitric acid (800/[.67 X 1.3 X 8.34]) is estimated to be needed daily for Longmont, Colorado.

COSTS (22, 23)

Capital cost estimates for sludge treatment using a VWCR are summarized in Table 10. The capital costs have a range which includes the differences in

TABLE 10. VWCR CAPITAL COST ESTIMATES FOR TREATING SLUDGE FROM VARIOUS SIZE WASTEWATER TREATMENT PLANTS (22)

Wastewater Treatment Plant Size, mgd	VWCR Plant Size, mgd	Reactor Diameter, Inches	Number of Reactors	Capital Cost Range, 10^6*
7.5	7.5	8	1	2 - 3
15.0	7.5	8	2	4 - 5
30.0	15.9	12	2	7 - 10
100.0	33.0	16	3	20 - 30

*Estimates based on 5000-6000 feet deep reactor, 600°F maximum temperature and 70 percent COD reduction. The capital cost range includes the cost of additional biological treatment for sidestreams and costs of different drilling situations. The ENR Construction Cost Index is 3510.

site geology (affecting well drilling costs), construction cost differences across the country and the need in some cases to include additional biological treatment for sidestreams. Odor control equipment is not included in this estimate. The capital cost estimates are for the generalized plant unit operations shown in Figure 8. Other assumptions are listed in the Table. Note that the VWCR unit size nomenclature uses wastewater flow quantities although the reactor is oxidizing the sludge generated by the wastewater treatment plant.

Table 11 summarizes operation and maintenance (O&M) costs based on those estimated for the 7.5 mgd VWCR proposed for Longmont, Colorado. See Figure 7 for definition of which unit operations contribute to these costs. Electric and chemical costs increases for the larger plants are straight line from the Longmont 7.5 mgd cost estimates. The previous sections on O&M and energy considerations have discussed the basis for some of these costs. Other assumptions are listed in the Table. Note that Longmont does not include biological polishing of the sidestream (effluent from the foam separation tank is returned to the headworks of the plant) and so both biological polishing and air odor control O&M costs are not included in this estimate. Table 11 also does not include energy generation from potential net heat production. For any given situation, net heat production can be estimated using the approach given in the discussion for Figure 12. The conversion efficiency from net heat to usable heat (energy) must also be considered. Life cycle costs of the energy recovery system minus costs of purchased energy replaced will complete the energy recovery cost evaluation. Finally, the O&M cost estimates are for steady-state operation and do not include start-up or equipment and reactor replacement costs discussed in the operation and maintenance section. Replacement of the stainless steel upcomer and downcomer within a 20 year period is estimated to cost roughly half the

TABLE 11. VWCR ANNUAL O&M COST ESTIMATES FOR TREATING SLUDGE FROM VARIOUS SIZE WASTEWATER TREATMENT PLANT (22)*

Item	7.5 mgd (Longmont)			15 mgd (2 - 7.5 mgd reactors)		
Power†	$100/day X 365	=	$ 36,500	$36,500 X 2	=	$ 73,000
Chemicals‡	110 gpd X 365 X $10	=	40,150	40,150 X 2	=	80,300
Maintenance Material Cost§	$2000/mo X 12	=	24,000	$4000/mo X 12	=	48,000
Maintenance Labor#	4 hr X 220 X $10	=	8,800	8 hr X 220 X $10	=	17,600
Operator Labor#	16 hr X 220 X $10	=	35,200	16 hr X 220 X $10	=	35,200
Laboratory Tech#	3 hr X 220 X $10	=	6,600	4 hr X 220 X $10	=	8,800
Sludge Removal Costs**	10 hr X 12 mo X $25	=	3,000	12 hr X 12 X $25	=	3,600
TOTAL			$154,250			$266,500
EXPECTED RANGE	$125,000 - $175,000			$190,000 - $300,000		

(continued)

TABLE 11. Continued

Item	30 mgd (2 - 15 mgd reactors)			100 mgd (3 - 33 mgd reactors)		
Power†	73,000 X 2	=	$146,000	146,000 X 3.33	=	$ 486,000
Chemicals‡	80,300 X 2	=	160,600	160,600 X 3.33	=	535,000
Maintenance Material Cost§	5000/mo X 12	=	60,000	15,000/mo X 12	=	180,000
Maintenance Labor#	8 hr X 220 X $10	=	17,600	24 hr X 220 X $12	=	63,360
Operator Labor#	16 hr X 220 X $10	=	35,200	32 X 220 X $12	=	84,480
Laboratory Tech#	8 hr X 220 X $10	=	17,600	8 hr X 220 X $10	=	17,600
Sludge Removal Costs**	24 hr X 12 X $30	=	8,640	32 hr X 12 X $50	=	19,200
TOTAL			$445,640			$1,385,640
EXPECTED RANGE	$400,000 - $500,000			$1,200,000 - $1,500,000		

* 70 percent COD reduction and 600°F maximum temperature. Power and chemical costs are straight line increase from a 7.5 mgd plant. ENR Construction Cost Index = 3510.

† 135 hp per 7.5 mgd size plant and $0.04/kwh. No credit included for potential energy recovery.

‡ 110 gal 67 percent concentration nitric acid per 7.5 mgd plant per day at $1.00 per gal.

§ Best estimate by VTR Corporation.

\# 220 working days per year per operator but 7 day per week shift coverage.

** Effluent sludge flow from the foam separator clarifier into the drying beds is 3 CY per day per 7.5 mgd plant size and 10 percent concentration. Sludge is removed once per month from the drying beds at 40% concentration.

initial cost of providing and installing all VWCR downhole components (excluding well drilling and casing costs).

Table 12 gives a preliminary life cycle cost estimate for a VWCR sized to treat sludge from a typical 7.5 mgd municipal wastewater treatment. It is emphasized that the figures given in Table 12 represent only best estimates. The exclusions discussed for Table 11 also apply for Table 12. Potential energy recovery credits are not included. The factors most affecting the life cycle costs of any VWCR are well drilling costs and sludge composition (from both energy recovery and corrosion/deposition considerations).

TABLE 12. PRELIMINARY LIFE CYCLE COST ESTIMATING FOR A VWCR SYSTEM CONTAINING AN EIGHT INCH DIAMETER REACTOR (23)*

Project Capital Costs (and expected service life)		
Well drilling and casing (40 yr)		$ 600,000
Vertical Well Chemical Reactor		
- Reactor heat exchange lines, air lines and casing (40 yr)		300,000
- Reactor upcomer and downcomer (10 yr)		300,000
Mechanical/electrical equipment (15 yr)		300,000
VWCR building (40 yr)		40,000
Existing WWTP modifications to accommodate VWCR		60,000
Construction Cost		$1,600,000
20% contingencies	320,000	
20% non-construction costs (engineering, supervision, etc)		320,000
Total Capital Cost (PW)		$2,240,000
Replacement Costs		
Reactor upcomer and downcomer - $300,000 X .50245 =		151,000
Mechanical/electrical equipment - $300,000 X .35615 =		107,000
Total Replacement COSTS (PW)		$ 258,000
Salvage Value		
Well drilling and casing 20/40 (600,000 X .25245) =		$ 76,000
VWCR heat exchange lines, air lines and casing 20/40 (300,000 X .25245) =		38,000
Mechanical/electrical equipment 10/15 (300,000 X .25245) =		50,000
VWCR building 20/40 (40,000 X .25245) =		5,000
Salvage Credit (PW)		($ 169,000)
Operation and Maintenance Costs (see Table 11) $154,250 X 10.49186 =		$1,618,000
		$3,947,000
Equivalent Annual Costs $ 3,952,000/10.49186 =		$ 376,000/Yr

*See Figure 7 for definition of system components.
The VWCR system is sized to treat sludge generated by a 7.5 mgd WWTP.
Discount rate = 7-1/8 percent; 20 year life cycle period; energy recovery costs and credits are not included. ENR = 3510.

SECTION 4

COMPARISON WITH EQUIVALENT TECHNOLOGIES (24)

Wet oxidation can be divided into three categories of oxidation which are primarily segregated according to the amount of COD reduced. The three categories are defined in Table 13. The low oxidation category of wet oxidation is often used interchangeably with sludge conditioning. This is because low oxidation primarily changes the composition of the sludge to improve its thickening and dewatering properties. The small reduction in COD demand is almost incidental. However, unlike sludge conditioning processes, air for oxidation is specifically added to the process.

This comparison uses as its basis the information contained in the EPA report, "Effects of Thermal Treatment of Sludge on Municipal Wastewater Treatment Costs" (24). It is recommended reading (24). The report represents an independent survey of costs associated with the various processes commercially available for thermally treating sludges normally generated during the treatment of municipal wastewaters.

Because virtually all of the equipment for the thermal treatment of sludge was supplied by Zimpro or Envirotech, the EPA study dealt largely with the processes and equipment used by those two manufacturers. Most sludge treatment plants contacted which were manufactured by Zimpro could be classified as low oxidation units. A few were intermediate oxidation units. One (Akron, Ohio) was a high oxidation unit. The sludge treatment plants manufactured by Envirotech were classified as thermal conditioning plants.

TABLE 13. WET OXIDATION CATEGORIES (24)

Oxidation Category	Typical Reduction in Sludge COD, %	Temperature °F	Pressure psi
Low	5	350 - 400	135 - 250
Intermediate	40	450	450
High	92 - 98	675	2650

The cost figures used in this section come from the EPA report and are in March 1975 dollars (ENR = 2128). Costs are for thermal treatment processes in general and wet oxidation in particular when it can be subdivided to that extent. Direct construction, fuel and electricity, manpower, and material and supplies costs are given and discussed below. Indirect sidestream treatment and more general factors which should be addressed when considering various methods for sludge treatment and disposal are given at the end of this section.

This comparison is more accurately termed a contrast with other equivalent technologies because the basis for comparison is not always the same. Differences are noted in the section as much as possible. Two major differences should be noted: Most above ground thermal treatment processes thicken the waste to about 4-5 percent in order that oxidation may occur in a smaller vessel size and the waste have a higher heating value. The VWCR does not because its configuration does not allow for sufficient air as oxygen to be added for oxidation of such high strength wastes. In fact, sludge wastes are normally diluted. The trade-off with thickening cost savings is potentially longer reaction times and a lower heating value of the waste. This cost comparison does not address thickening considerations. Secondly, the EPA cost figures are essentially summary costs of low to intermediate wet oxidation plants. VWCR cost estimates are for fairly high (500-650^{o}F, 75% COD reduction) oxidation operation. With these differences in mind, a contrast between the VWCR and other thermal treatment processes is made throughout the remainder of the section.

Figure 13, Curve A, gives average thermal treatment plant costs for sludge feed pumps; grinders; heat exchangers; reactors; boilers; gas separators; air compressors, where applicable; standard odor control systems; and piping, controls, wiring and installation services normally furnished by the equipment manufacturer. Curve B includes costs for typical building, foundation, and utility needs for the thermal treatment system.

Figure 13 construction costs can be roughly compared to similar sized VWCR cost estimates by noting that the nominal 7.5 mgd size wastewater treatment plant at Longmont is expected to generate about 7000 lbs. of dry solids per day for the VWCR. Average solids concentrations of the thickened sludge entering typical thermal treatment processes is 4.5 percent according to the EPA report. This results in a thermal treatment plant capacity of about 13 gpm and a construction cost of approximately $520,000 (Curve B). Assuming capital costs are 30 percent over construction costs and using the ENR index as an inflation guide (3510/2128), present worth capital cost is estimated to be $1,115,000. This can be contrasted with the $2-3 X 10^{6} range for the nominal 7.5 mgd VWCR plant cost estimated in Table 10 for a high degree of oxidation (about 75% COD reduction). VTR estimates about a $1,400,000 capital cost for a thermally self-sufficient VWCR operating at a low degree of wet oxidation (10-30% COD reduction).

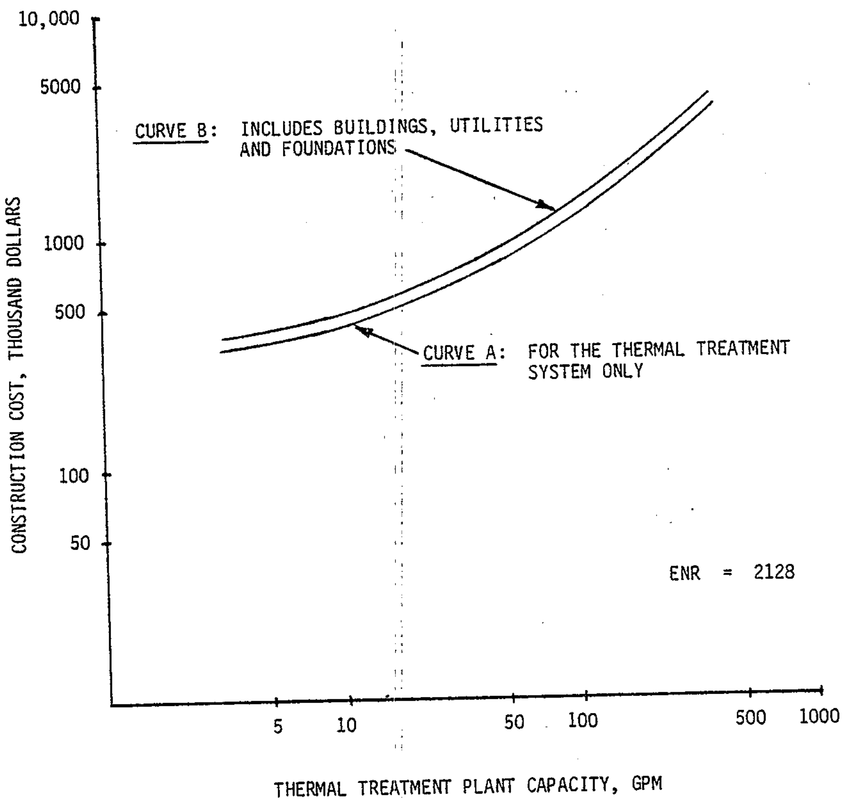

Figure 13. Typical direct construction costs for thermal treatment plants (24).

Annual costs versus typical thermal treatment plant sizes for both fuel and electricity are shown in Figure 14. The curves are for those plants incorporating air addition (wet oxidation) and not solely sludge conditioning. The curves, however, are for low oxidation conditions.

Fuel is used chiefly as a source of heat to produce steam which will heat the waste to temperatures adequate to support combustion. The amount of fuel used is influenced by the temperature to which the reactor contents are raised, efficiencies of the boiler and heat exchange systems, insulation properties, and the degree of heat producing oxidation which takes place in the reactor. (In the VWCR proposed for Longmont, fuel is not required after initial start-up because reaction proceeds autothermally.)

Electrical energy needs are determined by sizes and efficiencies of driven machinery, such as sludge and boiler water pumps, grinders, thickeners, and air compressors. The electrical energy curve includes an allowance for thermal treatment plant building and site needs such as lighting. Unit costs of $2.80 per million BTU for fuel and $0.03/KWH were used to draw the curves.

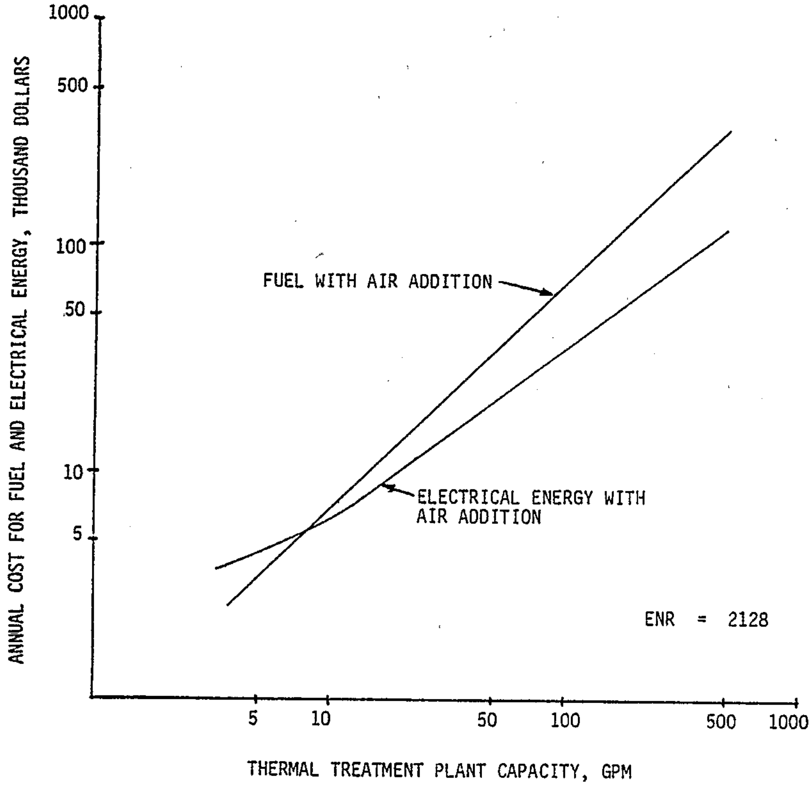

Figure 14. Typical power costs for thermal treatment low wet oxidation plants (24).

At a thermal treatment plant capacity of 13 gpm, Figure 14 indicates that total annual fuel and electrical energy costs are respectively $9000 + 7000 = $16,000. Using the ENR Index ratio of 3510/2128 results in a $26,000 current annual cost estimate. This can be contrasted to the $36,500 power cost estimate for the VWCR at a 7.5 mgd plant size in Table 11. As before, however, the basis is not the same because the VWCR is designed for high oxidation 600°F and 1600 psi pressures compared to the 350-400°F, 135-250 psi pressures found in the low oxidation category which Figure 14 summarizes. At high pressures, power for the air compressors represents most power demand (no fuel is needed since the reaction proceeds autothermally). A sludge disposal study done for the New York City-New Jersey Metropolitan Area estimated power requirements (electricity plus fuel as applicable) for the high wet oxidation category were approximately 3.9 times higher than those low oxidation above ground plants (25). Using this factor, a $101,400 versus $36,500 contrast seems more realistic. Neither of these figures includes potential energy recovery credits.

Labor for operation and maintenance presents one of the highest areas of cost in the operation of a thermal treatment plant. The labor costs summarized in Figure 15 are for preventative and routine repair work. The labor operation costs comprise time spent reading and logging data on the process, controlling and adjusting various systems and components, and laboratory work. Labor maintenance costs include cleaning and repairing process components, general upkeep of the process area, checking and repairing of controls and instrumentation, and performing preventative maintenance on a daily, weekly, monthly, etc., basis. They do not include major overhaul functions, such as reactor cleaning, pipe, tube, pump, compressor or boiler working parts replacement. Costs for these and similar items requiring skills of contracted specialists are included in a later discussion below on materials and supplies.

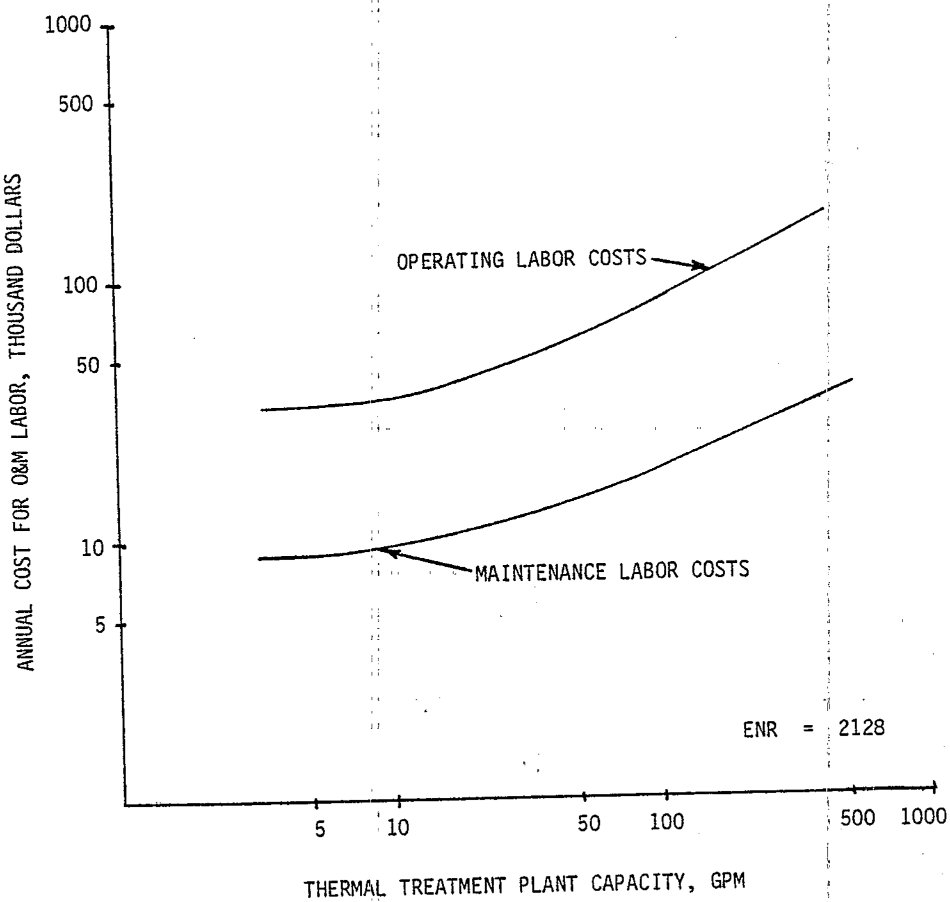

Figure 15. Typical operating and maintenance labor costs for thermal treatment plants (24).

From Figure 15, the annual cost for O&M labor at a typical 13 gpm capacity thermal treatment plant is approximately $38,000 + $10,000 = $48,000 at ENR 2128 or $79,000 at ENR 3510. This is contrasted to the sum of maintenance, operator, and laboratory labor ($8800 + $35,200 + $6600) equal to $50,600 estimated for the similar capacity 7.5 mgd nominal sized VWCR in Table 12. This is consistent with the expectation that labor costs should be lower for the VWCR than above ground thermal treatment plants because of the latter's complex array of high pressure vessels, heat exchangers, pressure reducing and control valves, piping, pumps and air compressors. Proper control of above ground high temperature and pressure processes requires constant oversight by skilled personnel.

Normal annual costs for materials and supplies required to operate and maintain the thermal treatment system are shown in Curve A of Figure 16. These costs include materials and parts such as seals, packing, coating, lamps, bearings, grinder blades and other items used in scheduled and normal maintenance. They also include operating supplies such as lubricants, cleaning chemicals, boiler feed water, and water treating chemicals. At 13 gpm, Figure 16, Curve A shows a $5800 annual cost at ENR 2128 or $9600 at ENR 3510. This is contrasted to the sum of chemicals and maintenance materials cost ($40,150 + $24,000) equal to $64,150 for the VWCR given in Table 12.

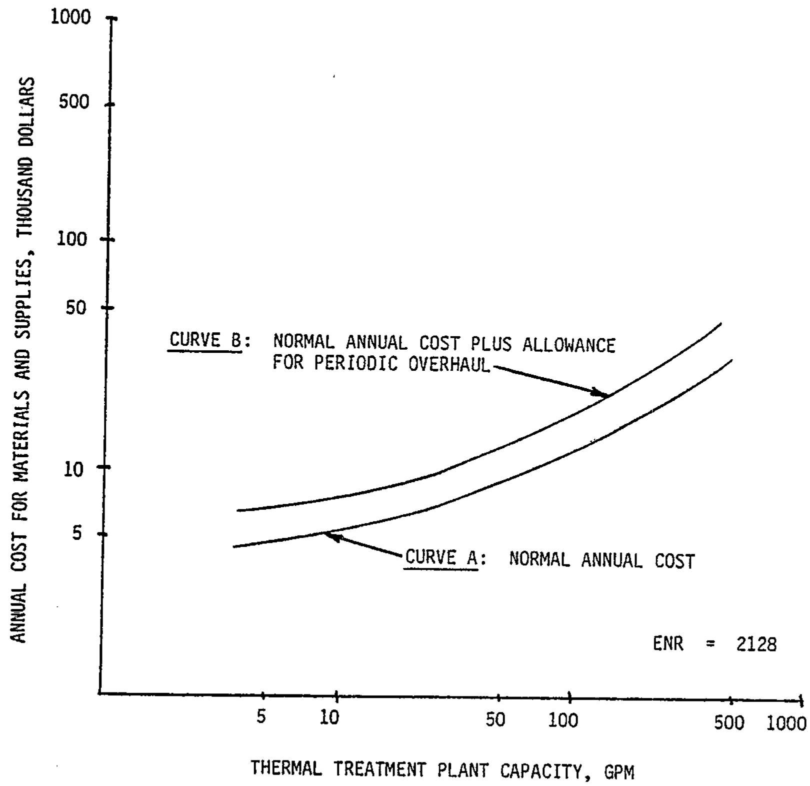

Figure 16. Typical material and supply costs for thermal treatment plants (24).

The estimate of materials and supplies for the VWCR is made with least confidence. This is because at this writing the VWCR has no long-term operating history and "typical" material and supply inventories and usage rates are not known. Chemical quantities and prices will greatly influence VWCR supply costs. Since the estimate in Table 12 is for high temperature and pressure operation, it is expected that corrosion and deposition control supply costs would be higher than those suggested in Figure 16, which largely summarize sludge conditioning and low wet oxidation data. Nevertheless, the greater than 6-fold difference seems high.

In addition to routine maintenance tasks required for typical thermal treatment plants as described by Curve A of Figure 16, additional costs for major overhaul work are incurred. This work includes such items as motor rewinding; major overhauls of pumps and compressors; major, non-routine rehabilitation or replacement of heat exchanger tubing piping and controls; and refitting of boilers. Such work might be done on an average of 6-7 years depending on the plant and the component. Curve B of Figure 16 summarizes typical overall costs including those under Curve A to give the total annual cost for materials and supplies. At this writing, the cost increment represented by Curve B cannot be estimated with any degree of confidence for the VWCR and no contrast is made.

Costs associated with the handling and treating of liquors resulting from thermal processing of sludge can significantly affect the total cost of treatment. Costs for processing the liquor depends on the method chosen to handle and treat the liquor, the sewage treatment process, discharge requirements and most importantly the characteristics of the liquor itself. Because wet oxidation with the VWCR normally is in the high oxidation category, it is expected that the liquor strength will not be as great as those from heat treatment processes which do not stabilize the waste to such an extent. The characteristics of the liquor expected for any given application must be determined from pilot or bench treatability tests. Once this is done, the cost of constructing and operating facilities to handle process liquor must be addressed. The EPA report outlines an approach for estimating indirect costs of sidestream treatment. Wastewater treatment plant capacity to handle high strength recycle liquor is selected as the variable having the greatest influence on costs for liquor treatment. Other variables, particularly BOD and suspended solids concentrations in the raw sewage, also influence cost.

Costs to treat concentrated, high-hydrocarbon streams coming primarily from gas separators or covered decanting tanks represent the second major sidestream impact on overall treatment costs. The EPA report notes that commonly, five to ten percent of the total costs for thermal treatment are for odor control. Again, odors resulting from high temperature and pressure oxidation in the VWCR are expected to be less because the waste is stabilized more than at low or intermediate oxidation plants. Odor treatment is not expected to be such a significant factor. The EPA report estimates costs for odor control in a similar manner to that done for effluent liquors. Costs are developed for three typical methods of odor control: incineration, carbon adsorption and chemical scrubbing. It must be emphasized that odor control systems for use in thermal treatment plants must be selected on the basis of what is needed to adequately treat the specific off-gas involved.

For proper toxics management, there are common questions which have to be answered, whichever the wet air oxidation process. These include identifying the form, stability, and toxicity of the compound after oxidation, establishing how much is in the liquid and solids fraction, and determining its leachability or degradability. Mechanical operation of the VWCR would be safer than conventional wet oxidation configurations because there are no high pressure vessels and associated transfer and control equipment. However, wells drilled through potable water bearing strata must be properly cased to protect groundwater quality.

A comprehensive comparison with equivalent technologies awaits further full-scale demonstration plant testing to verify design performance and cost relationships.

SECTION 5

ASSESSMENT OF NATIONAL IMPACT

The vertical well chemical reactor employs chemical oxidation to oxidize organic materials in water solution or suspension. In general, the desirability of using the VWCR is influenced by plant size, site-specific geological conditions, wastewater characteristics and sidestream treatment requirements. These considerations are not independent and are discussed below.

Table 14 summarizes some of the technical findings of the EPA 1980 Needs Survey (26). It estimates that over 6000 domestic wastewater treatment plants need to be built or upgraded by the year 2000 in order to meet the 1983 goals of the Clean Water Act. All of these will generate sludge and some wastewaters will have an industrial component increasing their strength, making them more attractive for potential wet oxidation using the VWCR.

At this writing, the smallest domestic wastewater treatment plant which can economically utilize a VWCR to treat sludge is estimated to be about 3 mgd (27). Minimum desirable reactor diameter and the requirement for enough sludge flow to maintain continuous operation of the VWCR determines plant size. (If VWCR operation is not dependent on sludge production and oxidizes the wastewater directly, the 3.0 mgd figure is not appropriate and the minimum size plant will largely be a function of wastewater characteristics.) Part B of Table 14 estimates that 135 to 572 of the new plants expected to be built by the year 2000 will be 3.3 mgd or larger. Using this information and the 3 mgd size restriction for sludge treatment, it can be estimated that the VWCR can potentially be considered for sludge treatment at at least 354 (the average of 135 and 572) domestic wastewater treatment plants expected to be built by the year 2000. Existing plants will also be upgraded, creating additional needs for sludge disposal facilities.

An important site-specific consideration is drilling costs. These will normally constitute the single largest capital outlay item. Drilling costs are a function of subsurface geology which must be characterized for the site. The availability of drilling equipment and know how must also be determined. Wastewater treatment sites having unused wells on site or nearby make wet oxidation of the wastewater or sludge by the VWCR more desirable. The VWCR should also be considered at sites where land is at a premium and sludge disposal a problem. And, wet oxidation is well suited for those wastewaters too toxic for direct biological treatment.

Thermal self-sufficiency will be required in most cases in order that the VWCR be cost effective. Figure 11 suggests that given an optimum temperature

TABLE 14. 1980 NEEDS SURVEY TECHNICAL SUMMARY EXTRACT (26)

A. Level of Treatment by Year and Number of Plants

Level of Treatment	Number of Plants 1980	2000	Change
Raw discharge	271 (0.9 mgd av.)	0	- 271
Less than secondary	3313 (1.8 mgd av.)	9 (2.7 mgd av.)	- 3304
Secondary	7838 (1.3 mgd av.)	11904 (1.5 mgd av.)	+ 4066 (52%)
Advanced secondary (AST)	2482 (3.5 mgd av.)	6539 (2.9 mgd av.)	+ 4057 (163%)
Tertiary (AWT)	262 (3.4 mgd av.)	826 (5.0 mgd av.)	+ 564 (215%)
No discharge	1361 (3.1 mgd av.)	2366 (0.5 mgd av.)	+ 1005 (74%)
Total*	15527	21644	Δ = 6177

B. Treatment Plant Flow Ranges by Year and Number of Plants

Flow Range (mgd)	Number of Plants 1980	2000	Change
0.0 - 0.105	5018 (0.05 mgd av.)	9417 (0.05 mgd av.)	+ 4399 (88%)
0.106 - 1.05	7024 (0.4 mgd av.)	8442 (0.4 mgd av.)	+ 1418 (20%)
1.06 - 10.55	2700 (3.3 mgd av.)	3137 (3.3 mgd av.)	+ 437 (16%)
10.56 - 50.19	418 (22.4 mgd av.)	524 (21.6 mgd av.)	+ 106 (25%)
50.2 +	96 (140.0 mgd av.	125 (132.8 mgd av.)	+ 29 (30%)
Total*	15256	21645	Δ = 6389

*Difference in totals are due to the method of data collection and evaluation of the survey.

differential of $2^{o}F$, general, wastes should have a COD of at least 500 mg/l COD and preferably higher for thermal self-sufficiency. Most domestic wastewaters are not this strong. Conversely, most waste sludges are much stronger, increasing the possibility of energy recovery. Thus, while wet oxidation with the VWCR is most desirable for sludges, high strength wastewaters (containing possibly domestic and industrial components, such as at Montrose, Colorado) should also be considered.

Treatment of sidestreams affects general wet oxidation economics and, therefore, desirability of using the VWCR (24). While wet oxidation improves the thickening and dewatering characteristics of sludge, it also transforms some insoluble organic substances to soluble materials in the liquor, a portion of which may be non-biodegradable. This refractory soluble portion is highly site-specific and a function of the make-up of the sludge. In addition, the strength of this portion depends on the volatile matter in the sludge and degree of oxidation achieved in the reactor. The potential of high strength liquors with refractory components underscore the importance of performing treatability studies at various wet oxidation temperatures and pressures on waste from the site under consideration to characterize expected VWCR effluent.

The other sidestream to be considered is odors from the sludge. Exhaust gases exiting from the stand pipe, solids separation, or sludge dewatering operations may be odorous and have to be treated. Common air pollution control alternatives are carbon adsorption, afterburning of volatile gases, or chemical scrubbing. As before, whether air pollution control is necessary is highly site-specific and depends on the make-up of the waste and degree of oxidation. It is not possible to generalize about sidestream treatment requirements.

Table 14 summarized expected domestic wastewater plant requirements and not industrial sector considerations. The potential of wet oxidation to destroy and detoxify toxic organic materials at moderate to supercritical pressures was discussed earlier in the wastewater composition section. In such cases where public health is a major immediate consideration, wet oxidation with the VWCR represents an attractive possibility.

In summary, the VWCR is a potential treatment technology for organic wastes when significant sludge volume reduction is required, where stringent requirements for solids disposal exist, when destruction of toxic materials and pathogenic organisms is necessary, and where potential energy recovery from high strength wastes is good. It is assumed that engineering and mechanical aspects are not limiting operation. A major goal remaining is to demonstrate VWCR steady-state operation at full scale. This experience will not only produce operational information, but will better define actual costs for various strength wastes so they can be more realistically compared to competing processes.

SECTION 6

CONCLUSIONS AND RECOMMENDATIONS

1. Configuration of the VWCR has both advantages and disadvantages:

   a. The VWCR uses little space compared to above ground wet oxidation configurations.

   b. The concentric tube configuration promotes efficient heat exchange between influent and effluent streams.

   c. The vertical tube configuration allows natural pressurization of the waste from weight of the liquid above it. The below ground natural pressurization is safer and cheaper than above ground mechanical pressurization, however, it is less flexible. Pressure at any point downhole in the reactor is relatively constant and, therefore, the maximum allowable temperature (not exceeding the waste boiling temperature) is fixed for any depth, approximately following the saturated vaporization curve for water.

   d. Reactor tube size limits the amount of air which can be added to support combustion. Standard operating procedure involves sludge dilution to meet maximum air and temperature limitations.

   e. VWCR configuration and compactness make downhole accessibility difficult. Mechanical reliability and maintenance of the VWCR system are important considerations.

2. Appropriate bench or pilot scale treatability tests using the waste to be oxidized are very important. The degree and rate of waste wet oxidation is significantly influenced by temperature and pressure. Temperature and pressure requirements affect VWCR depth and ultimately costs.

3. COD reduction experienced using a batch laboratory reactor has been close to that obtained at pilot plant scale under similar operating conditions. This supports the use of a bench scale reactor to model pilot COD reduction rates. Experience with the fate of metals or toxics is less definite.

   Specifically:

   a. The poorly understood interacting effects of metal solubility, adsorption and desorption at high temperatures do not permit a definitive explanation about the fate of metals in the VWCR. More work needs to be done in this area.

b. Independent but related laboratory scale studies investigating detoxification of specific organic compounds by wet oxidation has demonstrated wet oxidation to be an excellent method to detoxify those materials. Thus, wet oxidation using the VWCR is a potential method for treatment of toxic wastes. Studies using the VWCR for treatment of toxic wastes have yet to be done and are needed.

4. The VWCR is especially applicable to wastes having a high organic content so that a thermally self-sustaining reaction can be maintained. The minimum organic concentration for autothermal conditions will depend largely on the actual temperature differential between influent and effluent wastes.

5. When considering the feasibility of a VWCR, a subsurface geological investigation is necessary to identify aquifers, estimate well drilling costs, and determine the earth's thermal properties.

6. Sludge stabilization trends using a laboratory reactor designed to simulate VWCR oxidation conditions generally agree with historical above ground pilot and full-scale wet oxidation observations which indicate that as pressure and temperature increase:

   a. The rate and extent of COD reduction increases;

   b. The particulate waste fraction approaches an inert, readily settleable ash; and

   c. The soluble waste fraction becomes more biodegradable.

7. The VWCR is not yet fully developed in that all process variables normally expected in full-scale application have yet to be characterized:

   a. The efficacy of the acid wash system to control reactor scaling and corrosion has yet to be demonstrated;

   b. Verification of heat transfer and heat flow models which influence VWCR design and predict energy surplus or deficits is not complete; and

   c. Operation at steady-state autothermal conditions has not been done. Such operation will help define long-term operational variables and maintenance requirements.

8. A comprehensive comparison with equivalent technologies awaits further full-scale demonstration plant testing to verify design, performance and cost relationships. It is expected that data gained at the demonstration plant at Longmont, Colorado, will provide such a comparison.

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