AQUEOUS-PHASE OXIDATION OF SLUDGE USING THE VERTICAL REACTION VESSEL SYSTEM

by

The City of Longmont
Longmont, Colorado 80501

No. CS-809337-01

Project Officer

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FOREWORD

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water systems. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. The Clean Water Act, the Safe Drinking Water Act, and the Toxics Substances Control Act are three of the major congressional laws that provide the framework for restoring and maintaining the integrity of our Nation's water, for preserving and enhancing the water we drink and for protecting the environment from toxic substances. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Water Engineering Research Laboratory is that component of EPA's Research and Development program concerned with preventing, treating, and managing municipal and industrial wastewater discharges; establishing practices to control and remove contaminants from drinking water and to prevent its deterioration during storage and distribution; and assessing the nature and controllability of releases of toxic substances to the air, water, and land from manufacturing processes and subsequent product uses. This publication is one of the products of that research and provides a vital communication link between the researcher and user community.

In the 1970's a system utilizing technology from oil well drilling was developed for carrying out wet oxidation of municipal wastewater sludge underground. The pressure needed for the process could be obtained from hydrostatic head rather than by pumping. This report contains an evaluation of the process carried out at the Longmont, Colorado Wastewater Treatment Plant.

Francis T. Mayo, Director
Water Engineering Research Laboratory

ABSTRACT

The overall objective of this study was to provide plant-scale operating data on the wet-oxidation of municipal wastewater sludge utilizing the Vertical Reaction Vessel System. An important consideration in the evaluation was the effect of the return flow from the wet-oxidation process on the operation of the wastewater treatment plant. The investigation was carried out at the Longmont, Colorado, Wastewater Treatment Plant.

The Vertical Reaction Vessel System consists of a series of long concentric tubes placed in the earth using conventional oil field technology. Vertical construction produces a high hydrostatic head at the bottom of the system. The high pressure prevents boiling at the temperatures required for wet-oxidation. By utilizing hydrostatic pressure, the only pumping required is that to overcome frictional losses. The need to add energy for pressurization is eliminated. Sludge is introduced along with air or oxygen into the multiphase fluid downcomer, where it is heated by hot oxidized sludge rising in the outermost concentric space within the vessel. In the bottom of the vessel temperatures of 250°C or higher are attained and the oxidation of organic materials takes place with resulting heat production. At the center of the reaction vessel is a tubular heat exchange system which can either extract excess heat or provide heat for startup of the process.

At temperatures above 260°C total chemical oxygen demand reduction of about 80% and total volatile solids reductions of over 90% were consistently achieved. For the 25-cm reaction vessel installed at Longmont the capacity of the system using air was limited to five metric tons per day. Using oxygen it was possible to increase capacity to about 30 metric tons per day. Returning the supernatant liquid from the process to the wastewater treatment system did not significantly affect that system.

This report was submitted in fulfillment of Cooperative Agreement CS-809337-01 by the City of Longmont, Colorado, under the partial sponsorship of the U.S. Environmental Protection Agency. This report covers a period from February 1982 to September 1985, and work was completed as of September 1985.

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TABLES
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ABBREVIATIONS AND SYMBOLS

°C	degree Celsius
°F	degree Fahrenheit
Ag	silver
Al	aluminum
As	arsenic
ACS	American Chemical Society
ANSI	American National Standards Institute
ASTM	American Society for Testing & Materials
Ba	barium
BOD	biochemical oxygen demand
BOD_5	biochemical oxygen demand 5-day test period
BODS	biochemical oxygen demand soluble
BODT	biochemical oxygen demand total
Btu	British thermal unit
Ca	Calcium
Cd	cadmium
Ce	cerium
CBOD	carbonaceous biochemical oxygen demand
C.I.	Confidence Interval
cm	centimeter(s)
cm^2	square centimeter(s)
CODS	chemical oxygen demand soluble
CODT	chemical oxygen demand total
Cr	chromium
CRT	cathodic ray tube
Cu	copper
d	day(s) (English and metric units)
DO	dissolved oxygen
DS	dissolved solids
EP	extraction procedure
FC	final clarifier
Fe	iron
gal	gallon(s)
GC	gas chromatograph
GCMS	gas chromatography/mass spectrometry
gpd	gallons per day
gpm	gallons per minute
h	hour(s) (metric units only)
Hg	mercury
HHV	higher heating value
hp	horse power
hr	hour(s) (English units only)
ICIS	Tradename, data acquisition system hardware
K	potassium, or Kelvin
kg	kilogram(s)
L	liter(s)
lb	pound(s)
LBR	laboratory batch reactor
m^3	cubic meter(s)
max	maximum
mg	milligram(s)
Mg	magnesium
mg/L	milligrams per liter
mgd	million gallons per day
min	minimum
MM Btu/hr	million British thermal units per hour
MN/M^2	meganewtons per square meter
MPa	megapascal
MW	megawatt(s)
Na	Sodium
NH_3	ammonia
NH_3-N	ammonia nitrogen
Ni	Nickel
NIOSH	Nat'l Inst. for Occupational Safety & Health
NMR	nuclear magnetic resonance
NPDES	Nat'l Pollutant Discharge Elimination System
No.	number(s)
NVSS	non-volatile suspended solids
P	Phosphorous
Pb	lead
PC	Primary Clarifier
PEL	permissible exposure limit
pH	hydrogen ion solution concentration
P-lines	pressure measurement lines
ppb	parts per billion
ppm	parts per million
psig	pound(s) per square inch gauge
RBC	rotating biological contactor
RCRA	Resource Conservation and Recovery Act
RPM	revolutions per minute
SI	Systeme International d'Units
SO_4	sulfate
Se	selenium
Si	silicon
Sr	strontium
SS	suspended solids
Std. Dev.	standard deviation
TDS	total dissolved solids
TF	trickling filter
Ti	titanium
TKN	total Kjeldahl nitrogen
TLV	threshold limit value
TPD	tons per day
TS	total solids
TSS	total suspended solids
TVS	total volatile solids
TVSS	total volatile suspended solids
USEPA	U.S. Environmental Protection Agency
VRV	Vertical Reaction Vessel
VTR	Vertical Tube Reactor
WP	working pressure
wt.%	weight percent
WT	working temperature
WWTP	wastewater treatment plant
yr	year(s)
Zn	zinc

CONVERSION TABLE

CUSTOMARY UNIT	MULTIPLIER	SI UNIT
Btu	X 1.055 = = 0.9478 X	kJ
Btu/lb	X 2.326 = = 0.4300 X	kJ/kg
cu ft	X 2.832 X 10^{-2} = = 35.31 X	m^3
cu ft	X 28.32 = = 3.531 X 10^{-2} X	L*
cu in	X 16.39 X 10^{-6} = = 6.101 x 10^4 X	m^3
°F	0.555 (°F-32) = = 1.8 (°C + 32)	°C
ft	X 0.3048 = = 3.281 X	m
gal	X 3.785 = = 0.2642 X	L*
gal	X 3.785 X 10^{-3} = = 264.2 X	m^3
gal/min	X 6.308 x 10^{-5} = = 1.585 X 10^4 X	M^3/s
hp	X 745.7 = = 1.341 X 10-3 X	W
in	X 2.540 X 10^{-2} = = 39.37 X	m
lb(mass)	X 0.4536 = = 2.205 X	kg
lb/ft	X 1.488 = = 0.6720 X	kg/m
mil gal	X 3 785 = = 2.642 X 10^{-4} X	m^3
mgd	X 4.383 X 10^{-2} = = 22.83 X	m^3/s
mile	X 1.609 = = 0.621 4 X	km
ppb(by weight)	X 10^{-3} = = 1 000 X	mg/L*
ppm(by weight)	essentially = = essentially	mg/L*
psi	X 6895 = = 1.450 X 10^{-4} X	Pa
psi	X 7.031 X 10^{-2} = = 14.22 X	kgf/cm^2*
tons (short)	X 907.2 = = 1.102 X 10^{-3}	kg

* Not strictly an SI unit.

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SECTION 1
INTRODUCTION

1.1 OVERALL OBJECTIVE

The overall objective of this study was to provide plant-scale operating data on the destruction of municipal sludge utilizing the Vertical Reaction Vessel (VRV) System for aqueous-phase oxidation. Specific goals of the study were:

(1) to determine the operating parameters of the aqueous-phase oxidation process which would provide effective reduction of Chemical Oxygen Demand Total (CODT) and Total Suspended Solids (TSS) in sewage sludge; and

(2) to determine the effects of return flow from the wet oxidation process at the Longmont, Colorado Wastewater Treatment Plant (WWTP) secondary biological treatment process.

1.2 WASTEWATER TREATMENT PLANT LIMITATIONS

Longmont, Colorado is a growing city which is situated approximately forty miles north of Denver along the Colorado Rocky Mountain Front Range. Residential and commercial development have increased wastewater loads to the municipal treatment plant with resultant increased generation of sewage sludge.

The Longmont WWTP is a 31,000 m^3/d [8.2 million gallons per day (MGD)] facility which utilizes trickling filters in series with rotating biological contactors (RBC's) for secondary treatment. Longmont produces approximately 3,600 kg (8,000 lb) of sewage sludge daily, which after anaerobic digestion is disposed of in liquid form (undewatered) on agricultural land. Figure 1.2-1, the Site Plan of the Longmont WWTP, shows the plant layout and the VRV System expansion. Figure 1.2-2 shows the Plant Flow Schematic. The limiting unit process in Longmont's wastewater treatment capability was sludge treatment. Most of Longmont's WWTP processes were upgraded during previous expansion programs. The sludge disposal system, however, had adequate capacity for several more years. Industrial wastes concentrated in the sludge had retarded the anaerobic digestion process, requiring lower digester feed rates. This, in turn, decreased the overall capacity of the sludge disposal system. The digesters had experienced periodic upsets which greatly reduced the solids handling capacity of the entire plant. In addition to the strong odors produced by an upset digester and sludge thickener, the overall plant performance dropped and operating costs increased. These increasing sludge volumes and sludge hauling costs provided the incentive for Longmont to consider alternative methods for sludge disposal.

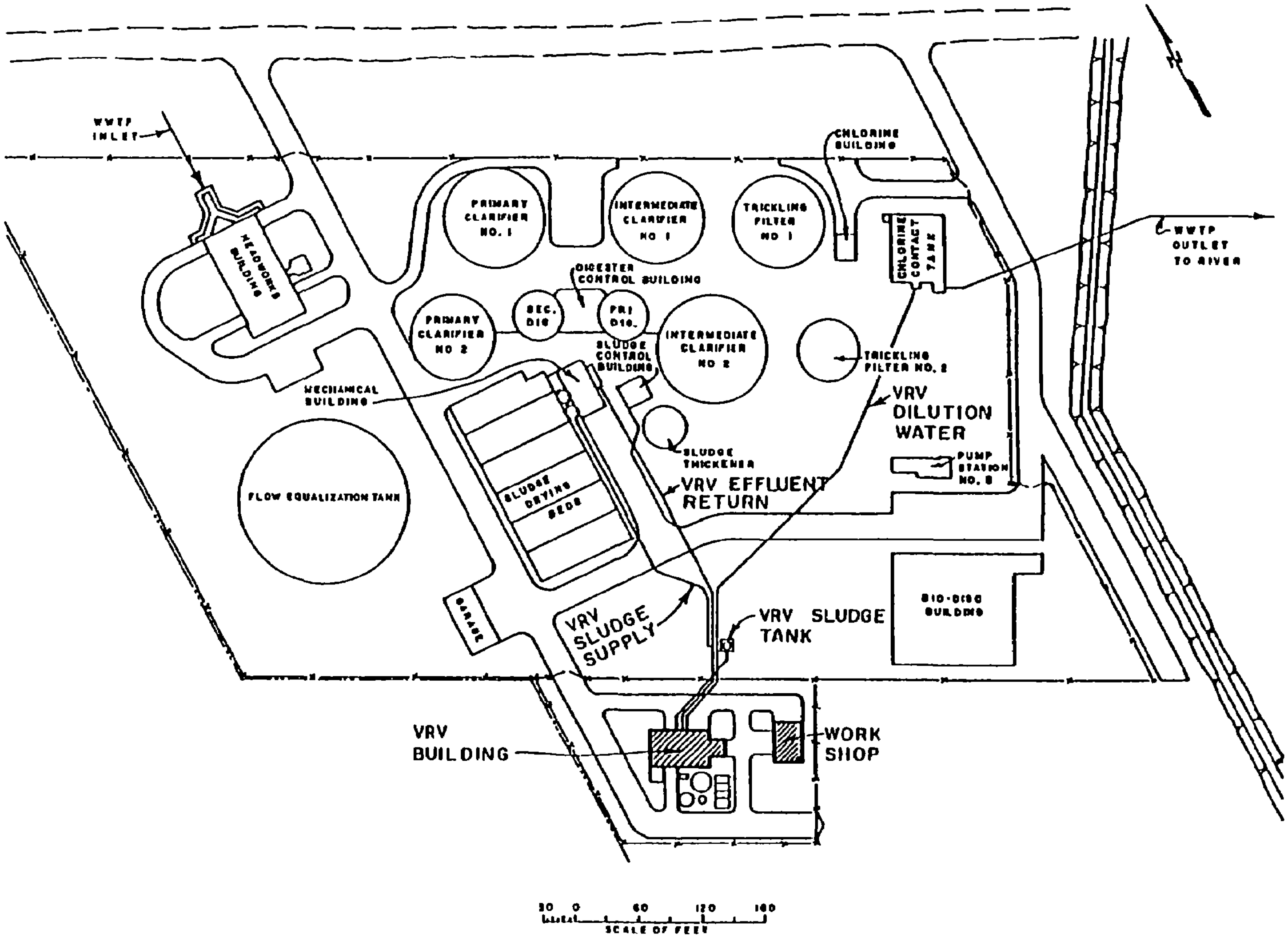


Fig. 1.2-1 Site Plan: City of Longmont WWTP

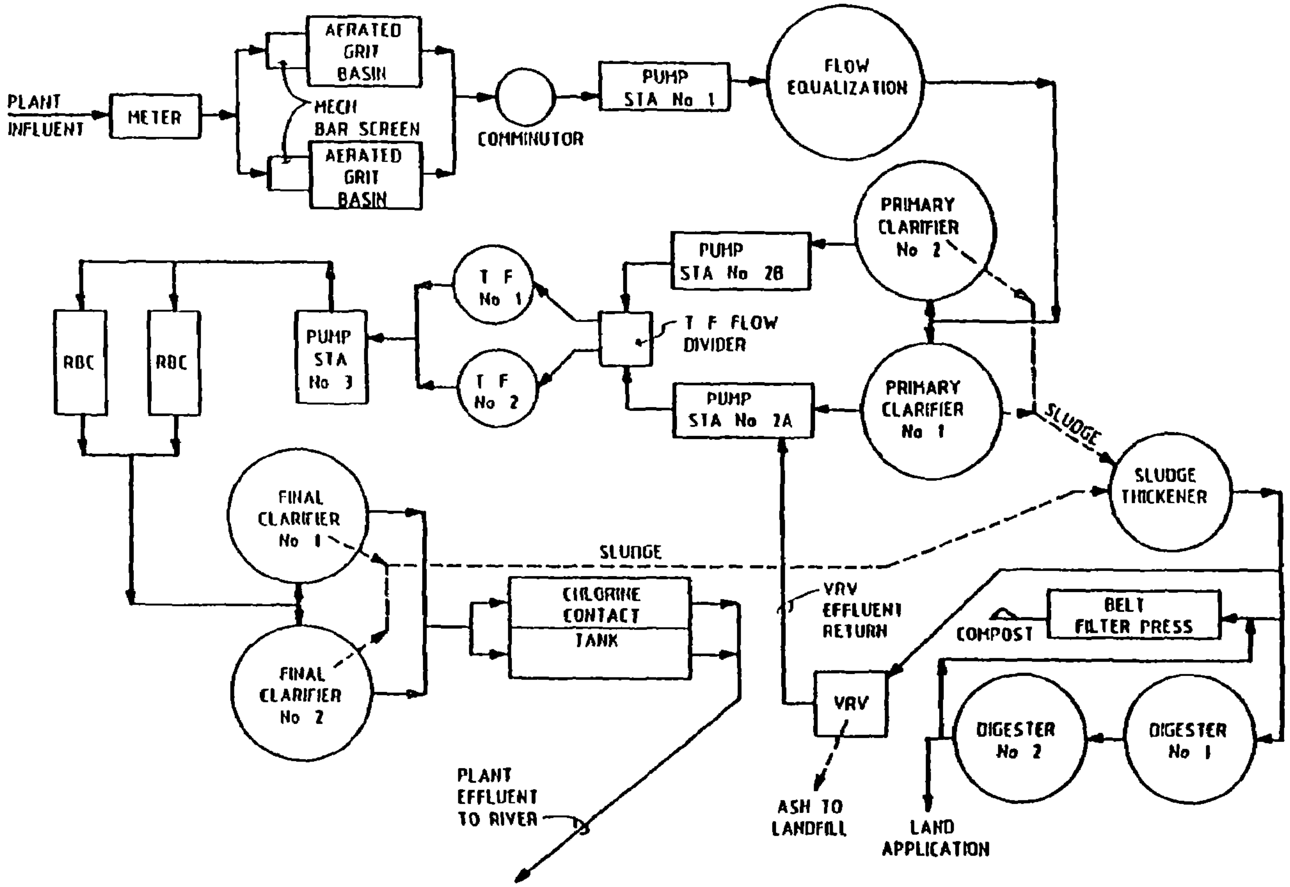


Fig. 1.2-2 Longmont Plant Flow Schematic

1.3 PROJECT DEVELOPMENT

Early in 1980, the City's sanitary consulting engineer, McCall, Ellingson, and Morrill, Inc. of Denver, approached Longmont's Director of Utilities. They presented a proposal to work with Dr. Jay McGrew, the developer of the subsurface aqueous-phase oxidation technology, to seek an EPA Demonstration Grant to construct and operate a prototype vertical reaction vessel at the Longmont WWTP. In February, 1982, the United States Environmental Protection Agency awarded Cooperative Agreement CS-809337-01 to the City of Longmont. The purpose of the cooperative agreement was to evaluate the Vertical Tube Reactor (VTR) Process, referred to in this report as the Vertical Reaction Vessel (VRV) system, for wet oxidation of municipal sludge.

1.4 VRV PROCESS OVERVIEW

The technology was further developed by VerTech Treatment Systems, and introduced as an innovative approach to applying established principles of aqueous-phase oxidation, commonly called "wet-air oxidation." Figure 1.4-1 shows a typical cross-sectional schematic of the Vertical Reaction Vessel (VRV). The design utilizes the natural laws of gravity and thermodynamics. Sludge is diluted to desired CODT concentration and pumped into the inner annular space of the concentric vertical tubes (downcomer). The reaction vessel in Longmont is constructed of stainless steel. Air or oxygen-enriched air is injected at a specified depth into the waste stream and the mixture flows down the tube. The process is initiated by heating the reaction vessel (and surrounding earth formation) by means of a central heat exchanger until reaching a temperature at which the oxidation process begins, about 175°C (350°F). At the bottom of the vessel a peak natural pressurization of about 9.6 MPa (1400 psig) is reached, due to the height and density of the fluid column above.

Oxidation of the waste substances occurs in the liquid phase, when sufficient oxygen, temperature, and pressure are present. The exothermic oxidation process produces excess heat which may be removed through the central heat exchanger for useful application at the surface. The fluid used in the central heat exchanger in Longmont is a high temperature organic heat transfer fluid, generally referred to as Dowtherm A.

The diameter and length of the vertical tubes are designed to provide sufficient residence time and hydrostatic head to complete the oxidation reactions. This high length-to-diameter ratio allows for efficient counterflow heat exchange between the downcomer influent and upcomer effluent, thereby conserving energy. The depth of the VRV provides the pressure necessary to keep the liquid from vaporizing.

The pumps injecting the diluted sludge need only overcome wall friction and a small differential head between upcomer and downcomer. They are not required to supply the high pressures experienced at the bottom of the well, thus reducing pump and compressor horsepower.

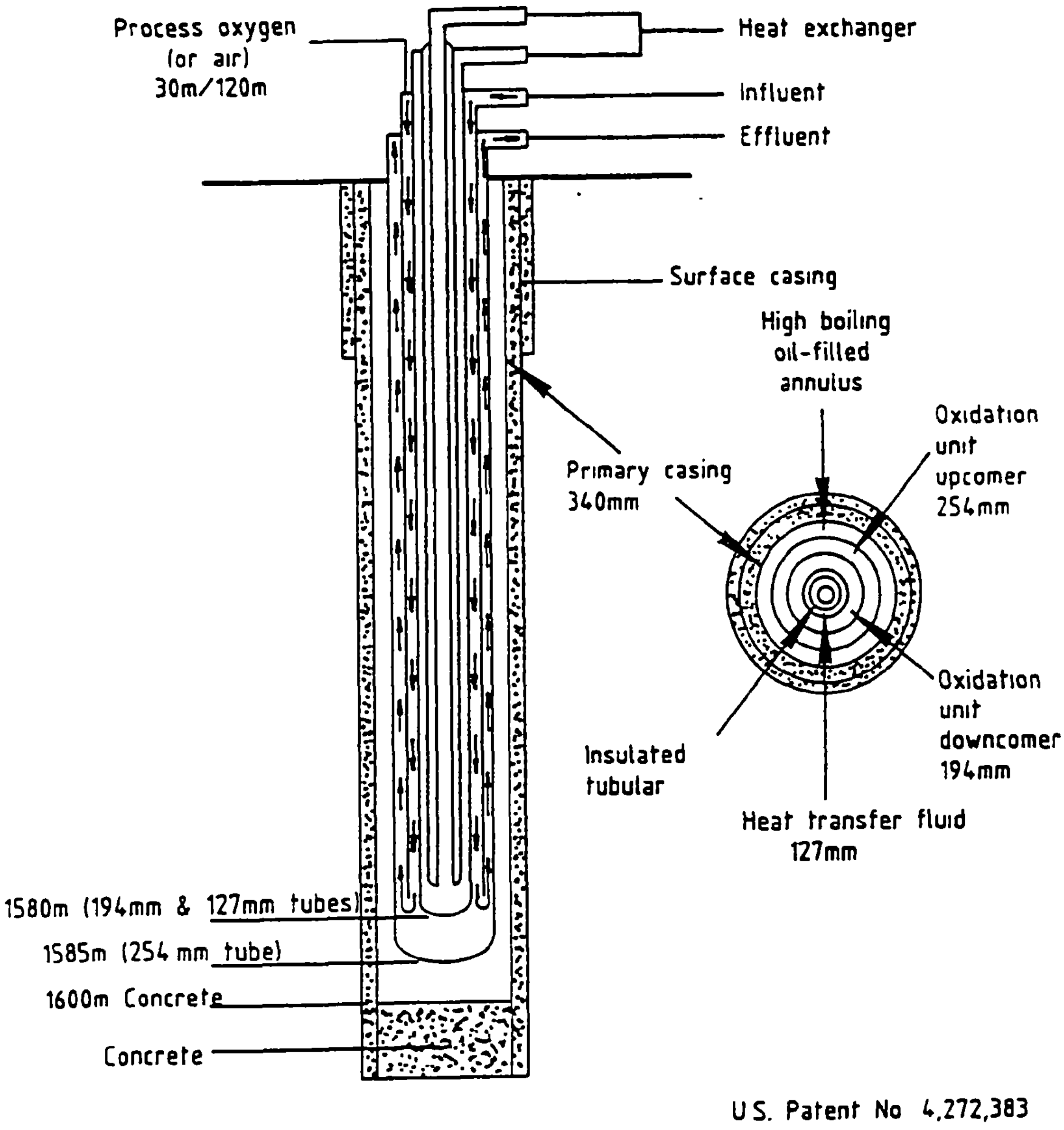


Fig. 1.4-1 VRV Subsurface Cross-Sectional Schematic

The CODT of the influent waste is significantly reduced during its residence time in the oxidation zone of the reaction vessel. The reacted effluent returns to the surface in an outer annular space (upcomer) of the vessel. The effluent flows into a gas/liquid separator and then to a solids/liquid separator. The low volume of inert solids from the VRV process dewaters more easily than the organic sludges obtained from conventional biological processes. The solids are reduced both in volume and in weight, with a small amount of inert ash remaining which can be disposed of in a sanitary landfill.

The process flow diagram for the Longmont VRV and associated surface equipment, with sampling points, is shown in Figure 1.4-2.

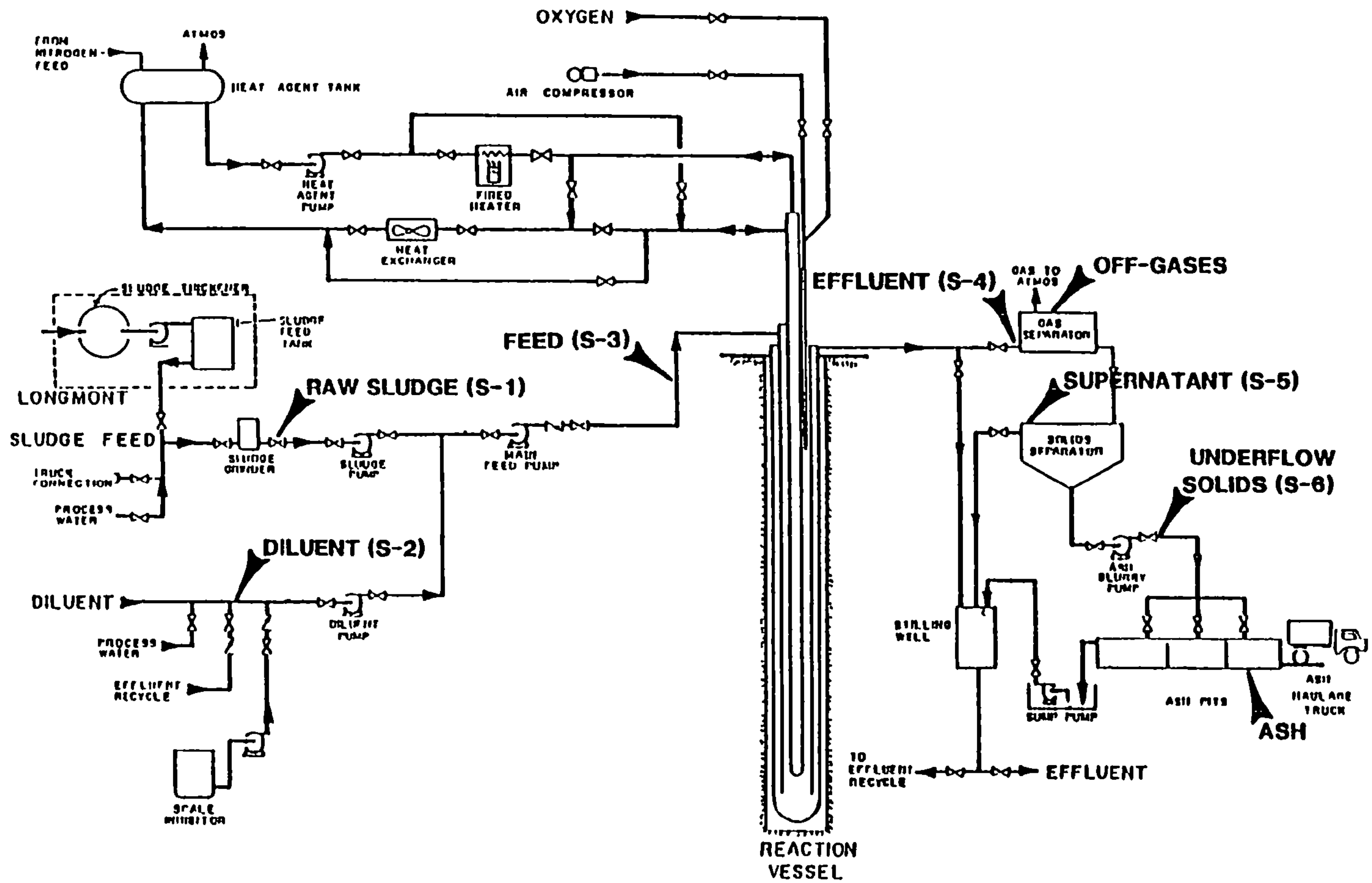


Fig. 1.4-2 Process Flow Diagram

SECTION 2
CONCLUSIONS

1. Major program objectives were met.

2. With the use of air, the system capacity was limited to 5 metric tons per day for the Longmont 10-inch reaction vessel. The use of oxygen increased system capacity to 30 metric tons per day.

3. For bottomhole temperatures of 500°F and above, CODT reductions of 75-80% were achieved and reproducible. Temperature had the largest effect on CODT reduction. By recycling the effluent, the reduction in CODT was increased about 5%.

4. BODT in the VRV effluent stream was readily biodegradable, showing a 140% increase in the efficiency of the trickling filter. As a result, the Longmont WWTP was able to process all the recycled BODT and still meet its NPDES discharge limit, even during periods when additional sludge was hauled in.

5. During autogenous operation TVSS reductions averaged 96.5%, TVS reductions averaged 93.9%, TSS reductions averaged 78.7%, and CODT reductions averaged 76.3%.

6. An Industrial Hygiene Survey indicated that trace components in the off-gas were usually about two orders-of-magnitude below the permissible limit for an 8-hour worker exposure.

7. A metallurgical inspection of the reaction vessel by Material Science Corp. showed insignificant corrosion, consistent with a 20-year life. Materials of construction for the VRV and the surface equipment proved satisfactory.

8. Based on the Longmont demonstration, it was possible to establish operating and maintenance costs for a 10-inch reaction vessel operating at maximum capacity. Operating and maintenance costs for a Longmont-sized unit are below $100 per metric ton with an energy recovery credit of $17 per metric ton.

9. The ash is non-hazardous. Leachates from the EP Toxicity Test were below limits set by EPA, usually be two orders-of-magnitude.

10. Ash in the VRV effluent was easily dewatered. Solid contents of 40-75% were obtained after dewatering by a centrifuge without any optimization of centrifuge operation.

11. The system operated from non-autogenous to extraction of heat. Operation in the autogenous mode was extremely smooth. Wash-out heat was limited to a temperature rise between influent and effluent of 11-17C° (20-30F°) during autogenous operation.

12. High mechanical availability (96.7%) of the system and its components did not limit the test program in any substantial way.

13. CODT reduction for the full-scale system at Longmont was successfully predicted from laboratory batch reactor (LBR) tests.

14. VRV operation was consistent and reproducible at fixed operating parameters.

SECTION 3
RECOMMENDATIONS

The following are recommendations for improving system design, based on the results of the demonstration period:

1. Biological treatment of the reaction vessel effluent should be further investigated to optimize CODT reduction. Benefits of anaerobic polishing should be tested.

2. The VRV effluent return appeared to influence the biological speciation and caused more rapid reduction of BODT. Identification of biological species before, during, and after oxidation system operating periods should be included in future tests.

3. Returning the VRV effluent stream to the headworks of the Longmont WWTP will provide flow equalization and reduce concentration prior to undergoing biological degradation. An option should be provided to allow VRV effluent return either to the headworks or to the trickling filters.

4. The unit installed at Longmont was oversized. A new reaction vessel more closely matching Longmont's sludge generating capacity should be installed and tested.

5. Higher influent heat transfer fluid temperatures were required for start-up due to welding failures which occurred in four sections of the insulated tubular. Coupling design also contributed to greater heat loss than expected. However, the system was still able to reach required bottomhole temperatures. Improved insulated tubular design will eliminate failures in future installations. The performance of the insulated tubular has minimal effect during autogenous operation.

6. Pressure measurement tubing caused organic fouling and suffered mechanical damage during installation and operation. Organic fouling limited the length of operating runs. This fouling is not anticipated to occur in a commercial reaction vessel, since downhole pressure measurements will not be required for VRV operation.

7. Mechanical dewatering of the ash slurry should be installed. Polymer addition should be optimized to reduce dewatering costs.

8. The use of ash as a filler material for brick manufacture was demonstrated and could be implemented at future installations where appropriate.

9. The VRV vessel should be insulated or constructed so as to reduce heat losses to the formation. High boiling temperature oil should not be present in the annular space between the reaction vessel wall and the primary casing string. These improvements will reduce initial heat-up and time to restart after a shutdown, as well as increasing the heat recovery.

SECTION 4
MATERIALS AND METHODS

4.1 LABORATORY ANALYSIS

4.1.1 Sample Storage

Samples of all sludge (S-1), dilution water (S-2), diluted feed (S-3), reaction vessel effluent (S-4), liquid/solid separator supernatant (S-5), and underflow solids (S-6) were immediately stored in closed polyethylene or glass vessels at $4 \pm 2^{\circ}C$. Sample containers were affixed with a pressure sensitive label which contained the following information in indelible ink: sampling date and time, sample point location, type of sampling (composite, split, or intensive), specific tests to be run, name of sampler, preservative added and any other specific information for that particular sample. The samples were transported in a closed, insulated carton from the test site to the J&A Associates, VerTech's testing laboratory, on a daily basis. Immediately upon receipt at the laboratory, samples were logged in, assigned individual sample numbers and again stored at ($4 \pm 2^{\circ}C$). Samples were removed from the storage unit only long enough to withdraw the amount required for testing. All samples were held for a period of 30 days pending completion of analyses.

4.1.2 Comparison of Longmont and J&A Associates Chemical Analyses

When reviewing and comparing the analytical results obtained by the Longmont WWTP Laboratory and the J&A Associates Laboratory for any given day, the method of sample collection was taken into account.

Longmont worked almost exclusively on 24-hour composite samples comprised of two-hour samples. Periodically, Longmont split the composite sample with J&A Associates thereby affording a direct comparison of results obtained for a given sample.

The majority of the samples analyzed by J&A Associates were single-grab intensive samples taken over a specific test run considered to be performed under ideal operating conditions. These samples were taken at short-time intervals, generally 5 or 15 minutes, over a 4-hour run.

CODT and solids were the primary parameters measured by both Longmont and J&A Associates over any given test period. Longmont employed a 2 ml sample for running CODT by the Hach Method. J&A Associates employed a 20 ml sample with a 2-hour reflux time for conducting all their CODT analyses. The USEPA recognizes both methods as being acceptable for CODT determination.

Data evaluation was limited to operating conditions at 260°C (500°F) or higher and VRV flow rates of 22.7 m^3/hr (100 gpm) or greater. These conditions indicated normal reaction vessel operation.

Samples taken during start-up and shutdown were erratic due to the continual change of operating parameters.

4.1.3 Analytical Protocols - J & A Associates

All chemical analyses were conducted in accordance with EPA-600/4-79-020, "Methods for Chemical Analyses of Water and Wastes," U.S. Environmental Protection Agency, 1979 (2). When these guidelines did not apply, "Standard Methods for the Examination of Water and Wastewater," 15th Edition (3) was followed. (Analytical protocols and procedures included the full quality assurance/quality control procedures recommended in the specific protocol.) Table 4.1-1 identifies each chemical parameter analyzed during the course of the program and the specific protocol used to determine it.

When necessary, modifications of existing USEPA or Standard Methods protocols were developed in order to meet specific requirements.

4.1.4 Analytical Protocols - City of Longmont

To insure that the data produced to assess the effectiveness and feasibility of the VRV System were both reliable and representative, the EPA required that a Project Quality Assurance (Q.A.) Plan be developed and submitted for approval. This plan was a joint effort of the Longmont Water Quality Laboratory staff and project engineers and technicians from VerTech Treatment Systems. The Quality Assurance Plan was reviewed and approved by the Project Director, Project Quality Assurance Coordinator, VerTech Project Manager, EPA Project Officer, and EPA Quality Assurance Officer.

The Quality Assurance Plan addressed the following topics: Q.A. objectives, sampling procedures, sample custody, calibration procedures and frequency, analytical procedures, data reduction, validation and reporting, internal quality control checks, performance and system audits, preventive maintenance, specific routing procedures used to assess data precision, accuracy, completeness, and corrective action. The procedures outlined in the plan were followed closely throughout the duration of the project.

All analytical methods used for the analyses were EPA approved. Internal quality control checks included the analysis of spiked, duplicate, standard, and EPA reference samples. Spiked and duplicate samples were run on every tenth sample. A standard was run daily on CODT analysis. EPA reference samples were run weekly.

A 95% confidence interval (C.I.) compiled from at least 20 data points, consisted of the mean $\pm$ 1.96 S.D. Upper and lower control limits were established in this manner and revised monthly. Whenever spike and standard recoveries fell outside these established limits, data were rejected and the analytical method investigated and the problem corrected.

TABLE 4.1-1
J & A ASSOCIATES
CHEMICAL ANALYSES AND PROTOCOLS

ANALYSIS	PROTOCOL
Biochemical Oxygen Demand (BODT)	EPA 504.1 (2)
Chemical Oxygen Demand (CODT)	Std. Methods 508 (3)
Total Solids (TS)	EPA 160.3 (2)
Total Suspended Solids (TSS)	EPA 160.2 (2)
Total Volatile Solids (TVS)	EPA 160.4 (2)
Total Volatile Suspended Solids (TVSS)	EPA 160.4 (2)
Total Kjeldahl Nitrogen (TKN)	EPA 351.3 (2)
Ammonia Nitrogen (AN)	EPA 350.2 (2)
Anions (inorganic)	Ion Chromatography*
Volatile Acids	Ion Chromatography*
Metals	EPA 202.1 - 289.1 (2)
pH	EPA 150.1 (2)
EP Toxicity Test	EPA SW846 - 8.49 through 8.60 (1)
Off-Gases	NIOSH, GC, 5840 hp (4)
Higher Heating Value (HHV)	ANSI/ASTM D2015-66 (5)
C/H/N	Perkin-Elmer 240C Elemental Analyzer*

*J & A Associates Internal Procedures

Precision of the analytical procedure was determined using duplicate analyses, and 95% C.I. was established for the analyses. Again, the 95% C.I. was ± 1.96 (S.D.). An upper control limit for the range percent was established and periodically revised. Whenever the upper control limit was exceeded, data were rejected and the analytical method investigated until the problem was identified and corrected.

Twice during the duration of the project, the Longmont laboratory analyzed a set of performance evaluation samples sent by the EPA's Quality Assurance Branch in Cincinnati.

A variety of analyses were performed to control the operation and assess the performance of the VRV. Additional analyses were run to characterize the effect of the VRV System on the wastewater treatment plant. Table 4.1-2 lists the sampling schedule followed for the program. The analyses run in conjunction with the project included the following: total and soluble CODT and BODT, chlorides, total solids, total suspended solids, total volatile suspended solids, total volatile solids, Total Kjeldahl nitrogen, ammonia nitrogen, dissolved sulfate, total alkalinity, volatile acids, calcium, magnesium, aluminum, chromium, cadmium, copper, iron, lead, manganese, nickel, selenium, silver, and zinc.

CODT was the most closely monitored parameter throughout the project. The Longmont laboratory analyses were performed, throughout the project, using the EPA-approved Hach CODT test system.

Total CODT and BODT analyses were run on the unfiltered sample. Soluble CODT and BODT analyses were performed on filtrate that passed through a Whatman, No. 934-AH glass microfibre filter.

Heavy metals analyses were performed by the atomic absorption spectrophotometer methods. All samples were digested according to the method outlined in the revised edition of the EPA 600/4-79-020, "Methods for Chemical Analysis of Water and Wastes."(2) Soluble metals were determined after filtration of the sample through a Whatman 934-AH glass microfibre filter.

4.2 BACKGROUND LIMITS TO OPERATIONS/TESTING

4.2.1 Heat Supply and Removal System

4.2.1.1 Heat Supply

One early limitation to operation was an inadequate heat supply system to deliver start-up heat to the VRV. A decision was made to surround the lower portion of the VRV with a stagnant high boiling temperature oil. This modification increased the amount of heat leakage to the surrounding earth formation.

Table 4.1-2 VRV System Analytical Testing Schedule

BY LONGMONT WATER AND WASTEWATER LABORATORY

	SAMPLE LOCATION						
PARAMETER	[1] RAW SLUDGE	[2] DILUENT	[3] REACTOR INFLUENT	[4] REACTOR EFFLUENT	[5] SETTLED EFFLUENT	[6] LAMELLA UNDERFLOW	[7] ASH PIT SUPERNATANT
Chlorides	--	--	--	D	--	--	--
COD	D	D	D*	D*	D	2W	2W
COD (Soluble)	W	W	D	D	D	--	--
BOD_5	--	--	--	2W	D	--	2W
BOD_5 (Soluble)	W	W	2W	2W	D	--	--
TS	D	D	D	D	D	--	--
TSS	--	D	D	D	D	2W(G)	--
TVS	D	--	D	D	D	--	--
TVSS	--	--	D	D	D	2W(G)	--
NH_3-N	2W	2W	2W	2W	2W	--	--
TKN-N	2W	2W	2W	2W	2W	--	--
SO_4	2W	2W	1W	1W	2W	--	--
pH	D	D	D	D	D	--	--
Total Alkalinity	--	--	1W	1W	1W	--	--
Bicarbonate Alkalinity	--	--	1W	1W	1W	--	--
Volatile Acids	--	--	1W	1W	1W	--	--
Calcium (Total)	2W	2W	D	D	D	2W(G)	--
Magnesium	2W	2W	D	D	2W	2W(G)	--
Aluminum	--	--	1M	1M	1M	1M(G)	--
Chromium (Total)	--	--	1W	1W	1W	1W(G)	--
Cadmium	--	--	1M	1M	1M	1M(G)	--
Copper	--	--	1W	1W	1W	1W(G)	--
Iron	--	--	1W	1W	1W	1W(G)	--
Lead	--	--	1M	1M	1M	1M(G)	--
Manganese	--	--	1M	1M	1M	1M(G)	--
Nickle	--	--	1M	1M	1M	1M(G)	--
Selenium	--	--	1M	1M	1M	1M(G)	--
Silver	--	--	1M	1M	1M	1M(G)	--
Zinc	--	--	1M	1M	1M	1M(G)	--
Ash Toxicity (EP Test)	--	--	--	--	--	1M(G)	--

NOTE: All Lamella effluent metal analyses are total and soluble.
*Morning and/or afternoon "grab" sample split from composite.

Sampling Frequency:
D - Daily
(X)W - Times per Week
(X)M - Times per month
G - Grab Sample

A second limitation was encountered during the early testing phase, when it was found that the insulation quality of the insulated tubular string had apparently deteriorated.

At start-up, heat transfer fluid flows down the inside of the insulated tubular string and reaches the bottom of the reaction vessel at the maximum temperature with minimal heat loss. This delivers the greatest amount of heat to the bottom of the VRV. The upflowing heat transfer fluid exchanges heat with the aqueous upcomer via radial transfer through the aqueous downcomer.

The deteriorated insulated tubular string caused a partial short circuiting of heat from the inside to the outside of the string. This caused an increase in the heat transfer fluid return temperature with two effects: higher wash-out heat from the water circuit and an overall increased temperature profile (especially at the top of the reaction vessel) which increased heat losses to the surrounding earth formation.

Unexpected heat losses required an increase in the start-up heat supply system. A conventional oil field hot oil truck (truck mounted pump and propane fired heater system) was temporarily brought on site to pump a higher volume of heat transfer fluid through the system and to increase the total heat supplied to the VRV. Additional heat was supplied by a small oil fired heater. These facilities allowed testing of the system at temperatures greater than 260°C (500°F), until permanent modifications were purchased and installed.

A second furnace with an economizer was purchased to increase the overall heat absorption capacity to 2.46 MW (8.4 MM Btu/hr). Two new pumps (one operating and one spare) were added to the system to increase heat transfer fluid flow rates. With the new heat supply equipment installed and operational, the VRV System could be brought to operating temperatures from a cold start in a matter of hours.

4.2.1.2 Insulated Tubular

Figure 4.2-1 presents representative calculated thermal conductivities throughout the operating period. The effective thermal conductivity more than doubled over the course of the project, introducing greater heat losses across the insulated tubular and consequently causing longer start-up periods.

During testing, this problem was overcome with the additional heat supply capacity installed after start-up. Upon removal of the VRV in September 1985, inspection of the insulated tubular revealed that four of the 133 joints had failed. All failures occurred near the top of the reaction vessel, and accounted for the heat losses across the insulated tubular to the aqueous stream upcomer and downcomer.

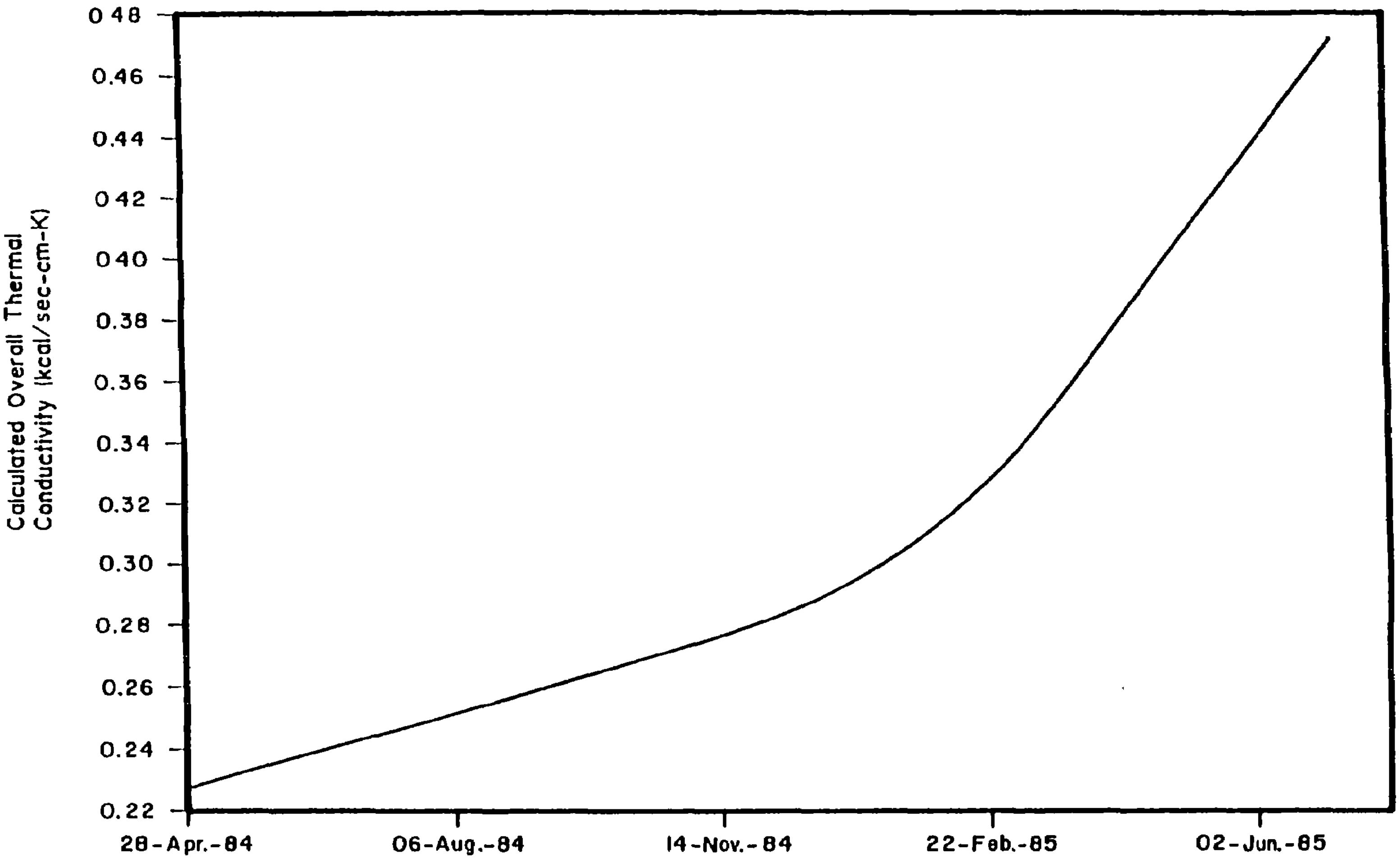


Fig. 4.2-1 Insulated Tubular Performance

Failures occurred at the welds between the inner and outer joints. Excess hardness levels in the heat-affected zone were noted on all defective inner tubulars. In one case insufficient fusion of the casing to the weld ring resulted in joint failure under high thermal stress. These stresses resulted from the large temperature difference between the hot heat transfer fluid (approximately 390°C) in contact with the inside surface of the inner tube and the cold return heat transfer fluid (approximately 80°C) in contact with the outer surface of the outer tube. Further examination of the failed areas showed these failures can be prevented in future designs. Hardness checks and other test procedures will eliminate any problem welds before shipment from the factory.

4.2.1.3 Heat Removal

In early 1985, high capacity tests were run to determine the maximum capacity of the VRV as installed. The heat removal system was originally sized to discharge approximately 0.37 MW (1.25 MM Btu/hr) to the atmosphere with an air fin type cooler. This system took the reversed heat transfer fluid flow from the reaction vessel and cooled it before returning to the expansion tank. A number of high capacity tests were restricted for safety reasons due to the limited size of this heat removal system.

4.2.2 Fouling

Organic plugging occurred on the pressure measurement tubes (P-lines) in the VRD. The P-lines suffered mechanical damage due to an improper welding procedure at the weld connecting the pieces of tubing. Tangled P-lines in each annulus caused multiple partial blockages inside the VRV, causing a high differential pressure across the reaction vessel. The solids fouled on the massed P-lines were periodically removed by various washing techniques. Excessive fouling significantly reduced the operating period between washings, and increased chemical consumption.

The tangled tubing provided multiple locations to catch and retain solids and stringy material in the incoming sludge. Improved material selection, welding inspection and testing techniques can eliminate this problem in future installations. The amount of instrumentation required for a commercial VRV System is substantially less than that provided for tests at the demonstration plant at Longmont. Future commercial plants can be operated without downhole pressure or temperature measurements on the process side if necessary.

4.2.3 Other Capacity Testing Limitations

The original VRV System design capacity was sized for approximately 5.4 metric tons per day (6 tons/day) of CODT using air as the source of oxygen. This design capacity closely matched the sludge production rate of the Longmont WWTP. Subsequent testing with oxygen-enriched air demonstrated that the VRV was capable of processing greater quantities of sludge than the City of Longmont could produce.

Therefore, in an attempt to establish the maximum capacity of the reaction vessel, sludge was imported by trailer truck from the nearby cities of Ft. Collins and Lafayette. This imported sludge was mixed with the City of Longmont sludge in a temporarily unused digester at the Longmont WWTP. With the additional supply of concentrated sludge, extended runs at high capacity were performed on various mixtures of the sludges.

When the oxygen-enriched air tests were designed, the system size set for the oxygen supply system was approximately 21.8 metric tons per day using 99.5% pure oxygen. As can be seen in Figure 4.2-2, the oxygen supply system consisted of a liquid oxygen tank, a cryogenic pump, atmospheric vaporizers, and flow controls. This equipment was leased from a commercial liquid oxygen supplier, and allowed operation over a wide range of oxygen feed rates.

4.2.4 Improvements to Increase System Capacity and Reliabilities

Certain improvements were installed to remedy plant limitations and to allow testing of the ultimate capacity of the VRV. Provision of automatic operating control equipment increased system reliability. Oxygen addition allowed an increase in reaction vessel capacity. Additional sludge pumping capacity was required to provide sufficient feed for the VRV. The plant normally operated with a single sludge feed pump with a 100% installed spare available. Modifications to the pump drive systems allowed their individual capacities to be increased by approximately a factor of 2. Modifications to the electrical switch gear allowed simultaneous operation of both pumps to increase the available feed capacity by approximately a factor of 4.

4.2.5 Improvements and Modifications to Mechanical Equipment

In order to accommodate construction and operation of the VRV System, several modifications were required at the Longmont WWTP. Increased natural gas service to the WWTP was sufficient to supply the VRV System, however, an additional electric meter was needed to monitor demand and power usage by the wet-oxidation test facility. A pump was installed in the chlorine contact tank influent well to provide dilution water for the influent sludge. Potable water mains were extended to provide service water, fire protection, and a back-up water supply for sludge dilution. Sludge piping was extended from the WWTP sludge drying beds to a new mechanically mixed storage tank adjacent to the test site. Effluent return flow piping was installed from the Lamella separator overflow to the influent well of the WWTP trickling filter feed pumps.

Originally, VRV effluent pressure was controlled by a pressure control valve directly in the three-phase effluent stream. This presented mechanical difficulties due to erosion on the downstream side of the letdown valve. A conventional gas/liquid separator was added in the effluent line which provided liquid hold-up to reduce fluctuations in flow to downstream solids separation equipment and to eliminate erosion. The

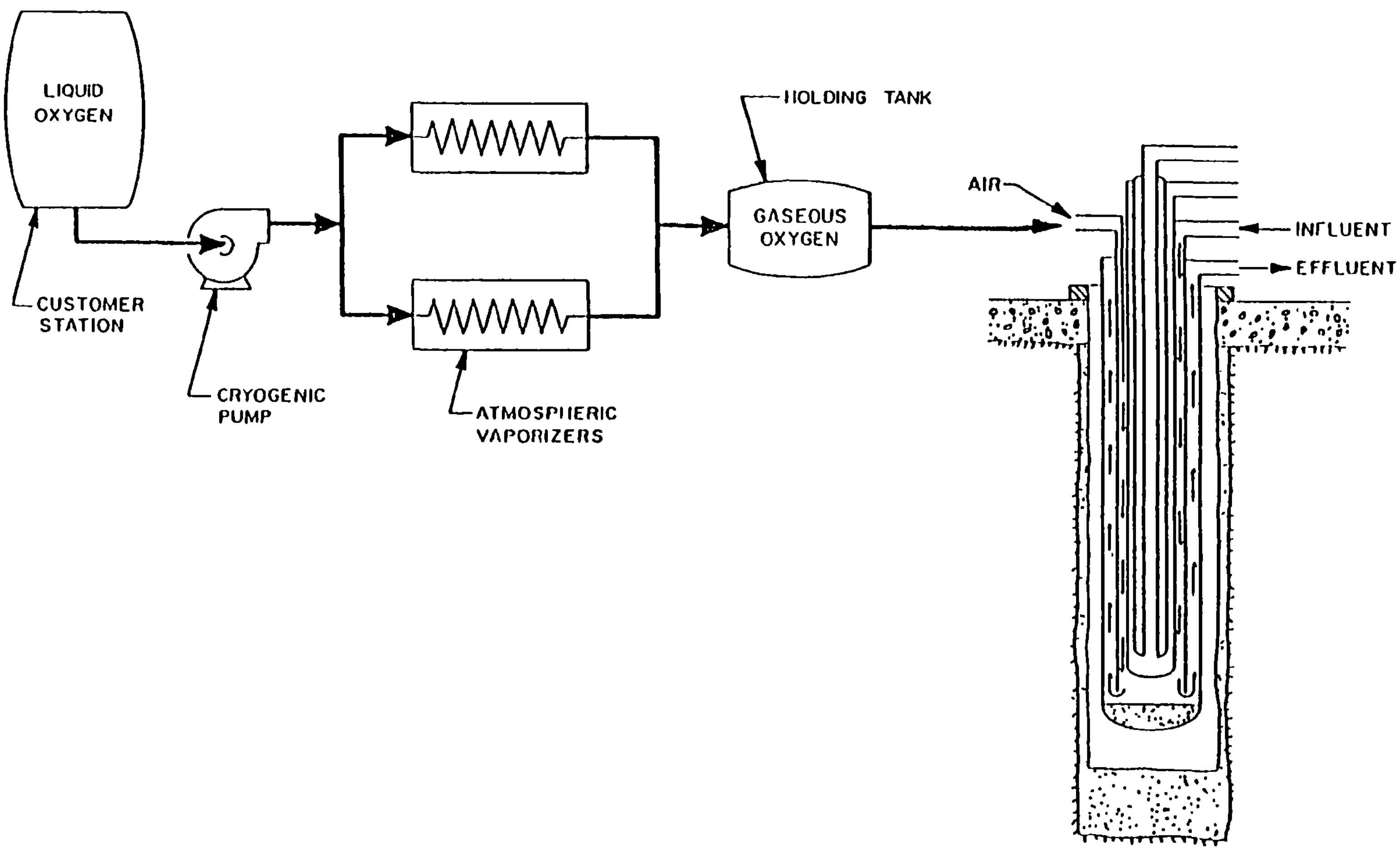


Fig. 4.2-2 Oxygen-Enriched Air Flow Diagram

addition of this equipment permitted stable operating conditions even during transient test conditions.

4.2.6 Back-up System for Sludge Treatment

A belt filter press and facilities for lime stabilization of raw sewage sludge were also installed as a back-up system for sludge treatment in the event that the aqueous-phase process was out-of-service for maintenance or modifications at a time when the anaerobic digesters were unable to accommodate the daily WWTP sludge production. All WWTP modifications were funded by the EPA grant, except for the belt filter press and lime stabilization equipment which was installed at the City's expense.

4.3 PROCESS MONITORING

4.3.1 Data Acquisition

All wastewater treatment unit processes were monitored at the Longmont WWTP during 1984 and 1985 to determine the effects of return flow from the VRV System on the Longmont WWTP. Composite samples were collected daily from the influent of each unit process and analyzed by the Longmont Water Quality Laboratory for TSS and BODT. A computerized data base was created from the WWTP and VRV System operating data to track performance of the Longmont WWTP during the various system operating campaigns.

4.3.1.1 Operating Data

The VRV System operating data were acquired using conventional instrumentation combined with both manual and computer data acquisition and storage. Manual data collection was utilized for acquisition of data for non-critical process operations and non-critical equipment. The computer data acquisition system instrumentation was hard-wired to a central computer facility. The data were recorded on a regular schedule, and available to the operator on request.

4.3.1.2 Demonstration Plant Data Logger

Process information, such as flow rates, temperatures, and pressures, was acquired by instrumentation at identified points. An ICIS 850 data acquisition system with CRT's, keyboards, printer and standby power was used to log data from hard wired instrumentation. These data were stored as 15-minute averages. Regular storage of data occurred for pressures, temperatures, flows, analysis signals and status indications. Regular data were acquired by the computer and averaged at one-second intervals. One-minute averages of these signals were output to CRT's and printers for the operators. The data logger then stored on disk 15-minute averages of the one-minute averages for each data point. Upon special request by the operator, or upon activation of a special trigger due to an alarm data point, the computer would store on disk the one-minute readings for a more detailed future analysis of a transient condition which had occurred in the process operation. The system proved valuable in evaluating the effect that an unexpected event, such as a power failure, had on the process operation. Some instrumentation was added for the high rate tests conducted early in 1985.

4.3.1.3 Manual Data Acquisition

Operating information that was either non-critical in nature or otherwise did not justify hard wiring to the computer was acquired on a manual basis by the process operator. This included such information as water consumption, air compressor operator data, oxygen supply system, and acid wash operation.

4.3.1.4 Spot Data

Spot data were also acquired for unexpected events and for special tests. Process operator observations were helpful in determining the effects of special operating conditions that were tested. This included such tests as the use of polyelectrolyte addition to improve settling in the liquid/solid separator and ash pits, centrifuge tests for ash dewatering and small-scale biological polishing tests of the VRV System effluent.

4.3.2 Sample Acquisition

Samples were collected by both the City of Longmont's laboratory and VerTech personnel. The City of Longmont conducted all the sampling for their WWTP process, special WWTP studies, and the composites of certain VRV streams at defined sampling points. VRV sample streams are shown in Figure 1.4-2. These stream points included the sludge pumped from the Longmont WWTP (S-1), final clarifier effluent used as diluent (S-2), VRV influent (S-3), VRV effluent (S-4), the liquid/solid separator clarified effluent (S-5), and the liquid/solid separator concentrated ash (S-6).

4.3.2.1 VRV Unit Composites/Splits

VRV influent (S-3) and effluent (S-4) samples were collected by the City of Longmont every two hours from 7 A.M. to 7 P.M. daily. Fixed volumes of liquids were added to the liquor taken at the previous sample times, and the mixed composite was refrigerated. Composite samples collected were split daily with half the samples sent to J&A Associates, Inc., VerTech's testing laboratory, and the remaining sample sent to the City of Longmont's laboratory for analyses. Total CODT, pH and metals measurements were then made by both laboratories.

4.3.2.2 Intensive Sampling

Periodic intensive sampling was conducted by VerTech to obtain a data base for statistically determining the CODT reduction through the unit for a given set of operating conditions. Samples were taken of the feed (S-3) and the effluent (S-4) at 15-minute intervals. A delay period equal to the hold-up time in the VRV for any given flow rate separated the start and finish of sampling for the feed and the effluent. The delayed sampling period gave VerTech matched sets of feed and effluent samples, and took into account the reaction vessel hold-up time. An intensive sampling period consisted of a minimum of 6 to 10 matched sets of influent and effluent samples. The individual samples were routinely analyzed for CODT. Composites of each matched set were analyzed for TS, TSS, TVS, TVSS, TKN, NH_3-N, BOD_5, metals, inorganic anions, organic acids and pH.

An intensive sampling period included a grab sample of the sludge being used for the feed (S-1) taken during the sampling period. This sample was analyzed for CODT, TS, TVS, carbon, hydrogen, nitrogen and higher heating value (HHV).

Samples taken during acid washes also allowed VerTech to determine the amount and components of the scale material.

4.3.2.3 Spot (Grab Sample)

VerTech operators took spot samples whenever they encountered an operating condition that they felt should be recorded in the data base. These samples were refrigerated at 4±2°C and transported to J&A Associates laboratories the morning of the following day.

4.3.2.4 Off-Gases

During the last eight months of the demonstration period, VRV unit off-gases were continually monitored by an on-line gas chromatograph (GC). The samples were taken from the pressurized line feeding the gas/liquid separator. The gas chromatograph was set on a 15-minute analysis cycle. The cycle was set to coincide with the process data being collected by the data acquisition system. This allowed VerTech to have a match up of off-gas analyses with downhole operating conditions. The off-gases were analyzed for oxygen, nitrogen, carbon dioxide, carbon monoxide, methane, and hydrogen.

Gas samples were occasionally collected at various points in the system for analyses. These samples were collected either in a pressurized stainless steel bomb attached directly to the pressurized line leading to the gas/liquid separator or by a gas bag or charcoal tube from a sample pump which took the gaseous discharge from the gas/liquid separator. These samples were analyzed by Gas Chromatography (GC), Gas Chromatography/Mass Spectrometry (GCMS), or High Performance Liquid Chromatography (HPLC).

Chemicals that were best analyzed by high pressure liquid chromatography were collected in a midget bubbler containing Girard-T reagent.

4.3.2.5 Ash Pits

The ash pits were not sampled on a fixed schedule. Samples were generally taken from the four corners and center of the pit then composited prior to analysis. A USEPA Extraction Procedure (EP) Toxicity metals analysis (1) was performed on each composite.

4.3.3 Instrumentation

Conventional process instrumentation was used to measure the operating parameters of the process streams.

4.3.3.1 P-lines

The operating conditions inside the VRV did not allow internal use of conventional instrumentation to measure pressures at various points. Therefore, conventional pressure measuring equipment was placed at the surface to measure the pressure required to bubble a small amount of air through a line to various depths within the reaction vessel. A small supply of air, available at approximately 3,500 psig, was bubbled through a flow controlling device at which point the pressure was measured. The computer corrected the surface pressure readings to values corresponding to the pressures at the depth inside the reaction vessel by calculating the effect of the weight and density of the air inside the respective P-line.

4.3.3.2 Temperature Readings

Thermocouples located inside protective thermowells were used to measure temperatures at various points in the process. Temperature readings were available to the operator from a panel-mounted temperature indicator display system and were also sent directly to the data acquisition system. The operator also had available the display of various temperature readings on his CRT. The operator generally selected 2, 3, or 4 critical temperature parameters, especially downhole temperature, to be displayed on a minute-by-minute basis for his observation.

4.3.3.3 CODT Versus Mass Flow

There was no equipment available to measure the CODT of influent or effluent streams on a current or continuous basis. Therefore, process control was affected by measuring the mass flow of the solids entering the VRV System. An initial assumption was made of the CODT to total solids ratio. This provided adequate control for start-up and was later corrected for effluent oxygen concentration as mentioned below.

4.3.3.4 Other Flow Measurements

Air flow, heat transfer fluid flow, and oxygen flow were all measured utilizing mass flow meters with good success. The use of mass flow meters eliminated the problems associated with conventional orifice readings where variations in density of the fluid causes errors in the flow measurement. Heat balances and mass balances were simplified because the use of mass flow readings eliminated pressure and temperature variation errors in measurements of the reactants.

4.3.3.5 pH

The pH of influent and effluent streams and of streams during acid washes was measured using hand-held pH meters and in-line instrumentation. Hand-held pH meters were utilized during special tests and acid washes to observe and control the pH during these operations.

4.3.3.6 Dissolved Oxygen

Dissolved oxygen readings were initially used to determine the concentration of oxygen remaining in the effluent after passage through the VRV System. This measurement was eventually replaced by direct observation of the oxygen in the effluent off-gas.

4.3.3.7 Effluent Off-Gas Component Concentration Measurement

To monitor the performance of the VRV System, a gas chromatograph was installed to check the concentrations of various components in the effluent off-gas. This gas chromatograph system continuously sampled the effluent off-gas and analyzed it for the concentration of oxygen, nitrogen, carbon dioxide, carbon monoxide, and other components. After every 15-minute analysis cycle, the oxygen concentration was available to the operator in the control room for his observation and correction of oxygen flow rates or sludge feed rate. This allowed more precise process control to compensate for the variations in sludge CODT loading for a constant mass flow rate of solids, particularly during the period when sludge was hauled in from neighboring communities and sludge quality was questionable.

4.4 OXYGEN AND CHEMICALS

4.4.1 Oxygen

The VRV System originally operated with compressed air as the oxygen source. In the second half of 1984, an oxygen supply system was commissioned at the site to allow testing with varying percentages of oxygen for sludge destruction. The oxygen supply system operated with few mechanical difficulties. Liquid oxygen pump suction supply problems were eliminated with pressure and timing modifications to the controls. Heat tracing of the oxygen line eliminated freeze problems. The pump plunger packing failed once of an unknown cause. It was repaired and put back into service without further problems.

4.4.2 Polyelectrolytes

Polyelectrolytes were added to the effluent stream to facilitate solids separation and decrease solids in the liquid effluent return to the Longmont WWTP. Various tests were run with polymer injection to the liquid/solid stream flowing to the Lamella separator, and also to the Lamella underflow going to the ash pits.

SECTION 5
OPERATING PROGRAM

5.1 OVERALL PROJECT OBJECTIVES

Program definition and analysis were based on a number of primary program objectives. Documentation of the technical viability of the VRV System was the overall objective, which included performance characteristics of the subsurface reaction vessel, reduction of Chemical Oxygen Demand (COD), and overall interaction and impact on the City of Longmont WWTP. Specific technical objectives included:

1. Reduce sludge volume
2. Achieve maximum reduction of TSS, TVS, TVSS and CODT
3. Demonstrate the use of air, oxygen-enriched air, and oxygen-enriched air up to 100% as oxidant sources
4. Achieve maximum downhole temperatures
5. Operate autogenously
6. Operate to recover energy
7. Validate hydrodynamic models for two-phase flow in the downcomer and upcomer
8. Demonstrate environmental acceptability of by-products
9 Demonstrate ease of operations

The operating program conducted at Longmont was substantially modified from the original program specified under the EPA Cooperative Agreement. The operating program was modified to permit testing with oxygen-enriched air and subsequently with 100% pure oxygen. Successful results led to testing the system at sufficiently high sludge rates to operate the system autogenously and finally, in a mode to recover energy from the system.

5.2 CHRONOLOGY OF OPERATING PROGRAM AND RESULTS

Operation under the EPA Cooperative Agreement was initiated on July 1, 1984, and completed in September 1985. Major operating campaigns from April 1984 through November 1985 are shown in Figure 5.2-1. A chronogram illustrating the development and demonstration of the VRV System is shown in Figure 5.2-2.

Aqueous-phase oxidation technology had been under development for more than ten years. Preliminary testing of the fundamental principles of vertical tube aqueous-phase oxidation began with construction of a Laboratory Batch Reactor (LBR) in 1973. After initial tests proved encouraging, a 460-meter (1500-foot) pilot plant reaction vessel was constructed at the Lowry Bombing Range in Denver and operated from 1977 to 1981. In 1982, the United States Environmental Protection Agency (EPA) issued a technology assessment of the VRV System, under the name Vertical Well Chemical Reactor.

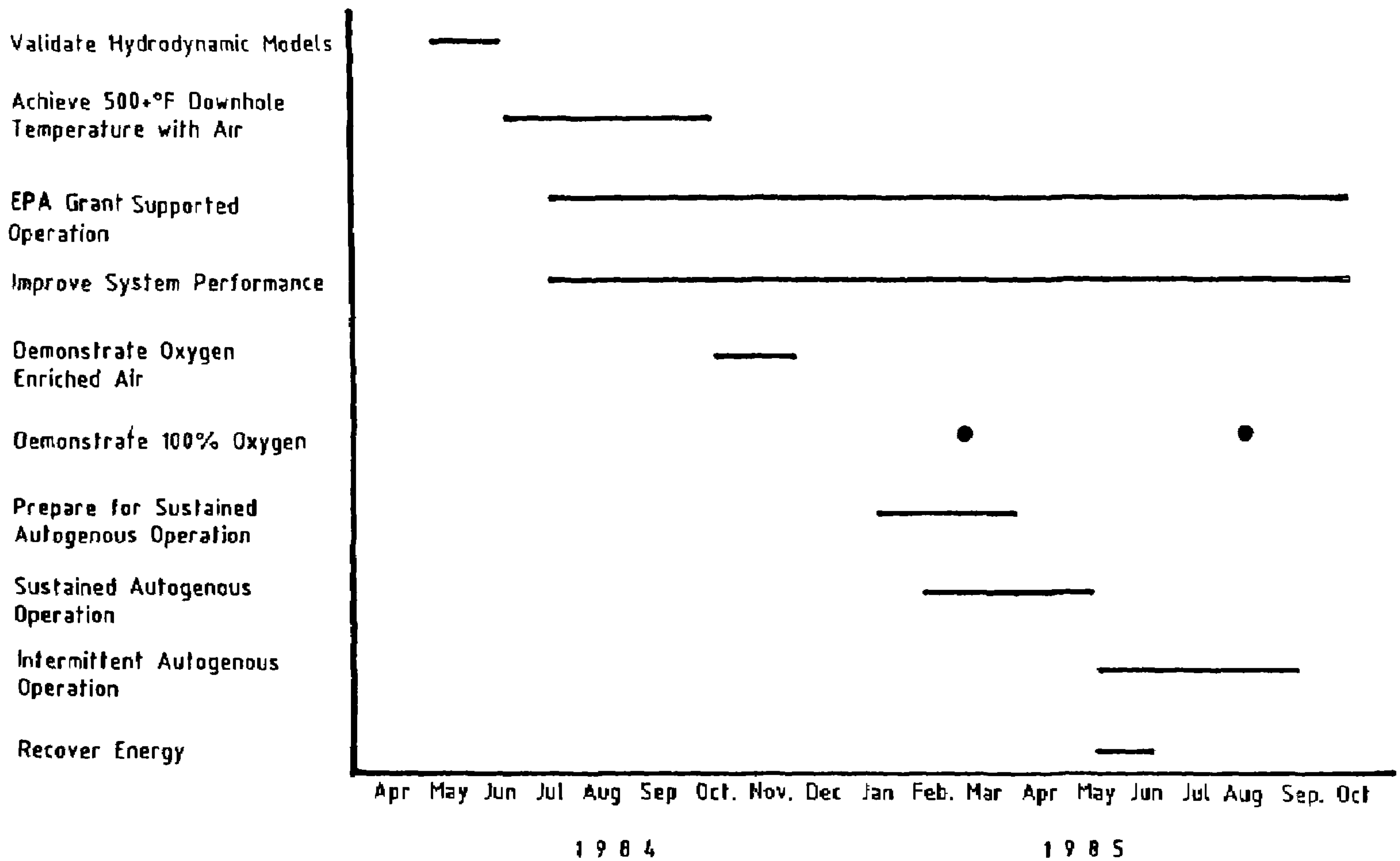


Fig. 5-2.1 Chronology of Major Operating Campaigns

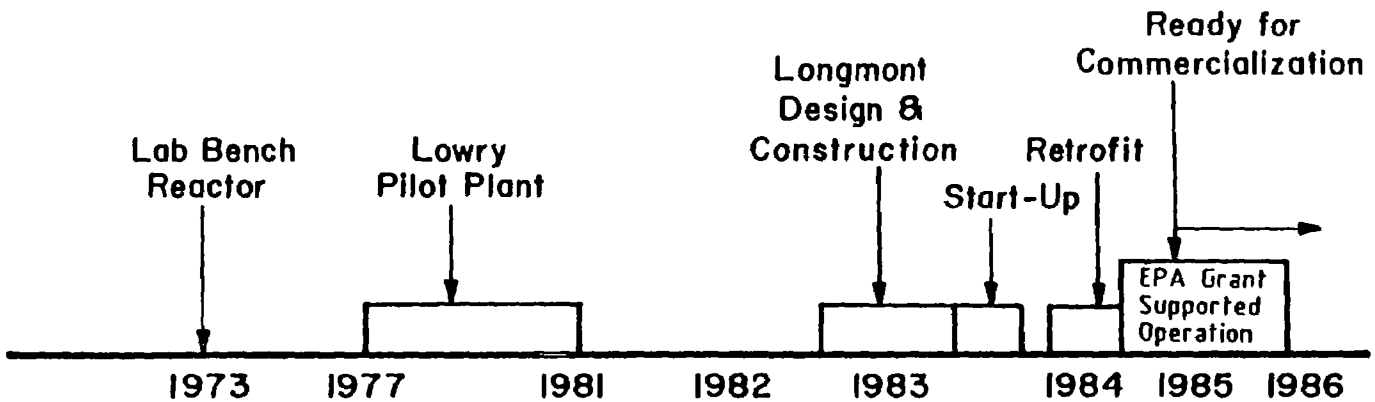


Fig. 5.2-2 VRV Chronogram

Construction of the system at Longmont began in October 1982, and the original start-up period began in June 1983. Prior to reaching design downhole temperature and CODT reduction, the unit was shutdown in August 1983 to make necessary modifications. At this time Bow Valley Resource Services Ltd. (BVRS) exercised its option to purchase rights to the patented waste destruction technology. BVRS is a diversified international company engaged in natural resource development and energy services. Private capital from BVRS was used for construction of the prototype facility. From September to November 1983, a detailed engineering review of the design criteria and operating results of the VRV and above-ground systems was conducted. The study led to an improved and simplified system design in the areas of installation, structural integrity, instrumentation, process control and data acquisition, reduced frictional pressure drop, heat transfer, and scale control. From November 1983 to March 1984, fabrication of below-ground components occurred with delivery beginning in February of 1984. Modifications to topside equipment began in February 1984, and were completed in May 1984. Installation of downhole piping and instrumentation began in April 1984 and was completed in May 1984.

In October 1984, VerTech installed a liquid oxygen supply system which greatly increased the sludge treatment capacity of the process. The VRV System was then able to treat more sludge than Longmont's WWTP produced. VerTech upgraded the plant during the winter of 1984-85 to process up to 27 metric tons per day (30 tons per day) of sludge. The first autogenous test runs were made during February 1985 in preparation for the sustained autogenous test period. During March and April, additional raw and digested sludge was hauled in and the process was tested exclusively at high capacity under autogenous operating conditions.

Plans were made to haul the VRV effluent in the event that the Longmont WWTP could not treat higher recycle biological load. This proved unnecessary since the WWTP efficiency was improved during operation of the VRV System.

After the steady state run was completed, the VRV system operated intermittently to process all the sludge. From May to August 1985, the VRV system was tested to determine the effect of start-ups and shutdowns on the Longmont WWTP. In September 1985, the reaction vessel internal strings of pipe were pulled for inspection. Insignificant corrosion was observed, making it possible to reinstall the unit.

5.2.1 Validate Hydrodynamic Model

The initial objective of validating the hydrodynamic model began in May 1984. At a given temperature, the flow rate of water was held at a predetermined constant rate, and the gas flow rate was varied. A comparison of Longmont VRV data and predictions of the hydrodynamic model are provided in Section 5.3.

5.2.2 Achieve Downhole Temperatures

The objective to achieve greater than 260°C (500+°F) bottomhole temperature required several system modifications which were described in detail in Section 4. These modifications were completed from July to December of 1984.

5.2.3 Demonstrate with Oxygen-Enriched Air

The primary reason for the shift from use of air to use of oxygen enrichment was the capacity limitations encountered when using air. An oxygen customer station was designed, engineered and installed from August to October 1984. A schematic of the oxygen customer station is shown in Figure 4.2-2, page 21.

The first tests with oxygen enrichment were carried out in October 1984. Since the air compressor was oil lubricated, a potential hazard existed with the injection of oxygen into the air stream. Oxygen was introduced into the diluted sludge directly, rather than combining with air upstream of the VRV. Immediate performance improvements were noticed when shifting to oxygen enrichment. More sludge was processed, a higher bottomhole temperature was attained and was easier to maintain, influent and back pressure on the reaction vessel were reduced, and higher CODT reductions were achieved. Tests were conducted at 40% oxygen, 50% oxygen, 80% oxygen and then 100% oxygen.

5.2.4 Autogenous Operation and Energy Recovery

The objectives for the sustained autogenous operation of the unit are shown in Table 5.2-1.

TABLE 5.2-1
OBJECTIVES FOR SUSTAINED AUTOGENOUS OPERATION

1. Determine the Lowest Possible Operating Rate of the VRV with Sludge from the City of Longmont.

2. Determine the Maximum Possible Operating Rate of the VRV System.

3. Study CODT Reduction as a Function of:
   + Bottomhole Temperature;
   + Residence Time; and
   + Influent Concentration.

4. Determine the Effect of Effluent Recycle on CODT Reduction and the Reaction Vessel Temperature Profile.

5. Determine the Effect of the Topside Heat Recovery on VRV Performance and Energy Balance.

6. Determine the Effect of High VRV System Operating Rates on Longmont's Waste Treatment Plant.

Several systems required modification to process sludge at rates of 18,000 kg/day (20 tons/day), since the original system design was for 5,400 kg/day (6 tons/day). A milestone schedule for autogenous operation was prepared, as part of the overall test plan, and is shown in Figure 5.2-3.

A series of short duration (20-48 hours) autogenous tests were carried out in February and March 1985. Sludge processing rates as high as 18,000 kg/day (20 tons/day), bottomhole temperature up to 270°C (520°F) with CODT reductions up to 88.5% were obtained. These results are discussed in Section 6.

Sustained autogenous tests were carried out in March and April 1985. Sludge was trucked in from nearby communities of Ft. Collins and Lafayette. During the autogenous test period, the system processed waste activated sludge and digested sludge, raw sludge and sludge from long-term storage in a lagoon.

As the capacity of the system was raised above 10,000 kg/day (11 tons/day), sufficient heat was generated from the exothermic oxidation reactions to shut off the external heat transfer fluid heater. As the bottomhole temperature continued to increase, the heat transfer fluid flow was reversed, and heat was brought to the surface and rejected to the atmosphere through an external air cooler. The capacity of the system was tested at rates of 23,000-27,000 kg/day (25-30 tons/day). Operation could not be sustained at these levels due to limited sludge supply, under capacity of the heat transfer fluid cooling system and oxygen supply system.

5.2.5 Environmentally-Acceptable By-Products

During the Longmont test program Chemical Oxygen Demand (COD) reductions were between 75% and 88.5% with an 80% average reduction. The remaining CODT, returned to Longmont's trickling filter, consisted of an environmentally-acceptable and readily biodegradable weak acetic acid stream which also contained other low molecular weight organic acids, such as formic and glycolic acid. An ash slurry consisting of oxidized inert solids was pumped into drying beds producing an odorless and sterile material which was removed periodically. Centrifuge dewatering tests showed the ash was readily dewatered to 50 wt.% solids (see Table 6.11-3).

Ash was determined to be a suitable filler for brick manufacturing. A more detailed report of the study is found in Appendix B.

Carbon dioxide comprised the majority of off-gas released from the air separation system with small amounts of carbon monoxide and oxygen present. Other organic components were present only in trace amounts at concentrations well below levels required for health and environmental consideration.

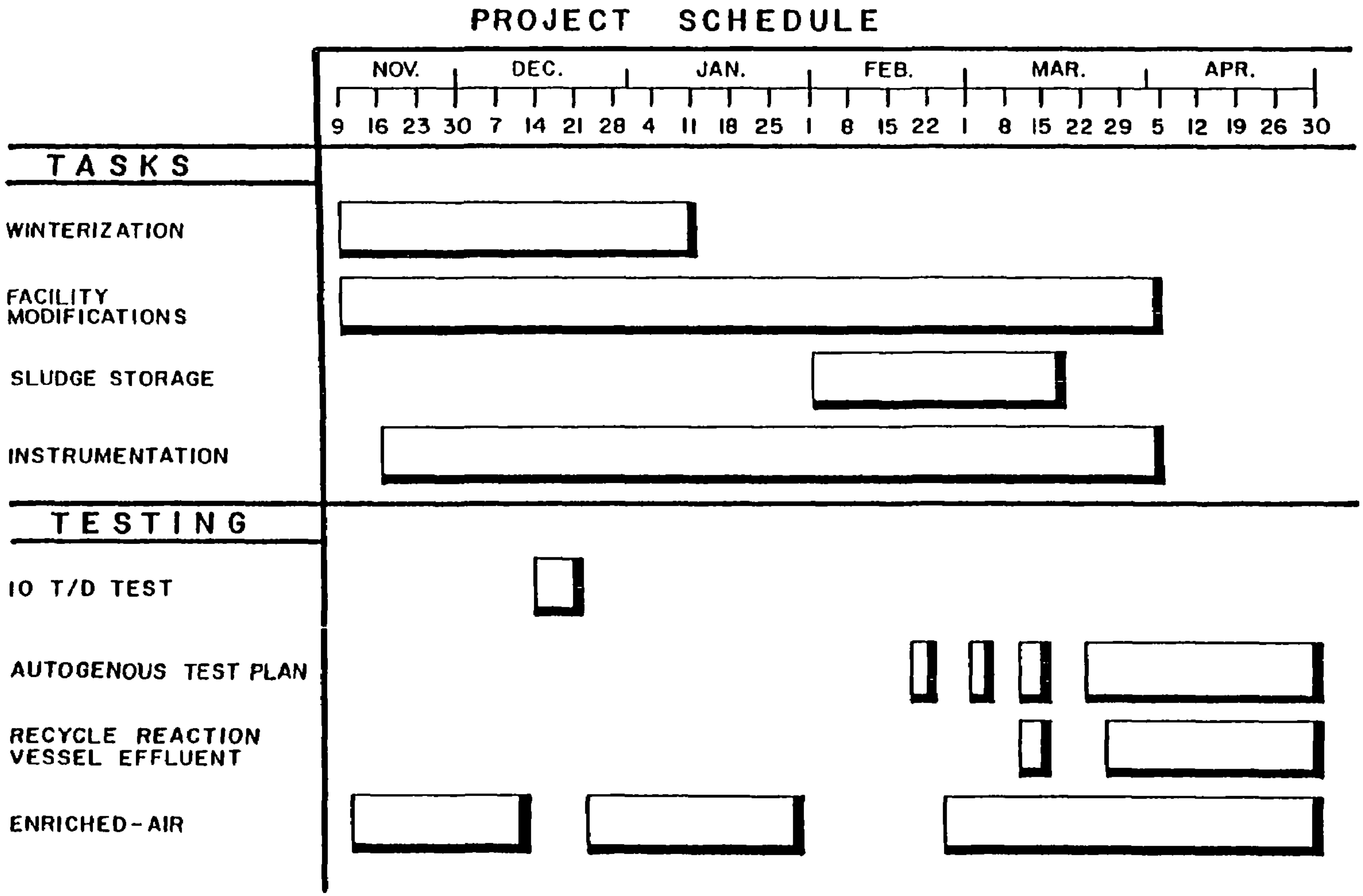


Fig. 5.2-3 Demonstration of Autogenous Capability

Most organically-bound nitrogen in the sludge feed exited the VRV process as soluble ammonia-nitrogen. Longmont had no NPDES ammonia discharge limitation at the time of testing although a limit may be implemented in the future. Trends toward ammonia discharge suggest the need for ammonia polishing. Ammonia stripping is a viable system design which could recover a 20% ammonia solution to be used as fertilizer.

5.2.6 Demonstrate Ease Of Operation

Many system changes were made to automate, simplify, and improve overall control. Improvements to the heat transfer fluid system, modifications to mechanical equipment, improvements of data collection, and improvements to system capacity and reliability were described in Section 4. These changes included mass air flow measurement to smooth out fluctuations in air supply and to simplify use of ratio control of air to total solids in the sludge feed. A gas chromatograph was installed to control oxygen feed rate. Installation of a data monitoring and collection system to provide the operator with one-minute averages for many of the temperatures, pressures, and flow rates was used to control the system. Installation of tanks and metering pumps simplified periodic acid washing of the reaction vessel.

5.3 PROCESS MODELING

5.3.1 Hydrodynamic Model

The hydrodynamic model is used to predict pressure profiles in the VRV. Given a temperature profile in the VRV and influent flow rates for liquid and vapor, the pressures can be calculated from two-phase flow relationships. The model is also used to assist in sizing of reaction vessels. The size of the tubing used for the downcomer and upcomer sections will determine the pressure drop and the vapor fraction throughout the vessel. Correct selection of tube sizes will give the required flow rates to get adequate mass transfer between the liquid and the oxygen in the gas phase.

The hydrodynamic model was used to help size the Longmont reaction vessel and to determine the required pressures topside. As discussed in section 5.2.1, verifying the hydrodynamic model flow calculations an initial major objective. Figure 5.3-1 demonstrates the accuracy of the hydrodynamic model simulations during the Longmont start-up tests, when no heat was supplied, only air and water flowed through the system. This model was often used to verify plant conditions and to predict response of the system before a process change was made.

5.3.2 Heat Exchange Model

The heat exchange model predicts the temperature profile in the VRV, given a pressure profile and flow conditions. It accurately calculates temperatures throughout the VRV and surrounding rock, as well as the energy balance, at any given reaction vessel conditions.

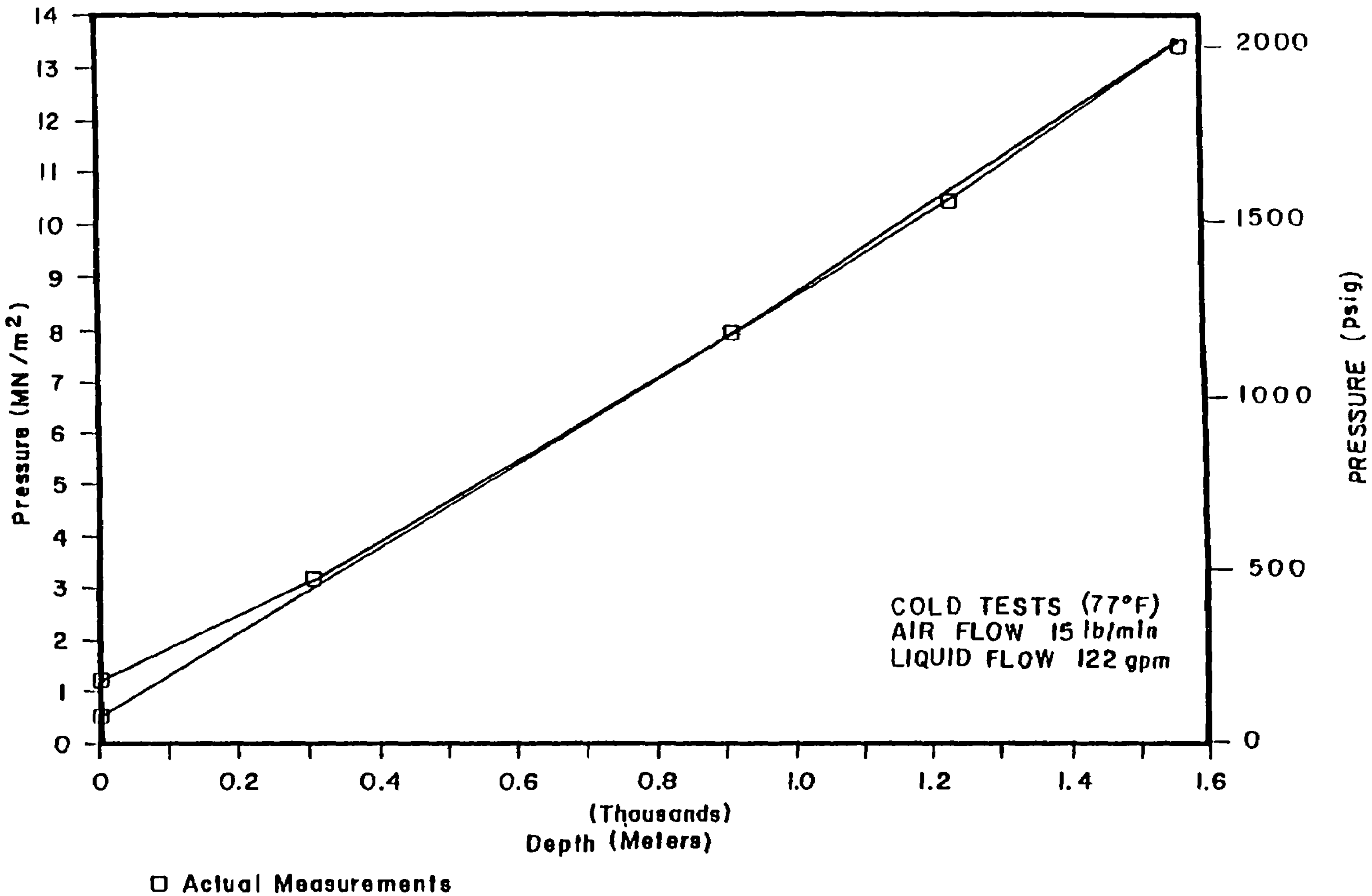


Fig. 5.3-1 Pressure Profile

5.3.3 Laboratory Batch Reactor

Since the hydrodynamic and heat transfer models can accurately simulate the actual reaction vessel conditions of temperature and pressure at different depths, they are used to create time, temperature, and pressure profiles to be used in the laboratory batch reactor (LBR).

The laboratory batch reactor duplicates the conditions of an element of fluid in the VRV. An element of fluid enters the reaction vessel at ambient temperature. In the downcomer, the fluid temperature and pressure increase with increasing depth in the VRV, as heat is exchanged from the upcomer and is produced from the combustion reaction. At the bottom of the VRV, the element of fluid is at the maximum temperature and pressure. In the upcomer, the fluid temperature and pressure decrease with decreasing depth in the reaction vessel, releasing heat to the downcomer and to the surroundings. At the surface, the fluid is only 16 C° higher than inlet temperature.

The hydrodynamic and heat transfer models produce the time, temperature, and pressure profile necessary for the LBR to properly duplicate the flow of an element of fluid under various operating conditions. Placing a mixture in the LBR with sufficient oxygen, the batch reactor is then heated to bottomhole conditions following the prescribed time and temperature profile, and is then cooled to outlet temperature. By following a time, temperature, and pressure profile calculated from the models, and by supplying adequate mixing, the LBR simulates the flow of an element of fluid through the VRV.

An example of a time and temperature profile used for a correlation run during a non-autogenous test is shown in Figure 5.3-2. The steep climb matches the observed non-autogenous temperature profile where the temperatures are higher in the top of the VRV.

A plot illustrating the accuracy of the LBR predictions is shown in Figure 5.3-3. Each square on the plot represents an LBR run made to match conditions in the VRV. Each LBR run matches a different time, temperature, and pressure profile predicted from the models. If the LBR simulated conditions in the reaction vessel exactly, all of the points would line up at corresponding CODT reductions. The line on Figure 5.3-3 is a best fit curve to the data points shown. The straight line fit indicates that the predicted CODT reductions from the LBR are lower than those obtained in the VRV at Longmont. This allows VerTech to test any sample in the LBR and be confident that the predicted reduction will be at least as good as that obtained in a full-scale VRV.

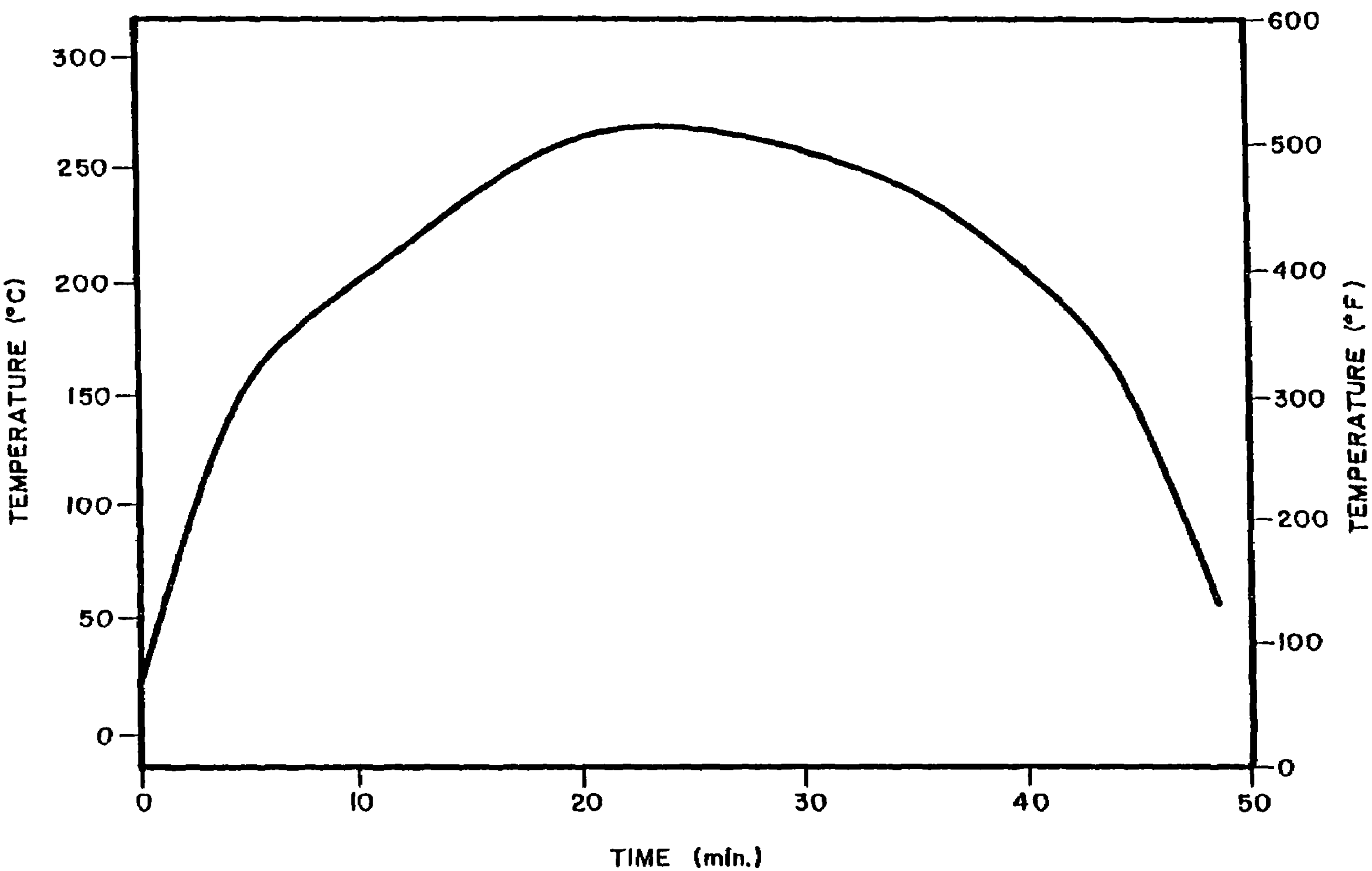


Fig. 5.3-2 Time and Temperature Profile

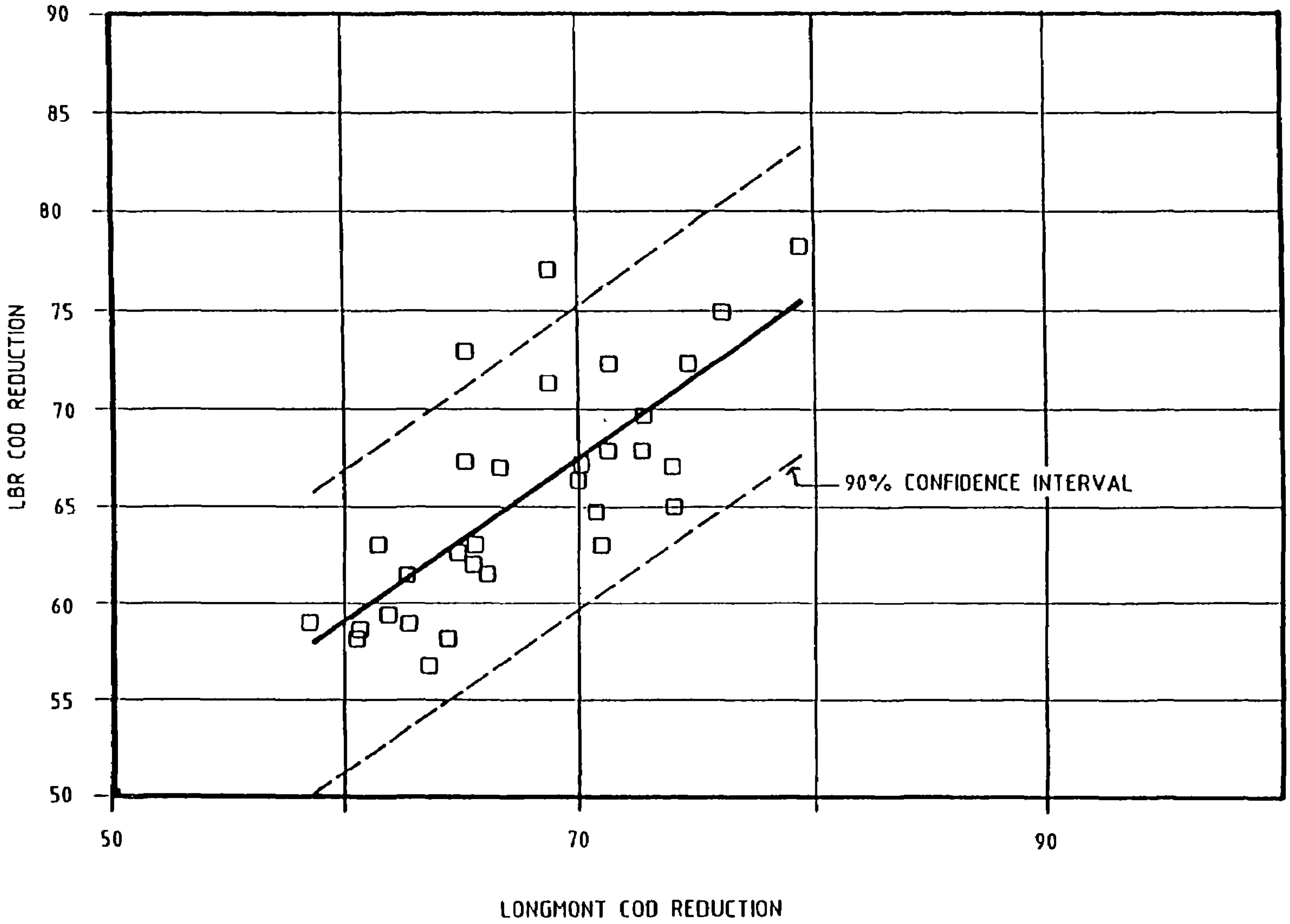


Fig. 5.3-3 LBR versus CODT Reduction

SECTION 6
RESULTS AND DISCUSSION

6.1 SYSTEM CAPACITY

6.1.1 Operating Range at Longmont

The operating program at Longmont covered the time period from June 1984 to September 1985. Table 6.1-1 summarizes the operating period, showing the number of days operated and the amount of sludge processed for each month of operation. VRV System operation was intermittent from May 1985 to September 1985. This allowed Longmont to store sludge to permit autogenous operation. During this time period, the VRV operated 295 days and processed a total of 1,283 dry tons of sludge. The reaction vessel capacity was increased by the change from air to oxygen as the oxidation source, and the system was successfully operated using sludge as the sole heat source. The days that the VRV did not operate were mainly due to system modifications expected in a demonstration facility. Mechanical reliability was 96.7%. The only problems encountered involved shutdowns of less than 24 hours.

One of the advantages of the VRV System was the wide operating range of the reaction vessel. The operating program in Longmont was split into two distinct modes of operation for data analysis and reporting purposes: non-autogenous and autogenous operation. Non-autogenous operation included all times when the VRV required additional outside heat to overcome the combined losses to the effluent and to the rock. This included all those periods of operation from June 1984 to February 1985. During this time period, the system operated with air and oxygen-enriched air, but insufficient sludge was available to supply the heat needed for autogenous operation.

Autogenous operation included all times when the system operated with oxygen-enriched air and pure oxygen, and when sufficient sludge was available to overcome the combined losses to the effluent and to the rock. During autogenous operation, sludge was either hauled in from outside sources, or Longmont stored sludge for intermittent operation. The capacity of the Longmont WWTP was insufficient for sustained autogenous operation. The energy balance for the two modes of operation is discussed in Section 6.2.

Table 6.1-2 shows the ranges tested for non-autogenous and autogenous operation and the results obtained from intensive sampling. Better CODT reductions were obtained while operating autogenously. This was partly due to the higher concentrations processed and the generally higher downhole temperatures during autogenous operation. The results summarized in Table 6.1-2 include all operating conditions tested, though not necessarily the most desirable. Reported CODT reductions were determined across the VRV without recycle. CODT reductions, as discussed in Section 5.3.3, were higher with recycle.

TABLE 6.1-1
OPERATING DAYS

YEAR	MONTH	DAYS OPERATED*	SLUDGE PROCESSED (Dry Tons)
1984	June	15	40
	July	29	109
	August	22	75
	September	28	58
	October	14	32
	November	25	146
	December	17	81
1985	January	26	81
	February	25	88
	March	23	173
	April	30	216
	May	15	41
	June	1	2
	July	8	30
	August	15	111
	September	2	0
Total		295	1,283

*Includes acid washes.

TABLE 6.1-2
OPERATING RANGE TESTED IN LONGMONT

	NON-AUTOGENOUS		AUTOGENOUS	
	Average	Range(Low-High)	Average	Range(Low-High)
Influent CODT S-3 (mg/L)	7,700	1,600-20,900	23,000	12,500-48,500
Effluent CODT S-4 (mg/L)	2,400	640-8,420	4,950	1,400-10,130
CODT Reduction (%)	67.7	51.0-86.1	78.2	65.8-88.5
Sludge Loading (lb/hr)	520	90-1,450	1,330	710-1,930
Sludge Solids (%)	6.7	2.4-10.5	4.7	1.9-7.2
Sludge Flow (gpm)	17	5-50	58	15-80
Total Flow (gpm)	118	100-180	109	68-134
Air Flow (lb/hr)	13.9	3.4-22.5	0.6	0-6.2
Oxygen Flow (lb/hr)	2.9	0-18.8	18.2	9.5-25.3
Heat Transfer Fluid (lb/min)	414	290-470	44.0*	0-300
Bottomhole Temp. (°F)	510	501-528	522	484-539
Number of Samples		498		158

*Extracting heat while autogenous.

6.1.2 Minimum Capacity

The reaction vessel was operated at an extremely low operating rate, but additional heat was then required to maintain the desired temperature profile. Since the external heat exchange system at Longmont provided enough heat to overcome the heat losses to the rock and to the effluent, the operation was not limited by low concentrations.

6.1.3 Maximum Capacity

There were four factors which limited the capacity of the VRV: heat transfer cooling system, oxygen flow rate, influent feed concentration, and liquid flow rate.

The maximum capacity at Longmont was limited by the liquid oxygen supply pump and the heat transfer fluid cooling system (no energy recovery system was installed). To increase the system capacity, VerTech installed an oxygen trailer. At start-up, when the surrounding formation was cold, it was possible to operate at a high sludge feed rate, thus simulating a higher heat removal capacity from the heat transfer fluid system. The reaction vessel was operated at a maximum capacity of 30,000 kg (33 tons) of CODT per day.

The hydraulic loading was not a limitation at Longmont since the inlet sludge density stayed at 6-7 wt.% and dilution was required. Typical liquid flow rates at Longmont were 80-120 gpm.

6.2 ENERGY BALANCE

6.2.1 Parameters Affecting Heat Losses at Longmont

Heat generated from the exothermic oxidation reaction was lost to the rock formation surrounding the wellbore, and to the effluent liquid stream. Flush-out losses to the effluent were due to the higher temperature in the effluent stream. This heat could be advantageously applied to downstream biological processes. Warm water will alleviate problems normally associated with operation during winter months. The temperature difference between influent and effluent streams is generally low, 8-17 C° (15-30 F°), due to efficient countercurrent heat transfer between the downcomer and upcomer flow.

While running non-autogenously, radial heat losses across the insulated tubular were greater than originally expected (see Section 4.2.1.2). Heat losses from the insulated tubular were transferred to the aqueous-phase downcomer and then to the upcomer. This increased the entire temperature of the aqueous streams, and increased the flush-out losses unexpectedly. Inefficiencies of the insulated tubular created an artificially greater radial temperature differential throughout the length of the VRV. Because of this higher temperature difference, heat losses to rock were greater during non-autogenous operation than during autogenous operation. An improved design will reduce heat losses considerably during non-autogenous operation.

Losses to the rock are determined by materials in the heat path between the reaction vessel and the formation, and by the radial temperature difference. A cross section of the VRV and surroundings is shown in Figure 6.2-1. The heat path between the VRV and the rock consists of four layers: insulation, convecting fluid, cement, and rock.

Heat transfer coefficients for natural convection in a liquid medium are an order of magnitude higher than those for natural convection in air. High boiling temperature oil was used in the annular space between the reaction vessel and the primary casing so that the reaction vessel housing would only have to withstand its own weight. The oil substantially increased heat losses to the rock. Use of a better quality cement with a lower conductivity, between the casing and the rock, helped reduce heat losses to the surroundings.

The type of rock also affects the heat losses. Heat conduction away from the wellbore depends on the temperature driving force and the thermal diffusivity of the rock. The lithology in Longmont is largely shale, with some layers of sandstone.

6.2.2 Non-Autogenous Operation

Non-autogenous operation requires energy input from the heat transfer fluid system to achieve the necessary downhole temperatures. This operating mode is necessary for initial start-up and after an acid wash. The only other time the reaction vessel requires additional heat input is when the heat produced from the exothermic oxidation reaction is less than the sum of the heat lost to the rock and the heat lost to the effluent stream.

The Longmont installation operated non-autogenously from June 1984 to February 1985. A typical energy balance during non-autogenous operation is shown in Figure 6.2-2. Energy inputs to the VRV are from the oxidation of the sludge (0.53 MW) and added heat from the heat transfer fluid (2.34 MW). Energy out of the VRV is lost to the rock (1.41 MW) and flushed out in the effluent (1.40 MW) as calculated below:

<u>CALCULATIONS:</u>

<u>Heat of Reaction</u>

Assume 6,000 Btu/lb heat of combustion
(430 lb sludge/hr) X (.7 lb reacted/lb feed) X (6,000 Btu/lb)
= 1,810,000 Btu/hr = 0.53 MW

<u>Added Heat from Heat Transfer Fluid</u>

Inlet Fluid Enthalpy = 318.3 Btu/lb
Outlet Fluid Enthalpy = 37.5 Btu/lb
(474 lb/min) X (318.3 - 37.5 Btu/lb)
= 7,990,000 Btu/hr = 2.34 MW

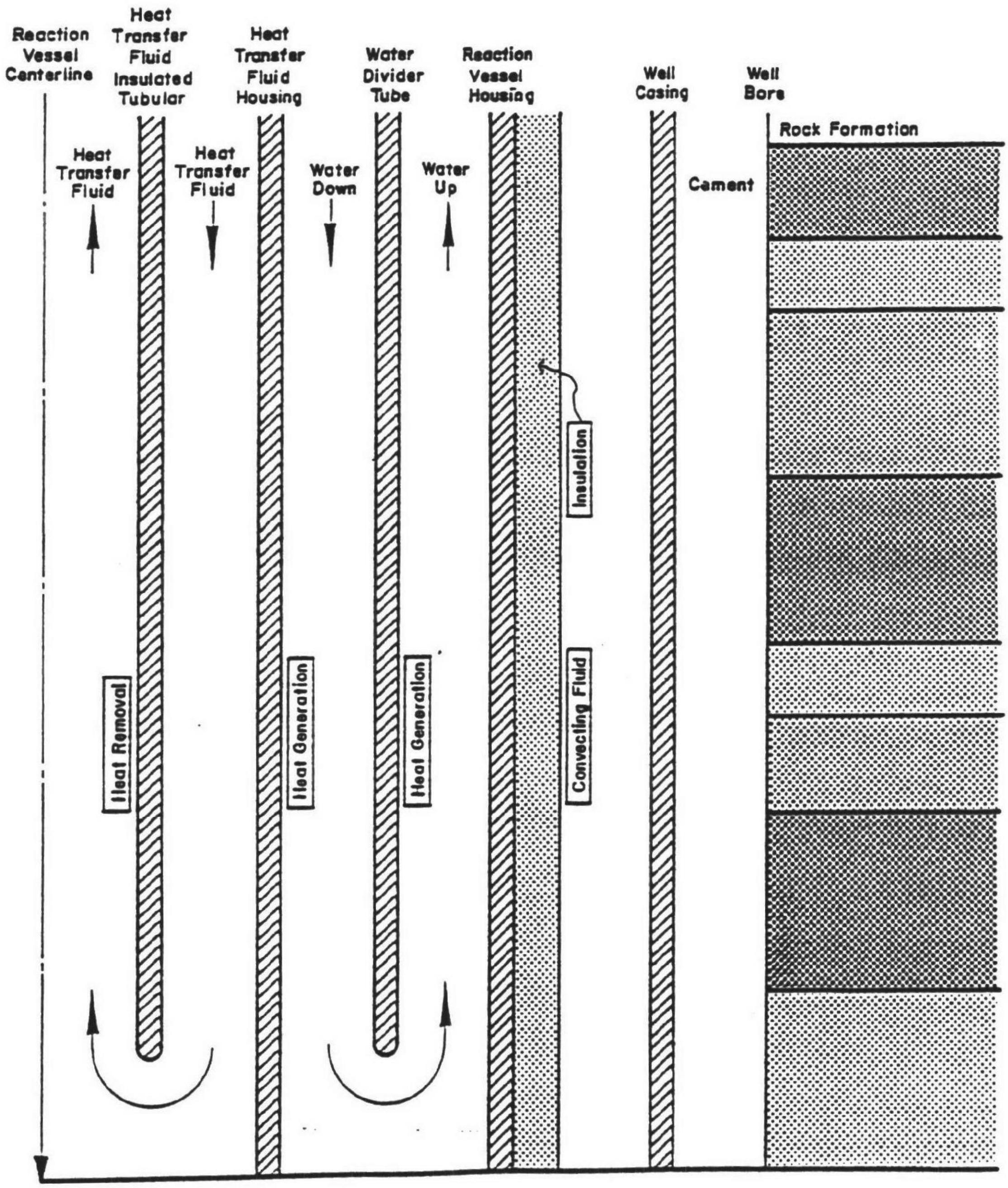
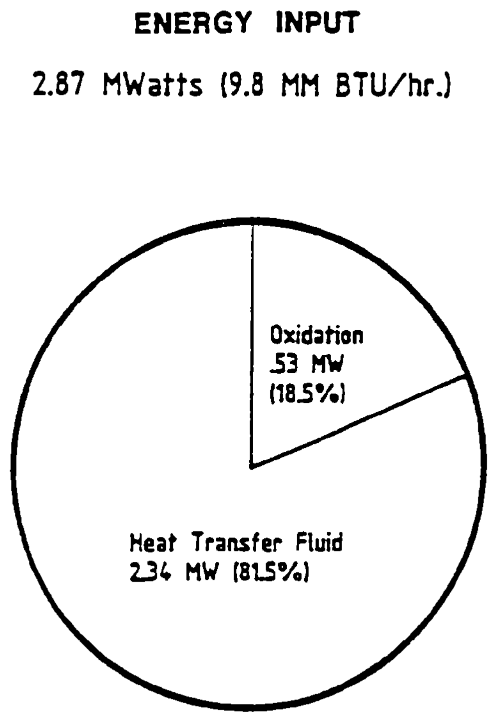


Fig. 6.2-1. VRV Cross-Sectional Schematic



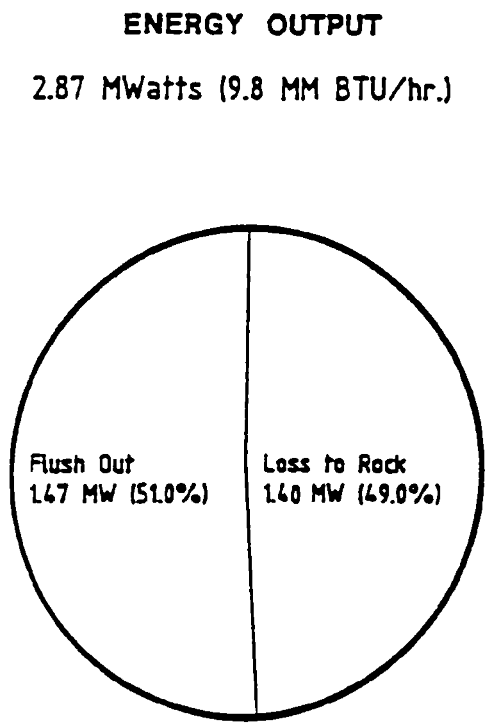


Fig. 6.2-2 Non-Autogenous Energy Balance

Effluent Flush-out Losses
(55,500 lb/hr) X (1 Btu/lb°F) X (150°F - 60°F)
= 5,000,000 Btu/hr = 1.47 MW

Rock Losses
By Difference:
Rock Loss = Heat Transfer Fluid + Heat Reaction - Flush-out
= 2.34 + 0.53 - 1.47 MW = 1.40 MW Rock Losses

6.2.3 Autogenous Operation

Autogenous operation is the point at which the heat generated from the exothermic oxidation reaction is at least equal to the sum of the heat losses to the rock and heat flushed out in the effluent stream. During autogenous operation, the system is self-sustaining; no external heat input is necessary.

In Longmont, the reaction vessel was operated autogenously from February 1985 to August 1985. During March and April, sludge was hauled in from neighboring communities to provide the additional fuel needed. Afterward the WWTP stored sludge while the system was not operating. A typical energy balance for autogenous operation is shown in Figure 6.2-3. Energy input, entirely from the heat of reaction, was 1.50 MW. Energy was lost to the rock (0.94 MW) and to the effluent (0.56 MW).

Flush-out and rock heat losses during autogenous operation are less than the losses experienced during non-autogenous operation. Since the heat transfer fluid was no longer needed to heat the VRV, the losses across the insulated tubular were effectively eliminated, reducing temperature differences from influent to effluent. Heat losses to the rock during autogenous operation were only 60-70% of those experienced during non-autogenous operation. The improved insulated tubular design will reduce heat losses during start-up and acid wash operation to the level experienced during autogenous operation.

CALCULATIONS:

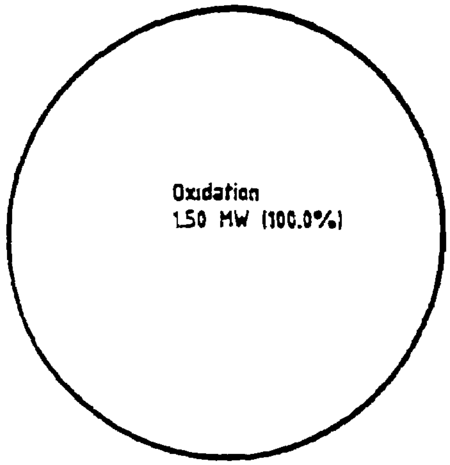
Heat of Reaction
(1,210 lb sludge/hr) X (.7 lb reacted/lb feed) X (6,000 Btu/lb)
= 5,100,000 Btu/hr = 1.51 MW

Effluent Flush-out Losses
(63,400 lb/hr) X (1 Btu/lb°F) X (90°F - 60°F)
= 1,900,000 Btu/hr = 0.56 MW

Rock Losses
Rock Loss = Heat of Reaction - Flush-out
= 1.51 - 0.56 = 0.94 MW Rock Losses

ENERGY INPUT

1.50 MWatts (5.1 MM BTU/hr.)



ENERGY OUTPUT

1.50 MWatts (5.1 MM BTU/hr.)

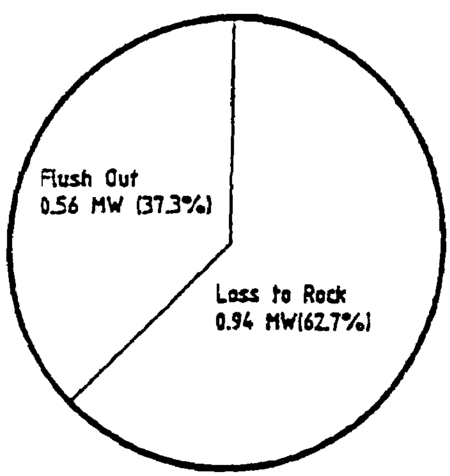


Fig. 6.2-3 Autogenous Energy Balance

6.2.4 Heat Recovery

Heat recovery was necessary when the heat produced from the exothermic oxidation reaction was greater than the flush-out heat and heat loss to the rock. If heat was not removed from the reaction vessel by the heat transfer fluid, the effluent temperature would have increased and fluid in the upcomer would begin to boil.

By flowing the heat transfer fluid in the opposite direction from start-up, heat was recovered from downhole. The heat transfer fluid flowed co-currently with the aqueous downcomer, removing heat from the downcomer across the heat transfer fluid housing. When the heat transfer fluid reached the bottom, it returned in the insulated tubular, retaining the high downhole temperature. The heat transfer fluid can be used to generate steam or hot water in conventional equipment above ground.

A small 0.37 MW air-cooled exchanger was used to waste any excess heat to the atmosphere. A typical energy balance for autogenous operation with heat removal is shown in Figure 6.2-4. Energy input from the oxidation reaction was 1.87 MW. Energy lost to the rock totaled 0.94 MW. The other half of the energy was lost to the effluent (0.56 MW) and wasted in the surface exchanger (0.37 MW).

Calculations are similar to those in Section 6.2.3, except that more sludge was processed to generate additional heat. The amount of sludge which can be processed is limited by the two-phase flow characteristics and by the heat exchanger size.

6.3 CHEMICAL OXYGEN DEMAND TOTAL (CODT)

6.3.1 CODT Reduction as a Function of Temperature

Reduction of CODT in the VRV is dependent on many different parameters, of which the most important are residence time and temperature. In Longmont, the residence time can be changed in the vessel by varying the liquid and gas flow rates. The Longmont demonstration vessel was designed for an approximate one-hour residence time, with the pump sizing restricting the possible flow rates and residence times through the vessel. Because of these restrictions, the residence time could not be varied enough to determine its influence on CODT reduction. Any influence of residence time on CODT reduction is negligible in the current reaction vessel design.

The influence of bottomhole temperature on the CODT reduction is shown in Figure 6.3-1. CODT reduction increases with increasing temperature. This figure represents 369 data points taken during intensive sampling periods while operating autogenously. The average CODT reduction over the entire temperature range (227-280°C) was 76.3%. Note the large variation in reductions obtained for each of the temperature values tested. The variation of ±10% from the straight line curve fit is

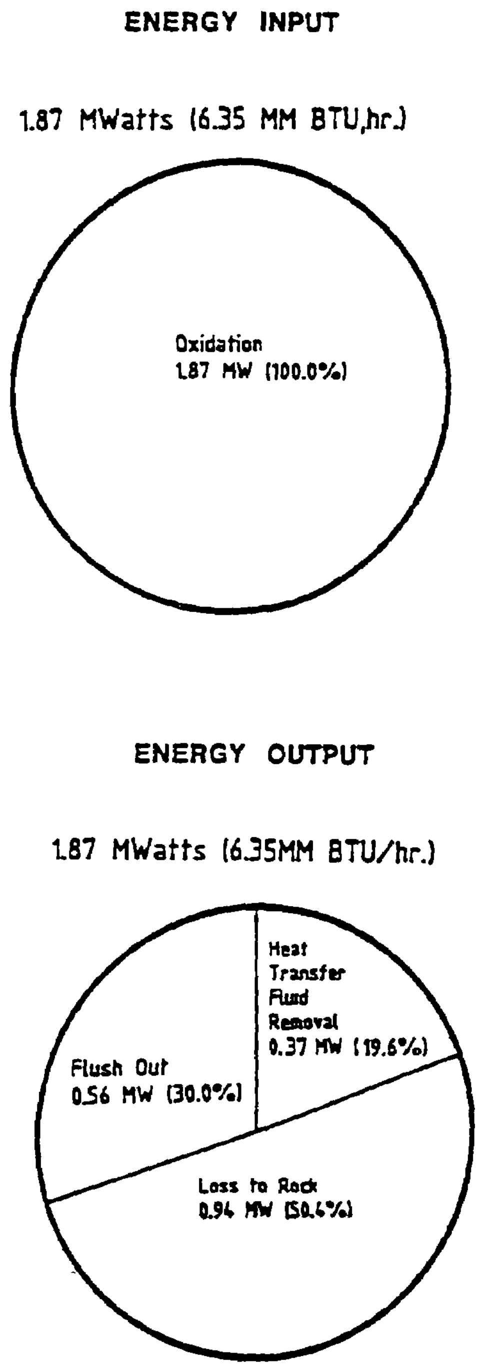
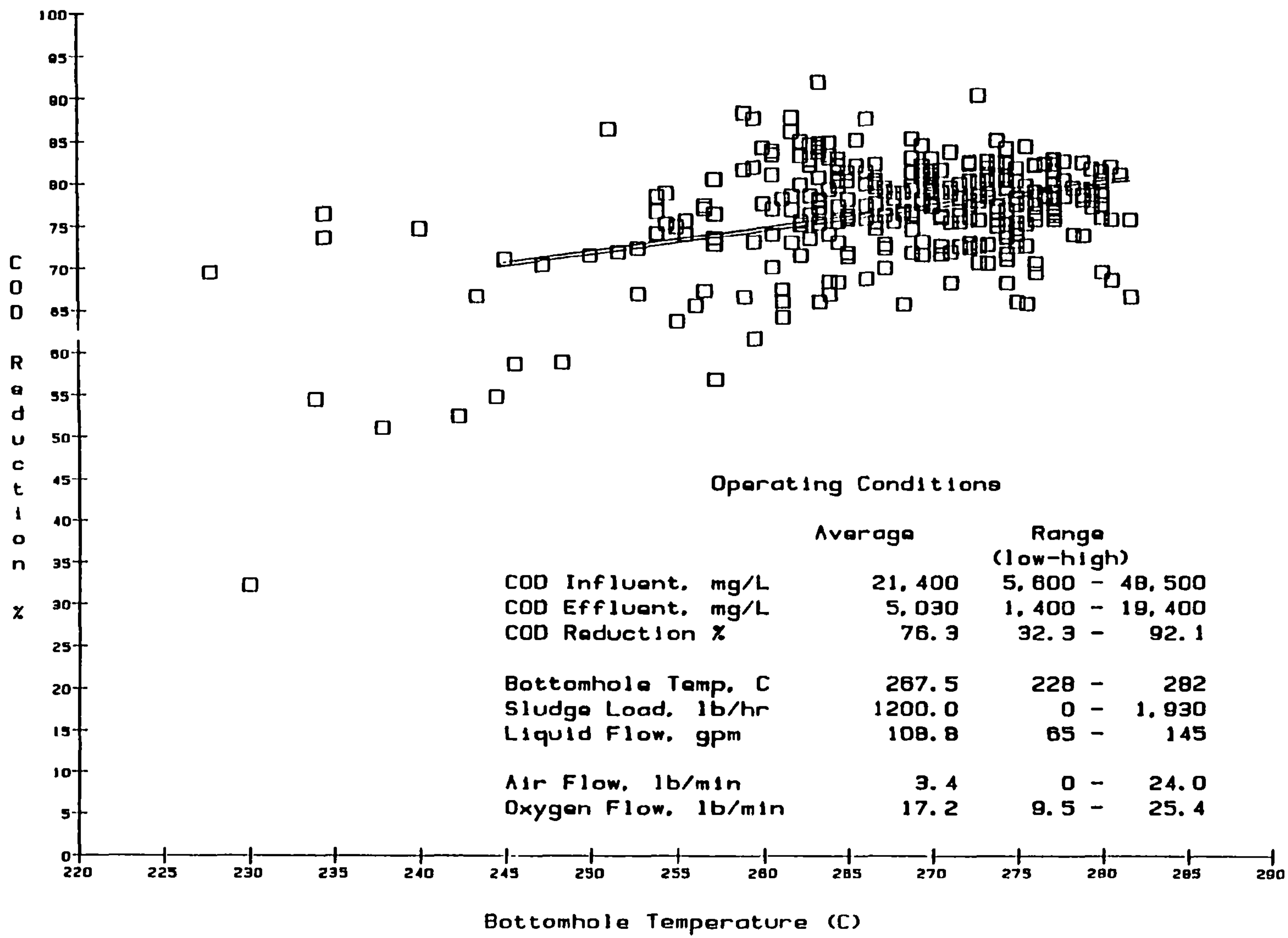


Fig. 6.2-4 Autogenous Energy Balance with Heat Removal



Operating Conditions

	Average	Range (low-high)
COD Influent, mg/L	21,400	5,800 - 48,500
COD Effluent, mg/L	5,030	1,400 - 19,400
COD Reduction %	76.3	32.3 - 92.1
Bottomhole Temp, C	267.5	228 - 282
Sludge Load, lb/hr	1200.0	0 - 1,930
Liquid Flow, gpm	108.8	65 - 145
Air Flow, lb/min	3.4	0 - 24.0
Oxygen Flow, lb/min	17.2	9.5 - 25.4

Fig. 6.3-1 CODT Reduction vs Bottomhole Temperature

due to other variables, such as liquid and gas flow rates, the overall temperature profile and influent concentration. Reductions greater than 80% were routinely obtained while operating the VRV under normal conditions.

6.3.2 CODT Reduction as a Function of Concentration

Figure 6.3-2 shows the dependency of CODT reduction on the inlet concentration. These data include all of the composite sampling done by J&A Associates over the course of the project. Most of the data points are at lower concentrations before autogenous operation started. The high concentrations represent average CODT reductions obtained while operating autogenously. The data are fit to a curve represented by the general equation which represents the response of a first order system to a step change:

$$\text{CODT Reduction} = A \times [1 - \exp(-\text{Influent CODT}/\text{tau})]$$

In the case of CODT reduction, the curve levels out at 77.4% reduction above 12,400 mg/L influent CODT concentration. This reduction is slightly lower than what would be achieved operating at ideal conditions. The scatter indicates the influence of other variables such as temperature on the concentration dependency.

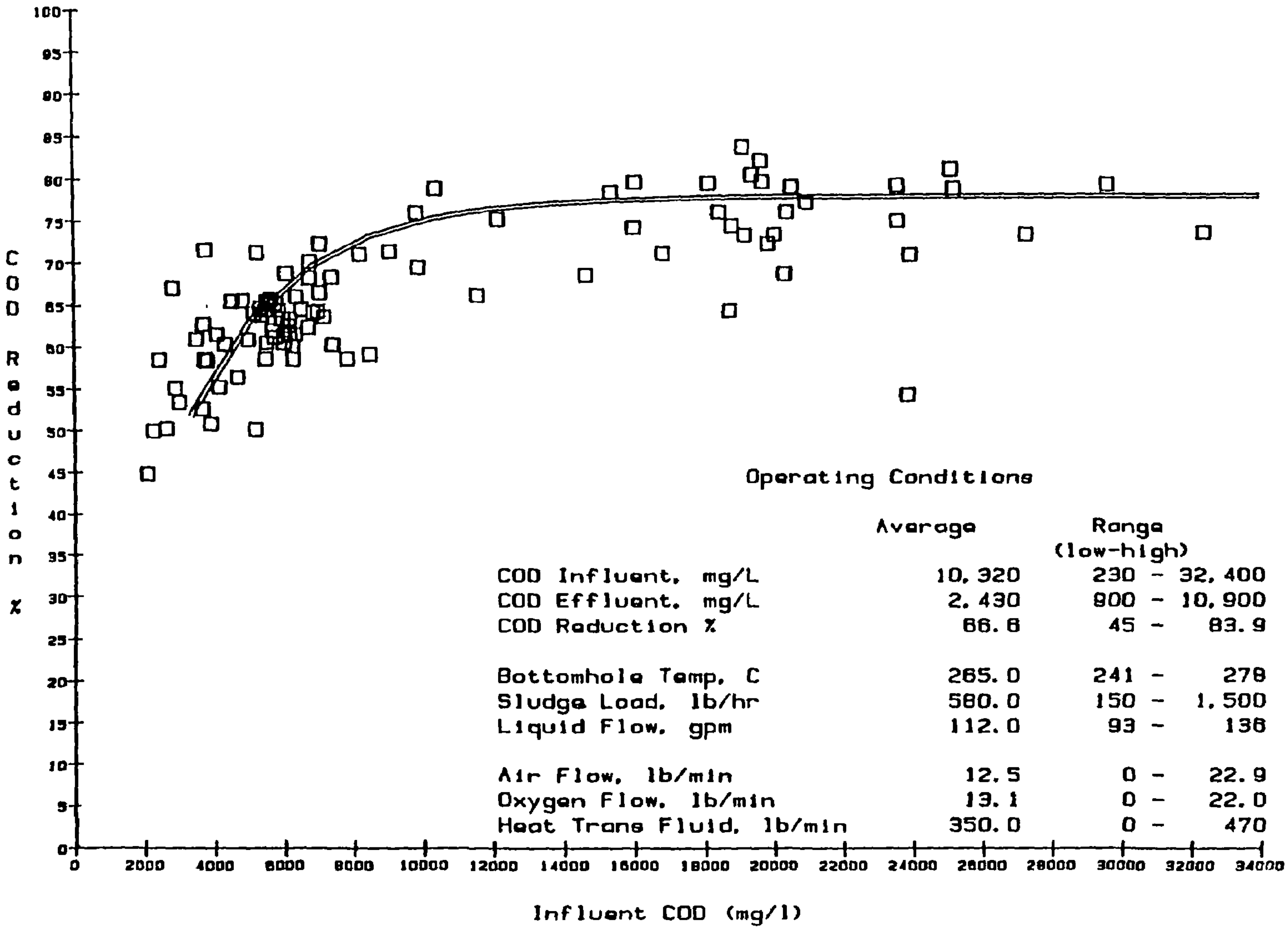
6.3.3 Effect Of Recycle On CODT Reduction

The raw sludge feed was normally diluted with clarifier effluent to the desired influent flow rate. Recycled VRV effluent was also used for this purpose. During autogenous operating periods, a fraction of the reaction vessel effluent was recycled to the inlet and reprocessed. Table 6.3-1 summarizes average results for CODT reductions with and without effluent recycle. More detailed data are presented in Tables 6.7-1, 6.7-2, 6.7-5, and 6.7-6, where BODT recycle is also discussed.

TABLE 6.3-1
CODT REDUCTIONS WITH AND WITHOUT EFFLUENT RECYCLE

	kg CODT Consumed / kg CODT Influent	kg CODT Consumed / kg CODT Processed
Without Recycle	0.791	0.791
With Recycle	0.737	0.847

As shown, CODT reductions across the reaction vessel itself decreased from 79.1% without recycle to 73.7% with recycle, but overall CODT reduction based on total CODT processed increased from 79.1% without recycle to 84.7% with recycle. This difference can be attributed to the accumulation of refractory compounds such as low molecular weight organic acids. These components, which are more resistant to oxidation, undergo further oxidation through recycling.



Operating Conditions

	Average	Range (low-high)
COD Influent, mg/L	10,320	230 - 32,400
COD Effluent, mg/L	2,430	800 - 10,900
COD Reduction %	66.6	45 - 83.9
Bottomhole Temp, C	265.0	241 - 278
Sludge Load, lb/hr	580.0	150 - 1,500
Liquid Flow, gpm	112.0	93 - 136
Air Flow, lb/min	12.5	0 - 22.9
Oxygen Flow, lb/min	13.1	0 - 22.0
Heat Trans Fluid, lb/min	350.0	0 - 470

Fig. 6.3-2 CODT Reduction vs Influent CODT Concentration

6.3.4 Effect of Oxygen Consumption on CODT Reduction

Oxygen consumption during sludge processing was determined by CODT analysis of VRV influent and effluent. An on-line gas chromatograph (GC) was used to monitor oxygen, nitrogen, carbon dioxide and carbon monoxide concentrations in the VRV off-gas every 15 minutes.

Several oxygen balances were performed during intensive sampling periods for quality control checks of analytical CODT data and process instrumentation. A sample oxygen balance during oxygen-enriched air operation is presented in Table 6.3-2. The average O_2/CODT ratio was 1.014 indicating excellent agreement.

Continuous oxygen monitoring in the off-gas determined the effect of excess oxygen on efficiency of CODT removal. Figure 6.3-3 shows that increasing excess oxygen in the off-gas had no effect on process CODT reductions. Excellent reductions at stoichiometric oxygen addition can be attributed to excellent mass transfer of oxygen into solution during oxidation.

6.3.5 Solids Reduction Related to CODT Reduction

This section presents the results of reduction of TVSS, TVS, and TSS as related to CODT reduction in the VRV. Graphs show results obtained from the City of Longmont daily analyses, as well as a similar plot drawn from the composite analyses of J & A Associates.

Figures 6.3-4 and 6.3-5 present the results of TVSS Reduction. Even at low CODT reductions of 50%, volatile suspended solids reduction was greater than 75%. Section 6.4 provides more TVSS results. Figures 6.3-6 and 6.3-7 give results of total volatile solids reductions. TVS reduction is about 15% greater than CODT reduction. Figures 6.3-8 and 6.3-9 present results for total suspended solids reductions. TSS reduction closely follows CODT reduction.

Note that the pairs of graphs presented for each of the parameters investigated agree closely, indicating that although the analytical and sampling techniques discussed in Section 4 differed between the Longmont City Laboratory and J & A Associates, the results were very similar.

6.4 TOTAL VOLATILE SUSPENDED SOLIDS (TVSS)

6.4.1 TVSS Reduction as a Function of Temperature

Figure 6.4-1 shows the influence of bottomhole temperature on TVSS reduction in the reaction vessel. The temperature dependency on TVSS is clear. Volatile suspended solids destruction is nearly complete in the VRV at high temperatures.

During the entire operating period, composite samples analyzed for TVSS indicated an average reduction of 92.3%, with a maximum of 98.4%. An average TVSS reduction of 96.5% was achieved during autogenous operation.

Table 6.3-2 OXYGEN BALANCE

	GAS CHROMATOGRAPH DATA					INTENSIVE SAMPLING DATA			OXYGEN BALANCE				
TIME	% N_2	% O_2	% CO_2	% CO	% OTHER	CODT In mg/L	CODT Out mg/L	% RED.	O_2 In kg/hr	O_2 Out kg/hr	CODT RED. kg/hr	O_2 RED. kg/hr	O_2/CODT Closure %
13:00	46.99	4.89	41.96	3.11	3.05	10710	2360	78.0	241.0	18.6	225.4	222.4	98.6
13:15	47.72	4.88	42.51	3.09	1.80	9840	2250	77.1	241.0	18.3	204.9	222.7	108.7
13:31	47.95	3.56	43.49	2.90	2.10	9920	2170	78.1	241.0	13.3	209.2	227.7	108.8
13:46	47.79	3.55	43.75	2.46	2.45	10240	2160	78.9	241.0	13.3	218.1	227.7	104.4
14:01	47.15	4.22	44.14	2.09	2.40	10240	2090	79.6	241.0	16.0	220.0	225.0	102.2
14:16	47.33	4.37	43.99	2.02	2.24	9740	2150	77.9	241.0	16.5	204.9	224.4	109.5
14:32	46.98	6.45	42.23	2.09	2.25	11470	2090	81.8	241.0	24.6	253.2	216.4	85.4
14:47	47.06	6.51	42.02	2.18	2.23	10640	2110	80.2	241.0	24.8	230.3	216.2	93.9
Average	47.37	4.80	43.01	2.49	2.32	10350	2173	78.9	241.0	18.2	220.8	222.8	101.4
Std.Dev.	0.37	1.08	0.86	0.44	0.36	537	86	1.4	0.0	4.5	16.1	4.5	7.9

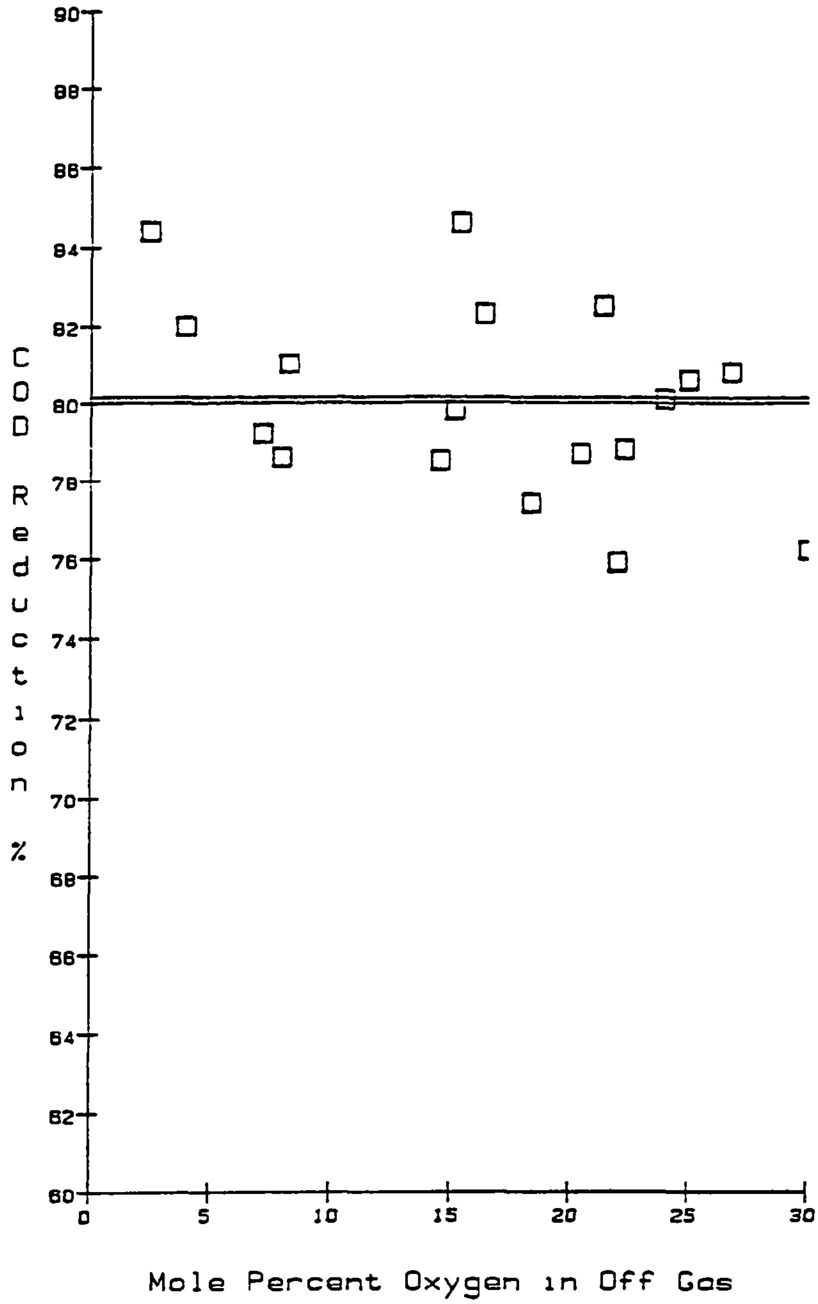


Fig. 6.3-3   CODT Reduction vs Oxygen in Off-Gas

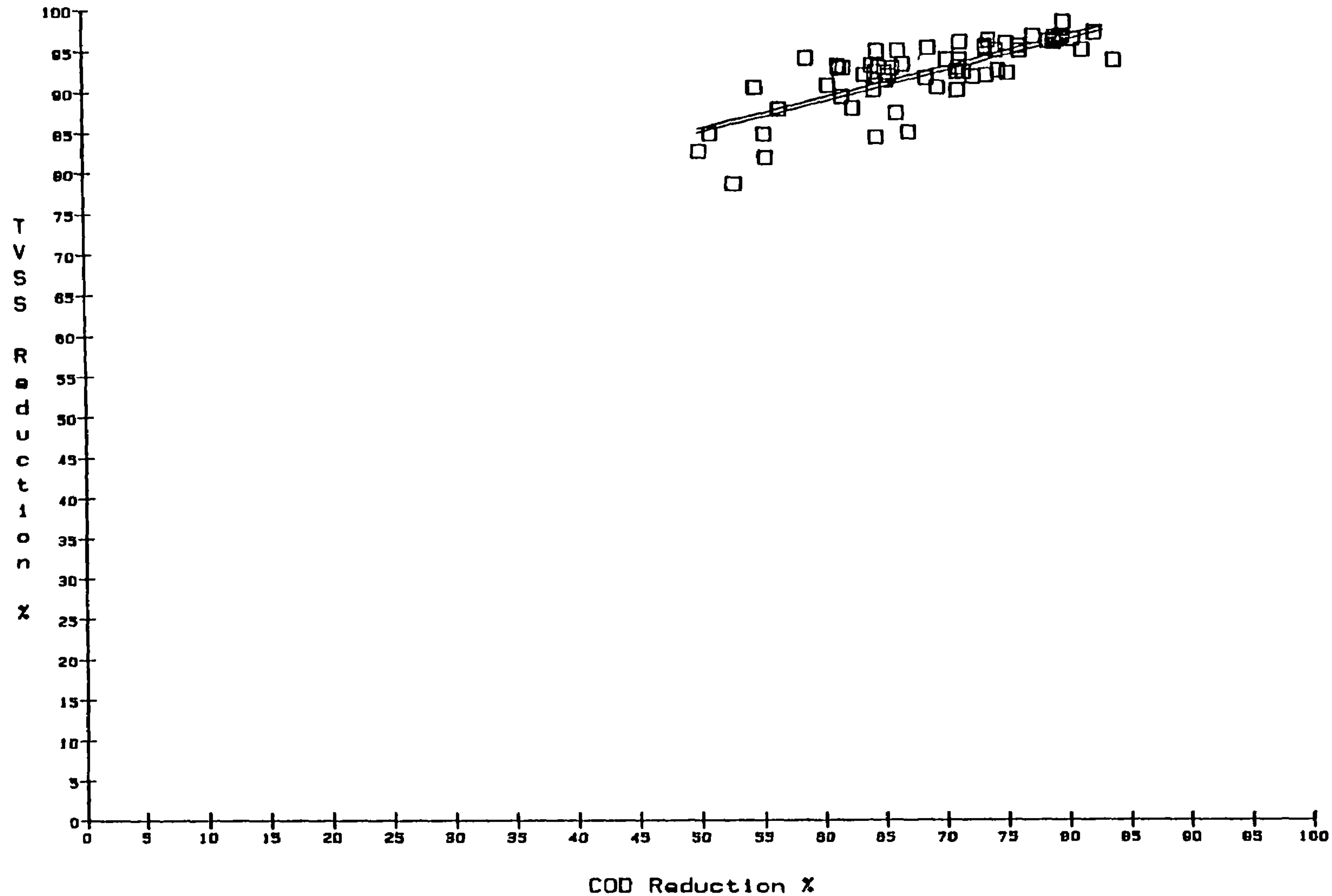


Fig. 6.3-4 TVSS vs CODT - J & A Data

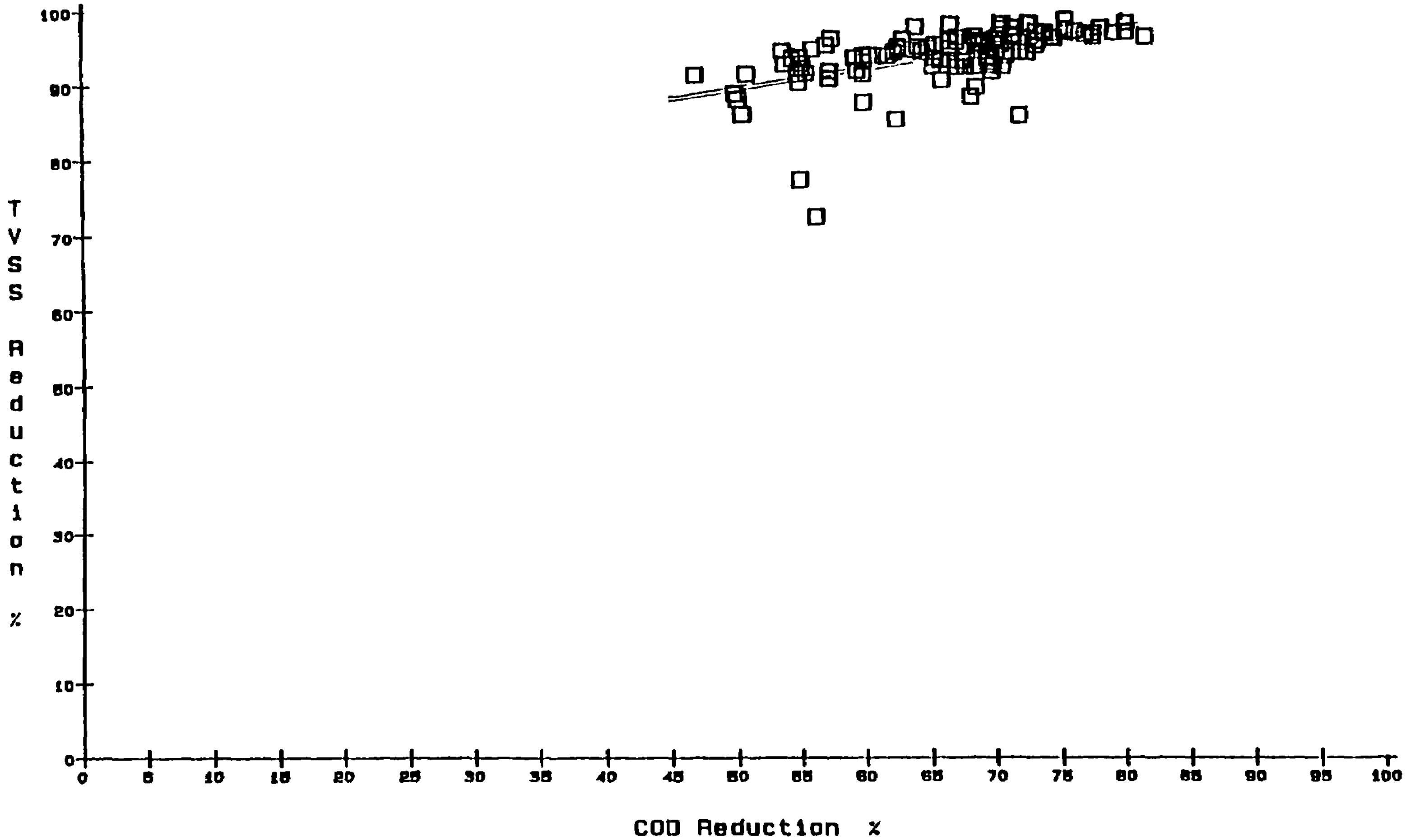


Fig. 6.3-5   TVSS vs CODT - City of Longmont Data

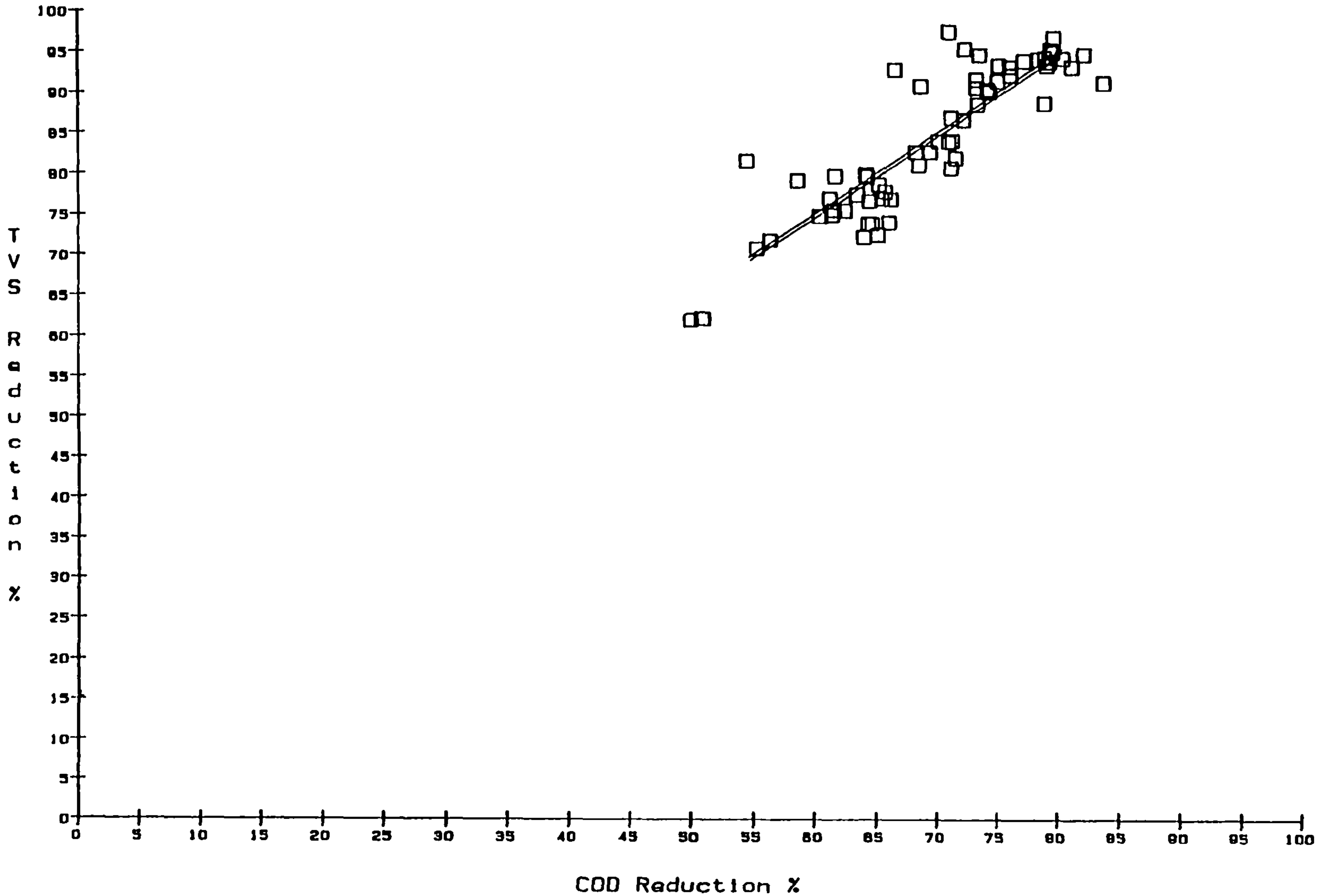


Fig. 6.3-6 TVS vs CODT - J & A Data

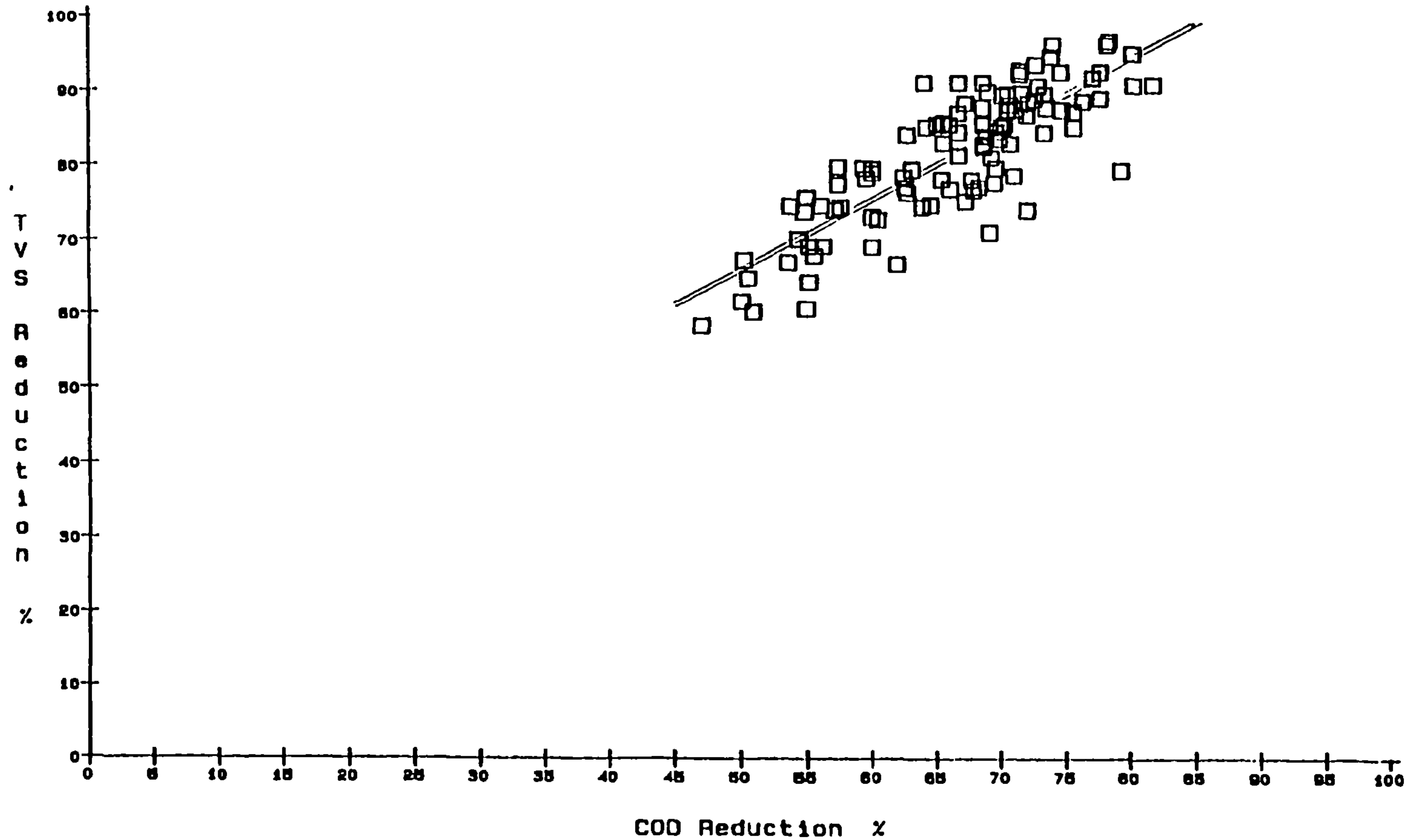


Fig. 6.3-7 TVS vs CODT - City of Longmont Data

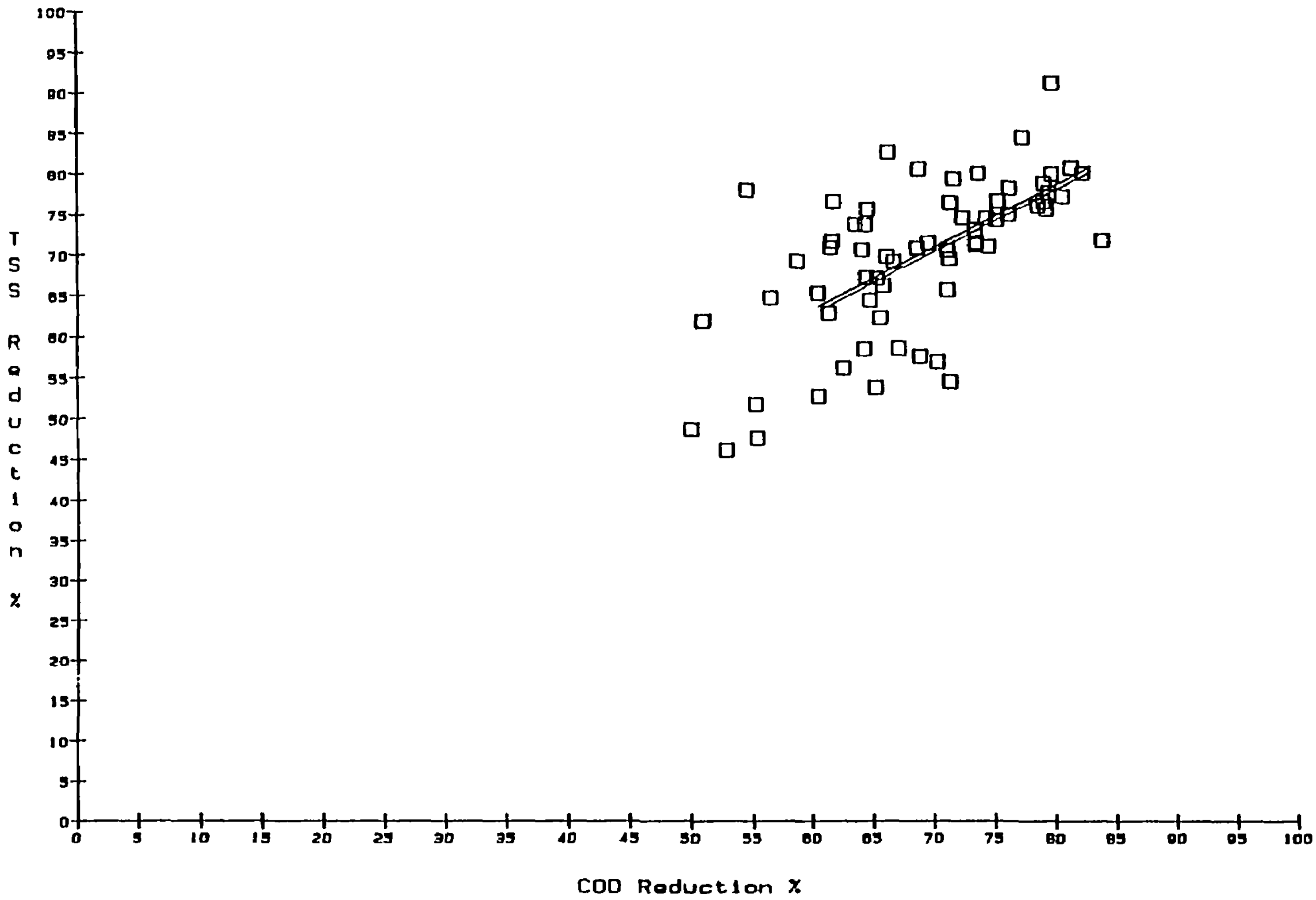


Fig. 6.3-8   TSS vs CODT - J & A Data

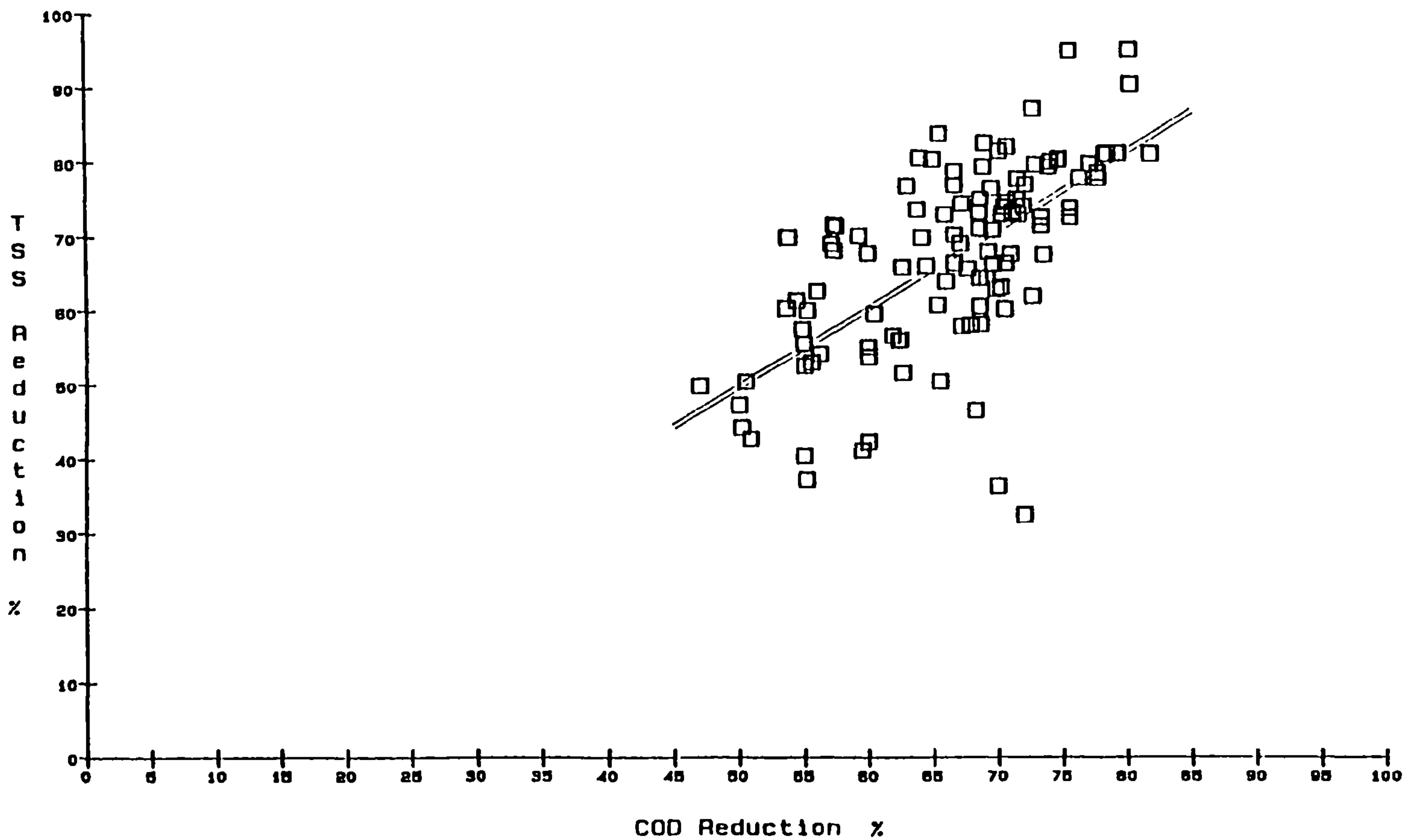


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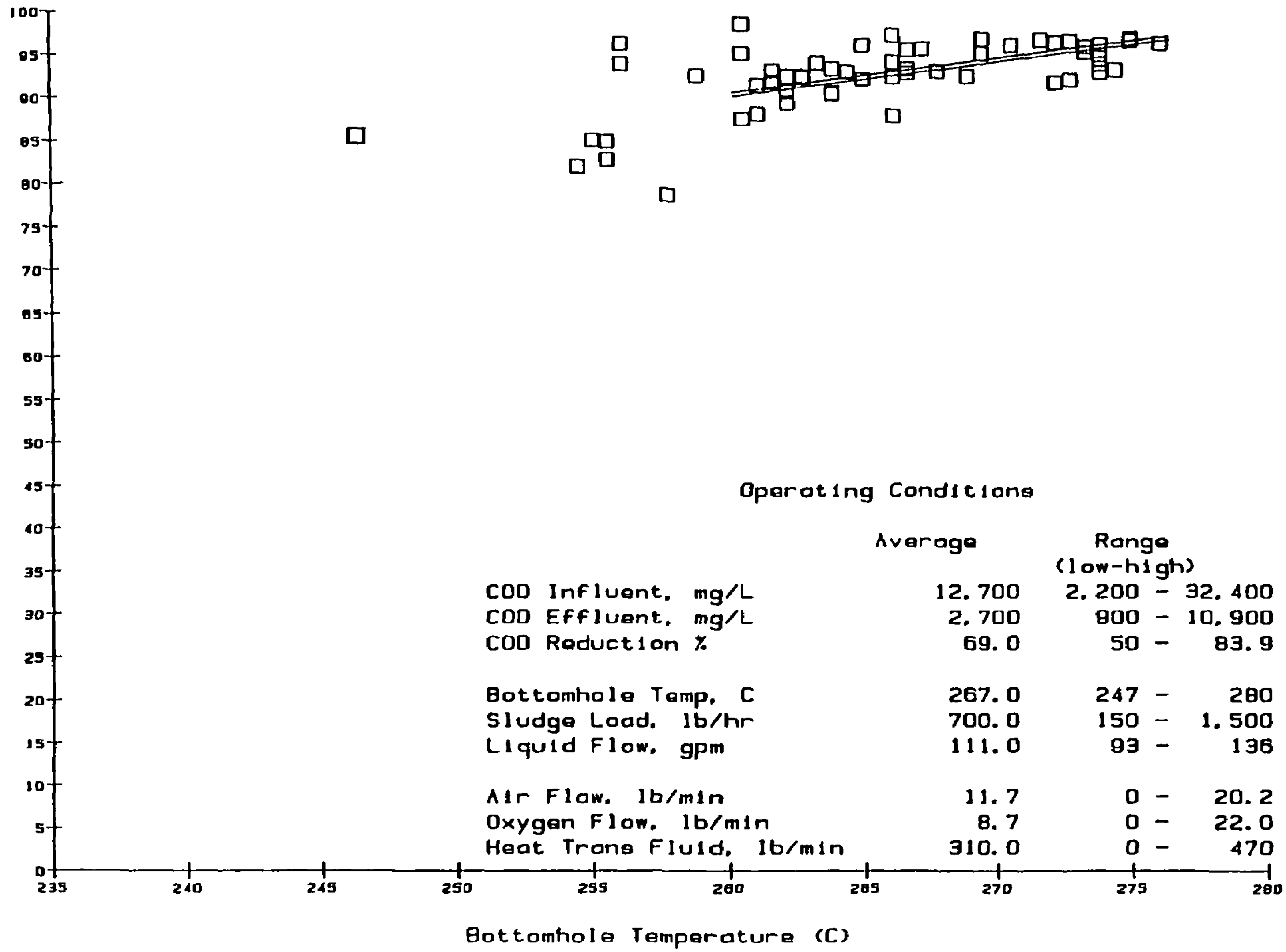
Fig. 6.3-9 TSS vs CODT - City of Longmont Data



Operating Conditions

	Average	Range (low-high)
COD Influent, mg/L	12,700	2,200 - 32,400
COD Effluent, mg/L	2,700	900 - 10,900
COD Reduction %	69.0	50 - 83.9
Bottomhole Temp, C	267.0	247 - 280
Sludge Load, lb/hr	700.0	150 - 1,500
Liquid Flow, gpm	111.0	93 - 136
Air Flow, lb/min	11.7	0 - 20.2
Oxygen Flow, lb/min	8.7	0 - 22.0
Heat Trans Fluid, lb/min	310.0	0 - 470

Fig. 6.4-1 TVSS Reduction vs Bottomhole Temperature

6.4.2 TVSS Reduction as a Function of Concentration

TVSS reduction dependency on concentration is shown in Figure 6.4-2 For influent TVSS concentrations greater than 3400 mg/L, there is virtually no influence of feed concentration on TVSS reduction. This curve suggests that reductions will level out at approximately 95.7% TVSS reduction, regardless of influent concentration. Greater reductions are obtained by increasing the bottomhole temperature and the residence time.

6.4.3 Effect of Demonstration Facility on Longmont WWTP TVSS

City of Longmont TVSS data were collected daily for each stage of operation from December 1984 to September 1985. TVSS values were also averaged over the entire period with results given in Table 6.4-1 Average percent removals for TVSS from WWTP influent to effluent with the VRV System operating were 86.0% and without the VRV system operating were 85.6%. As shown, system operation had no significant effect on overall TVSS removals in the WWTP.

TABLE 6.4-1
TSS/TVSS AVERAGE FOR LONGMONT WWTP
DECEMBER 1984 - SEPTEMBER 1985

	WWTP OPERATING WITHOUT VERTECH (mg/L)		WWTP OPERATING WITH VERTECH (mg/L)	
	TSS	TVSS	TSS	TVSS
Influent	145	125	151	129
Equalization Effluent Basin	307	236	342	250
Primary Clarifier Effluent	111	89	122	99
Trickling Filter Influent	131	102	154	109
Trickling Filter Effluent	129	102	156	112
Rotating Biological Contactor Effluent	149	106	178	119
Final Clarifier Effluent	27	18	27	18
Avg.% Removal	81.4%	85.6%	82.1%	86.0%

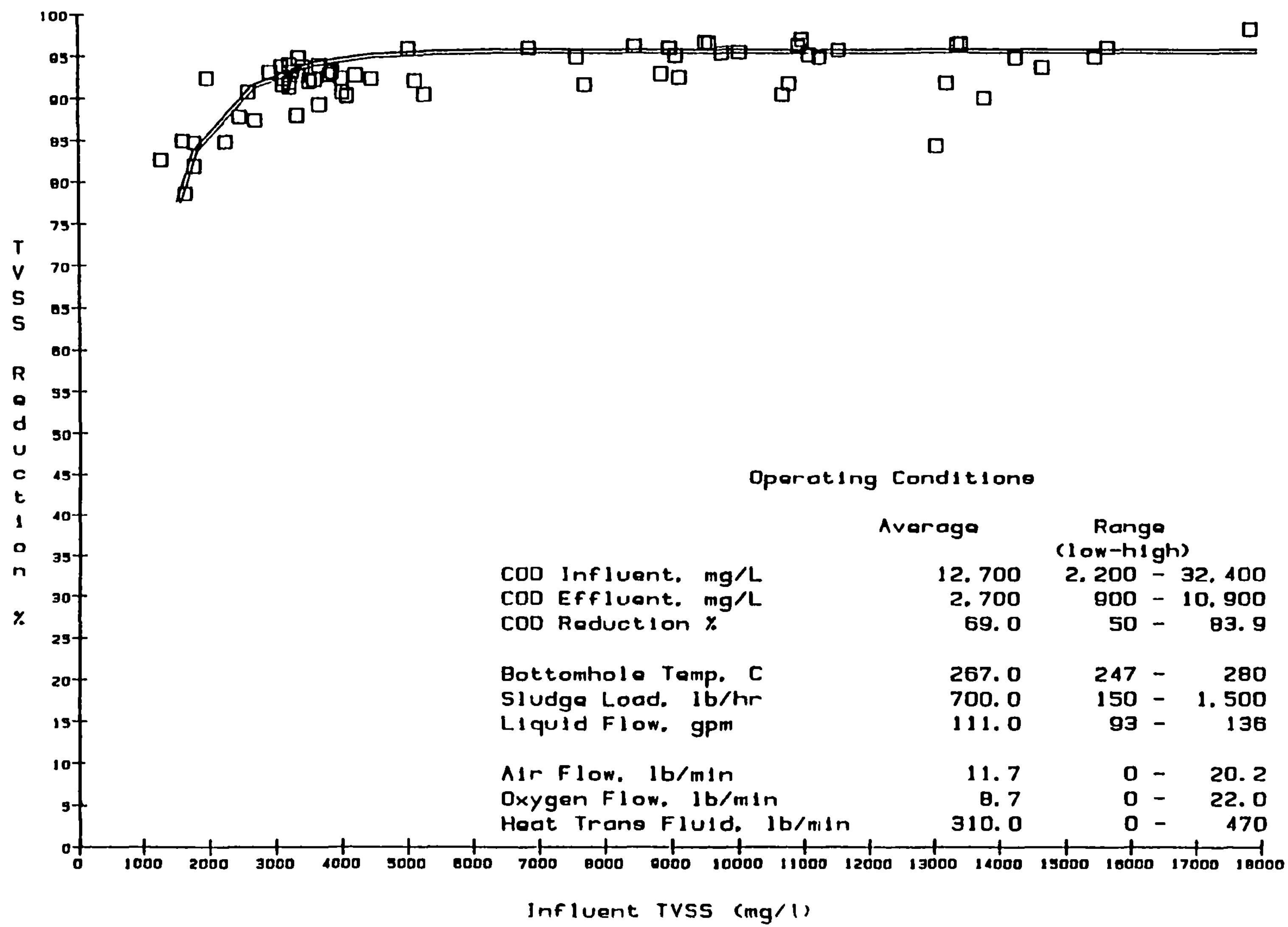


Fig. 6.4-2 TVSS Reduction vs Influent TVSS Concentration

6.5 TOTAL VOLATILE SOLIDS (TVS)

6.5.1 TVS Reduction as a Function of Temperature

Figure 6.5-1 illustrates total volatile solids reductions obtained at various bottomhole temperatures. Each point represents a composite sampling period at various operating conditions. The linear regression curve fit indicates an increasing TVS reduction with increasing temperature.

During the entire operating period, composite samples showed an average TVS reduction of 83.7%, with a maximum reduction of 97.5%. The average TVS reduction during autogenous operation was 93.9%.

6.5.2 TVS Reduction as a Function of Concentration

TVS reduction dependency on reaction vessel influent concentration is shown in Figure 6.5-2. TVS reduction levels out at 93.3% at concentrations greater than 9100 mg/l.

6.6 TOTAL SUSPENDED SOLIDS (TSS)

6.6.1 TSS Reduction as a Function of Temperature

The influence of bottomhole temperature on suspended solids reduction is presented in Figure 6.6-1. The curve fit suggests increasing TSS reduction with increasing temperature, as expected. The wide scatter illustrates the fact that high temperatures alone will not insure high reduction. For a constant bottomhole temperature, the high reductions are obtained at generally higher TSS concentrations, while the low reductions are at lower TSS concentration.

TSS reductions averaged 69.8% based on composite sampling for the entire operating period, with a high of 91.5%. During autogenous operation, TSS reductions averaged 78.7%.

6.6.2 TSS Reduction as a Function of Concentration

TSS reductions ranged from 45-91% and are shown in Figure 6.6-2. As illustrated by the curve fit, reductions increased with increasing concentration up to 7400 mg/l, at which point the TSS reduction leveled out at 79.0%.

6.6.3 Effect of the Demonstration Facility on WWTP TSS Removal

Longmont TSS data were collected daily for each operating stage from December 1984 to September 1985. TSS values were averaged over the entire period with results shown previously in Table 6.4-1. Average percent removals for TSS from WWTP influent to effluent were 82.1% with the VRV System operating and 81.4% with VRV system shutdown. VRV System

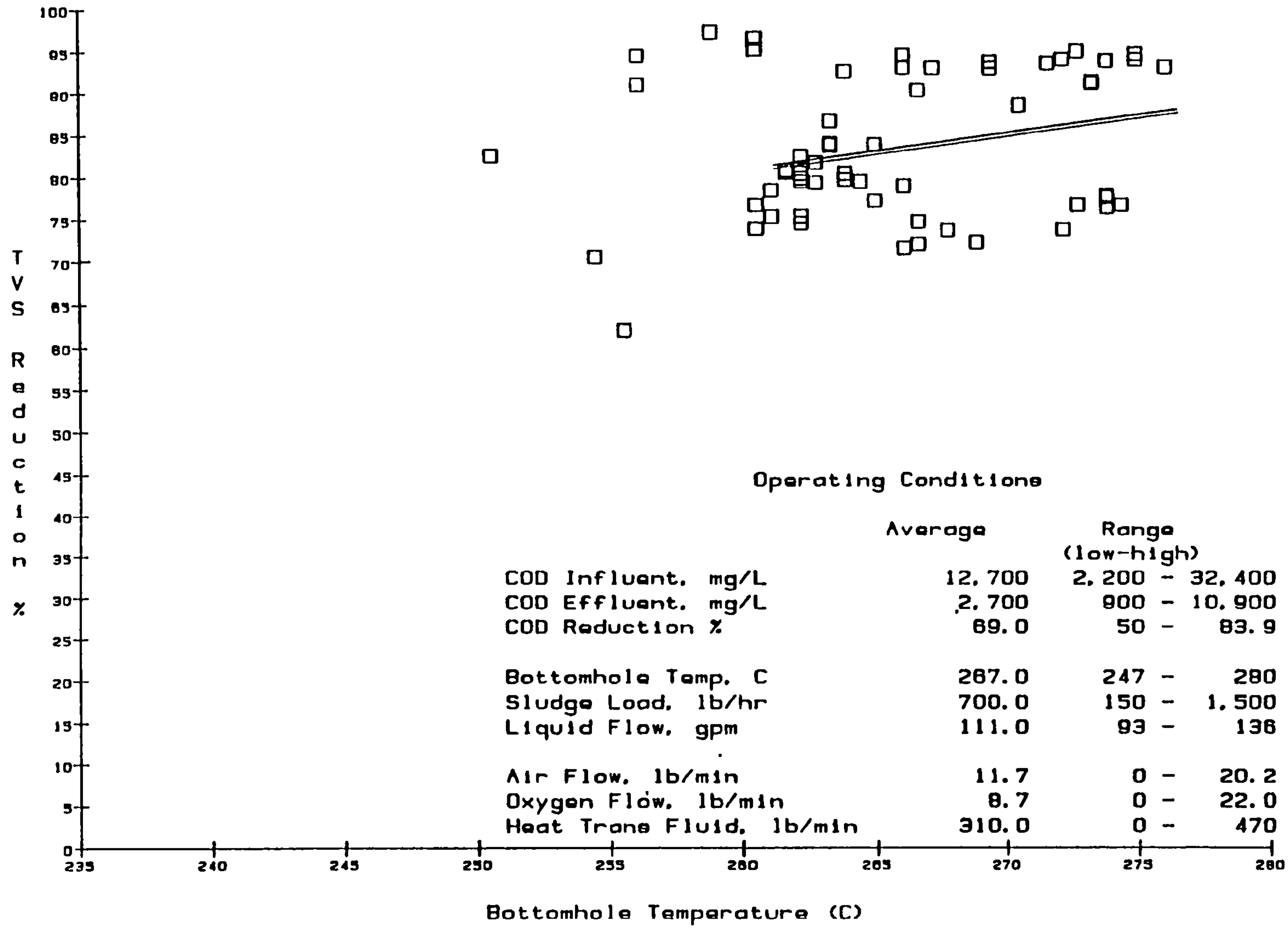


Fig. 6.5-1 TVS Reduction vs Bottomhole Temperature

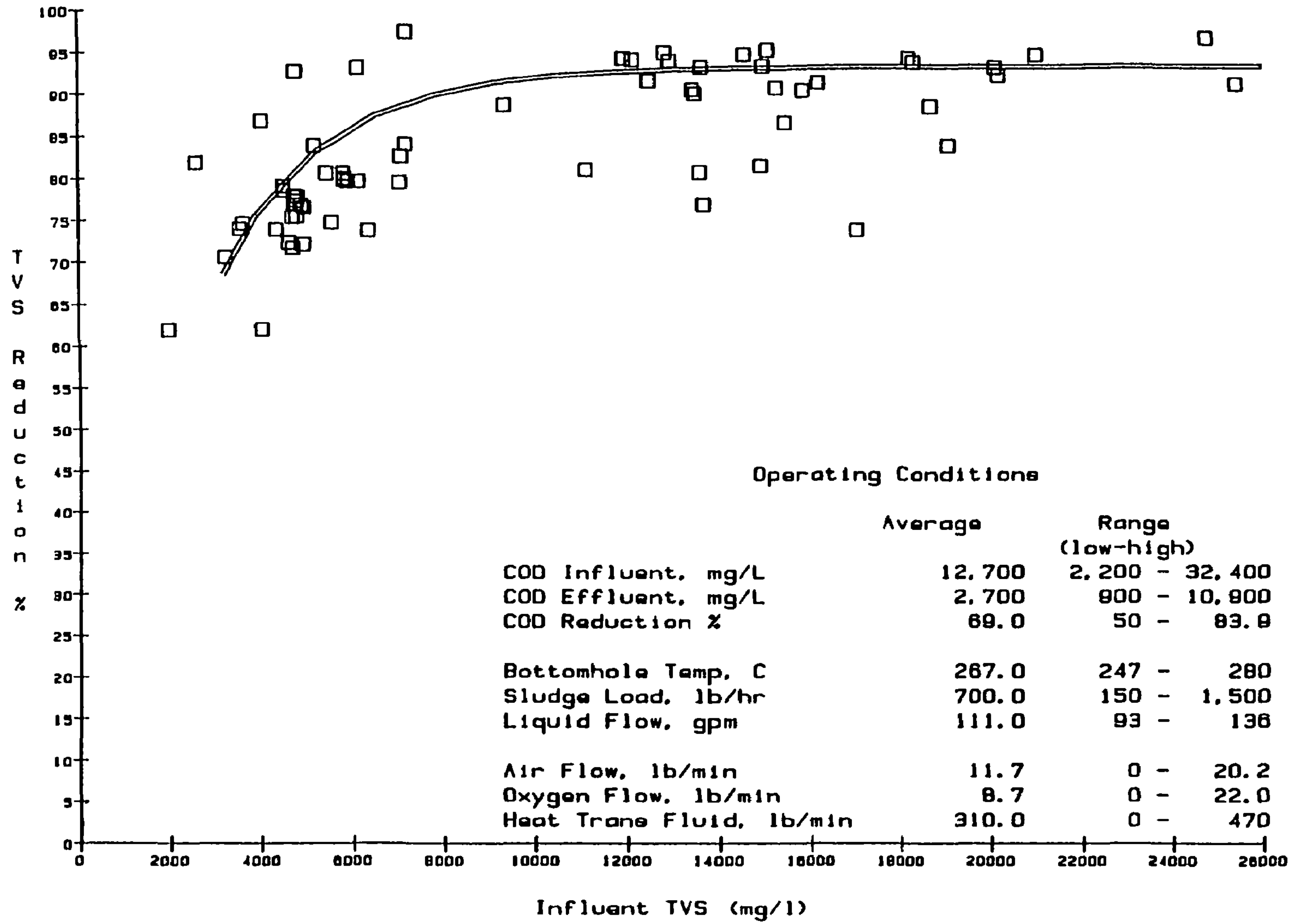


Fig. 6.5-1 TVS Reduction vs Bottomhole Temperature

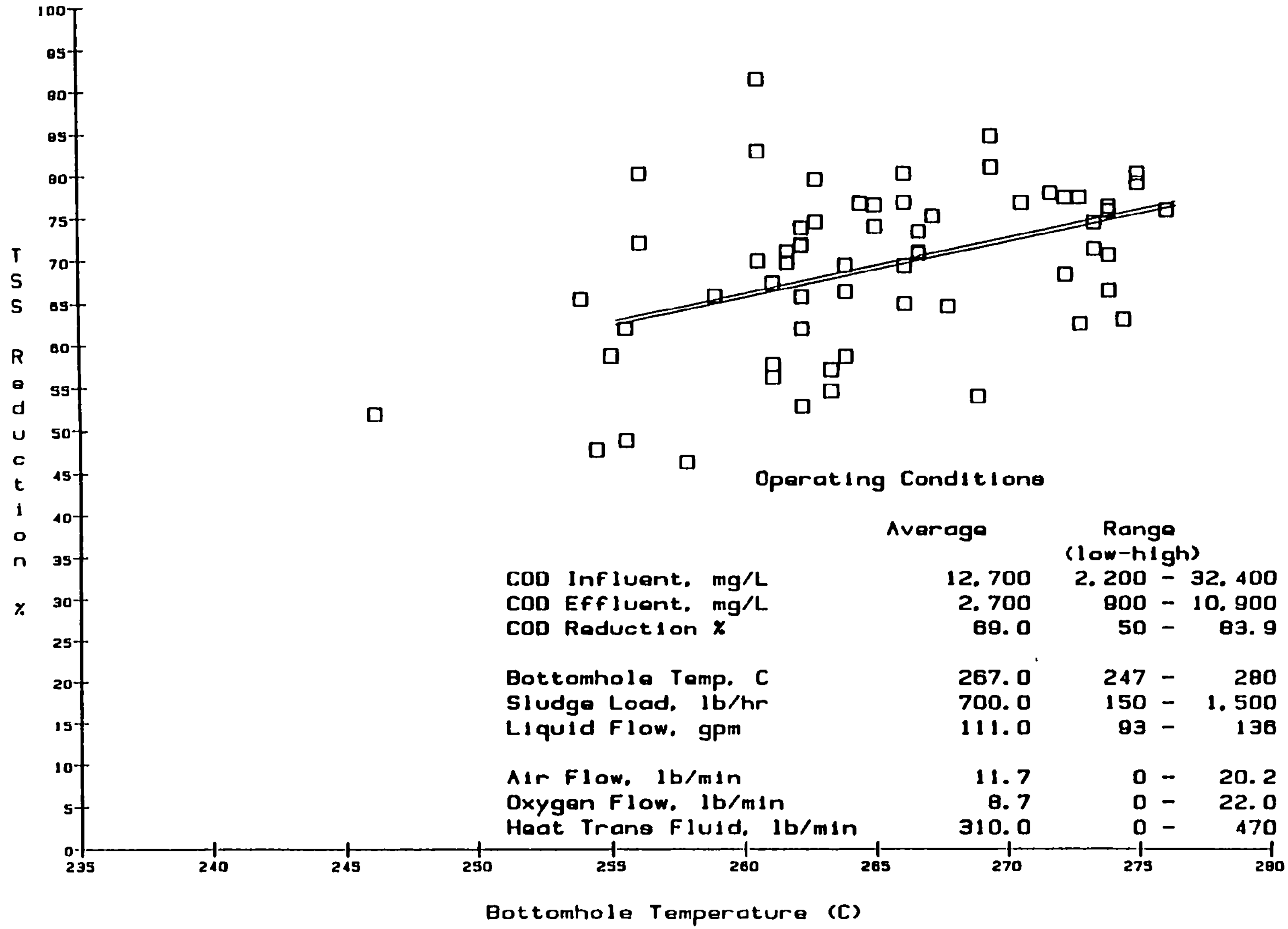


Fig. 6.6-1 TSS Reduction vs Bottomhole Temperature

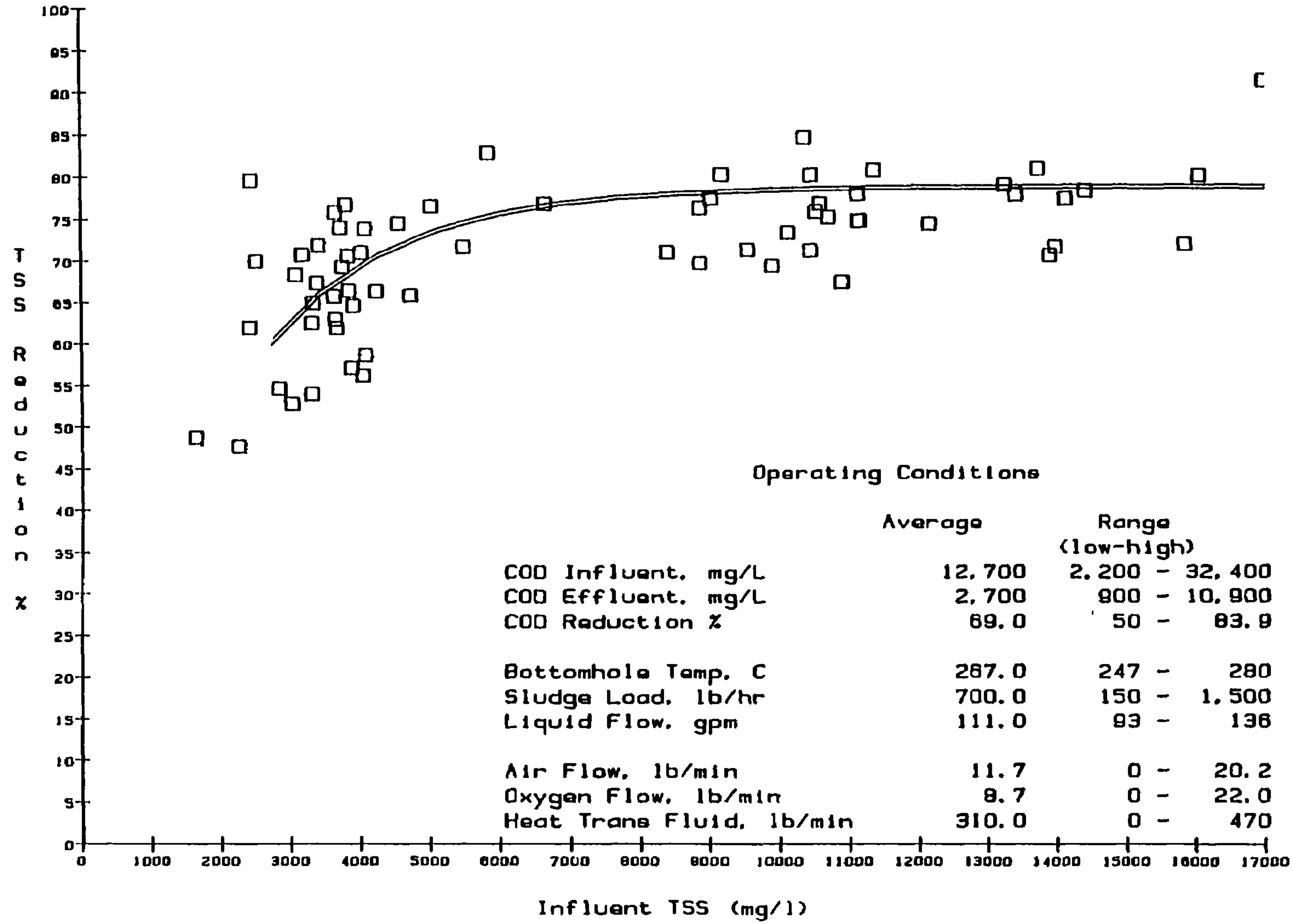


Fig. 6.6-2 TSS Reduction vs Influent TSS Concentration

operation had no significant effect on overall TSS removal in the WWTP. The Longmont WWTP was able to produce a final effluent TSS within its NPDES Discharge Permit Limitations of 30 mg/L,. whether or not the VRV System was operating.

6.7 BIOCHEMICAL OXYGEN DEMAND TOTAL (BODT)

6.7.1 Effect of VRV Recycle on BODT Reduction

During autogenous operating periods in March and April 1985, composite samples of reaction vessel influent and effluent were analyzed for CODT and carbonaceous BOD_5 to determine the effect of recycling VRV effluent.

Removal rates based on concentrations of VRV influent and effluent (mg/L) from 12 tests with no recycle (Table 6.7-1) and 5 tests with varying amounts of recycle (Table 6.7-2) show that a 5% decrease in CODT and BODT reductions occurred when recycling. However, removal rates based on actual mass of sludge processed show that recycling provides an additional 10% reduction in BODT (Tables 6.7-3 and 6.7-4), and a 6% reduction in CODT (Tables 6.7-5 and 6.7-6).

TABLE 6.7-1
LONGMONT CODT/BODT REDUCTIONS
AUTOGENOUS WITHOUT RECYCLE

CODT S-3 (mg/L)	CODT S-4 (mg/L)	% Reduction CODT S-3 to S-4	BODT S-3 (mg/L)	BODT S-4 (mg/L)	% Reduction BODT S-3 to S-4
15,920	3,980	75.0	---	---	---
25,720	4,590	81.8	7,450	3,000	59.7
20,530	4,240	79.3	6,500	2,980	54.2
15,250	3,240	78.8	5,640	2,250	60.1
18,410	4,370	76.3	5,650	3,230	43.9
23,590	5,020	78.7	9,000	3,650	59.4
16,040	3,220	79.9	5,720	2,230	61.0
31,860	6,480	80.0	9,200	4,620	49.8
24,300	4,550	81.3	7,050	2,950	58.2
16,110	3,160	80.4	5,430	2,230	58.9
19,640	3,470	82.3	6,400	2,640	58.8
19,670	3,970	79.5	6,130	2,780	54.6
	Average	78.7		Average	56.2

TABLE 6.7-2
LONGMONT CODT/BODT REDUCTIONS
AUTOGENOUS WITH RECYCLE

CODT S-3 (mg/L)	CODT S-4 (mg/L)	% Reduction CODT S-3 to S-4	BODT S-3 (mg/L)	BODT S-4 (mg/L)	% Reduction BODT S-3 to S-4
18,930	6,060	68.0	---	---	---
24,780	5,790	76.6	8,520	4,210	50.6
19,230	5,230	72.8	7,860	3,690	53.0
20,010	5,300	73.5	6,790	4,020	40.8
20,950	4,740	77.4	8,220	3,180	61.3
	Average	73.7		Average	51.4

TABLE 6.7-3
LONGMONT BODT REDUCTIONS
AUTOGENOUS WITHOUT RECYCLE

BODT/HOUR FED (S-3) kg	(lb)	BODT/HOUR DISCHARGED (S-4) kg	(lb)	kg BODT CONSUMED / kg BODT FED	AVERAGE TEMPERATURE °C	(°F)
170.5	(376)	71.2	(157)	0.582	272	(523)
175.0	(386)	82.9	(183)	0.526	277	(531)
156.9	(346)	64.8	(143)	0.587	276	(529)
159.2	(351)	92.0	(203)	0.422	268	(515)
234.5	(517)	98.4	(217)	0.580	274	(526)
140.1	(309)	56.7	(125)	0.596	275	(527)
193.6	(427)	101.6	(224)	0.475	274	(525)
148.7	(328)	64.8	(143)	0.764	279	(535)
122.9	(271)	52.6	(116)	0.572	269	(516)
155.1	(342)	66.2	(146)	0.573	276	(528)
147.4	(325)	69.4	(153)	0.529	270	(518)
			Average	0.546		

TABLE 6.7-4
LONGMONT BODT REDUCTIONS
AUTOGENOUS WITH RECYCLE

BODT/HR S-1 kg (lb)	BODT/HR S-2 kg (lb)	BODT/HR TO VRV kg (lb)	BODT/HR S-4 kg (lb)	BODT CONSUMED / BODT S-1	TEMP. °C (°F)
--- ---	--- ---	--- ---	--- ---	---	264 (507)
--- ---	--- ---	--- ---	--- ---	---	252 (485)
159.7 (352)	39.1 (86.2)	198.7 (438)	108.1 (225)	0.605	277 (530)
170.1 (375)	43.5 (95.8)	213.6 (471)	103.9 (229)	0.645	268 (514)
130.6 (288)	59.9(132.0)	190.5 (420)	116.6 (257)	0.566	274 (526)
154.7 (341)	44.7 (98.5)	199.6 (440)	79.9 (176)	0.774	273 (524)
			Average	0.648	

Assumes S-2 (recycle) concentrations are equal to S-4 concentrations.

TABLE 6.7-5
LONGMONT CODT REDUCTIONS
AUTOGENOUS WITHOUT RECYCLE

CODT/HR FED (S-3) kg	(lb)	CODT/HR DISCHARGED (S-4) kg	(lb)	kg CODT CONSUMED / kg CODT FEED	AVERAGE TEMPERATURE °C	(°F)
383.0	(844)	99.3	(219)	0.740	257	(495)*
578.8	(1,276)	109.3	(241)	0.811	272	(523)
553.8	(1,221)	118.4	(261)	0.786	277	(531)
525.5	(938)	92.9	(205)	0.781	276	(529)
509.4	(1,123)	124.7	(275)	0.755	268	(515)
615.1	(1,356)	135.6	(299)	0.779	274	(525)
392.4	(865)	81.6	(180)	0.792	275	(527)
671.3	(1,480)	142.4	(314)	0.788	274	(525)
512.1	(1,129)	99.8	(220)	0.805	279	(535)
365.1	(805)	74.4	(164)	0.796	269	(516)
476.7	(1,051)	87.1	(192)	0.817	276	(529)
472.6	(1,042)	98.9	(218)	0.791	270	(518)
			Average	0.791		

*Low temperature not included in average.

TABLE 6.7-6
LONGMONT CODT REDUCTIONS
AUTOGENOUS WITH RECYCLE

CODT/HR S-1 kg (lb)	CODT/HR S-2 kg (lb)	CODT/HR TO VRV kg (lb)	CODT/HR S-4 kg (lb)	CODT CONSUMED CODT S-1	TEMP. °C (°F)
367.4 (810)	104.3 (230)	471.7 (1040)	156.5 (345)	0.858	264 (507)
263.1 (580)	76.2 (168)	339.3 (748)	134.7 (297)	0.778*	252 (485)
524.4 (1156)	54.0 (119)	578.3 (1275)	140.2 (309)	0.836	277 (530)
461.3 (1017)	61.7 (136)	523.0 (1153)	147.0 (324)	0.815	268 (514)
483.1 (1061)	79.4 (175)	562.5 (1240)	153.8 (339)	0.846	274 (526)
441.4 (973)	66.7 (147)	508.0 (1120)	119.3 (263)	0.881	524 (524)
			Average	0.847	

*Low temperature not included in average.
Assumes S-2 (recycle) concentrations are equal to S-4 (effluent) concentrations.

6.7.2 Effect of VRV System Operation on the BODT in Longmont WWTP

Figure 6.7-1 illustrates the overall Longmont WWTP flow diagram and the point at which the VRV System's effluent was returned upstream of the trickling filter. Daily composite samples were collected and analyzed for BODT and BODS during the test program.

Average BODT and BODS concentrations are presented in Table 6.7-7 for each WWTP process with and without the VRV System operating during the period from December 1984 to September 1985. This is the same period used for the analysis in Table 6.4-1. An average increase of 38 mg/L BODT and 25 mg/L BODS was found at the trickling filter influent where VRV effluent was returned. When the VRV System did not operate, Longmont sludge was sent to the digesters. Digester supernatant was land applied and not returned for secondary treatment. Therefore, when the reaction vessel was operating, secondary treatment was able to handle the increased load due to the VRV effluent. Increased loading to the WWTP shows a slightly decreased overall efficiency in BODT and BODS removals.

Percent removals for each stage of the secondary treatment process for the period of December 1984 to September 1985 are presented in Table 6.7-8.

Percent removals calculated for BODT show VRV System operation had little effect on the primary clarifier. The removal rates through the trickling filter were much better with the system operating even though

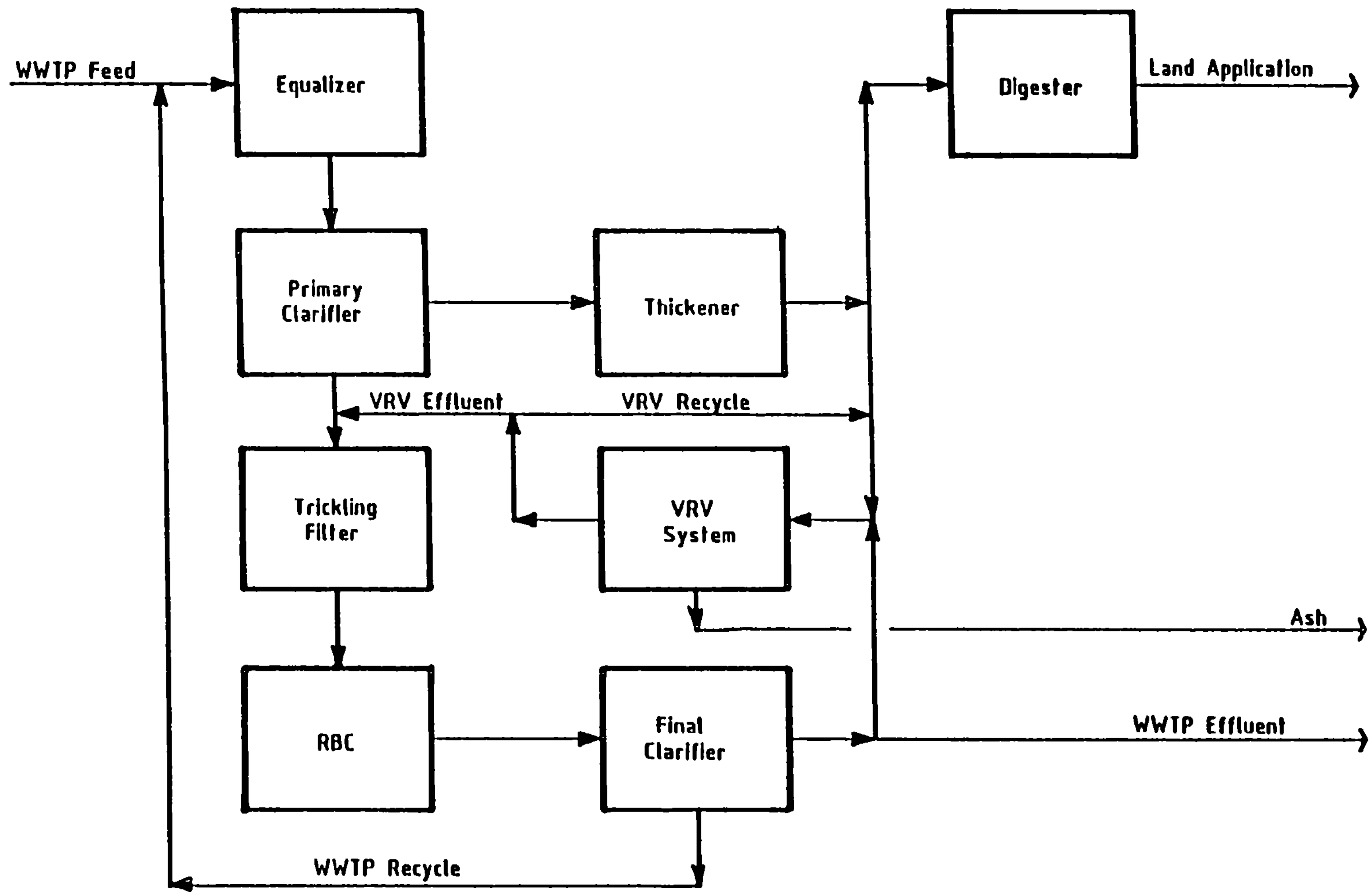


Fig. 6.7-1 Longmont WWTP Flow Diagram

TABLE 6.7-7
BOD_5 CONCENTRATION FOR LONGMONT WWTP
December 1984 - September 1985

	WITHOUT VRV SYSTEM 109 DATA DAYS		WITH VRV SYSTEM 116 DATA DAYS	
	BODT mg/L	BODS mg/L	BODT mg/L	BODS mg/L
Influent	185	73	181	75
Equalization Basin Effluent	260	69	265	66
Primary Clarifier Effluent	131	57	134	56
Trickling Filter Influent	136	55	174	80
Trickling Filter Effluent	109	35	126	49
Rotating Biological Contactor Effluent	87	21	102	30
Final Clarifier Effluent	21	13*	30	17*
Average Percent Removal	88.7%	82.2%	83.4%	77.3%

* BODS average is from December 1984 to May 1985 only.

TABLE 6.7-8
BOD PERCENT REMOVAL
FOR LONGMONT WWTP
December 1984 - September 1985

	% REMOVAL			
	WITHOUT VRV SYSTEM 109 DATA DAYS		WITH VRV SYSTEM 116 DATA DAYS	
	BODT	BODS	BODT	BODS
Primary Clarifier	49.6	17.4	49.4	15.2
Trickling Filter	19.9	36.4	27.6	38.8
Rotating Biological Contactor	20.2	40.0	19.1	38.8
Final Clarifier	75.9	38.1	70.1	43.3
Trickling Filter Influent to Final Clarifier Effluent	84.6	76.4	82.8	78.8

approximately 38 mg/L BODT was added from the VRV effluent return. The rotating biological contactor efficiency for BODT removal was about the same with the VRV System operating. A decrease in BODT removal was seen at the final clarifier. A drop in removal efficiency through the final clarifier with the VRV System operating can be attributed to additional loading placed on an undersized clarifier.

Percent removal was calculated from daily BODT analyses from January through April 1984, before VRV System start-up. These values were compared with BODT analyses and percent removals for January through April 1985 while the system operated nearly every day. This analysis, presented in Table 6.7-9, determines the effect of the VRV System operation on the efficiency of the WWTP processes. The average percent removals during 1985 are consistently higher than corresponding values in 1984 for all WWTP processes. This indicates that an increased BODT removal rate was accomplished through the WWTP with the VRV System operating. Increased biomass in the trickling filter probably accounts for the increased efficiency during 1985.

TABLE 6.7-9
WWTP MONTHLY AVERAGE BODT

DATE	PRIMARY CLARIFIER Effluent mg/L	TRICKLING FILTER Influent mg/L	TRICKLING FILTER Effluent mg/L	TRICKLING FILTER % Removal	ROTATING BIOLOGICAL CONTACTOR Effluent mg/L	ROTATING BIOLOGICAL CONTACTOR % Removal	FINAL CLARIFIER Effluent mg/L	FINAL CLARIFIER % Removal
1984								
JAN	153	153	125	18.3	112	10.4	31	72.3
FEB	140	140	116	17.1	101	12.9	26	74.3
MAR	137	137	118	13.9	101	14.4	25	75.3
APR	123	123	109	11.4	91	16.5	27	70.3
1985								
JAN	137	158	123	22.2	93	24.4	24	74.2
FEB	148	154	127	17.5	108	15.0	24	77.8
MAR	148	181	146	19.3	123	15.8	26	78.9
APR	138	174	140	19.5	115	17.9	30	73.9

To smooth out the daily variation in BODT influent loading and present the results graphically, daily BODT loading on the WWTP influent during January to April 1984 and 1985 was plotted for each day of the week, Figures 6.7-2 through 6.7-8. Table 6.7-10 gives a statistical analysis of the daily and arithmetic mean values. The least scatter in data was observed for Friday data points, Figure 6.7-7. Using Friday data only, and an average of 0.2 kg BODT returned per kg sludge processed, percent removal was calculated and compared to the average percent removal without the VRV System operating. Figures 6.7-9, 6.7-10, and 6.7-11 show the average percent removal of BODT for Fridays for each of the secondary processes. Each of the squares on the plot represents a percent removal at a specific sludge feed rate to the VRV. The double line is a best-fit through these squares. Figure 6.7-9 shows an increase in percent removal of BODT in the trickling filter with the VRV System operating and also shows steady removal at high reaction vessel feed rates. Figure 6.7-10 shows slightly lower percent removals in the RBC with the system operating. Figure 6.7-11 shows a small decrease in the final clarifier effluent removal with VRV operating.

Based on these analyses, VRV System's effluent return to the WWTP improved the efficiency of the secondary processes and maintained an effluent quality that met the NPDES Specifications. The improved secondary BODT removal efficiencies allowed the WWTP to process returned effluent when the VRV System treated up to 18,000 kg/day (20 TPD) of sludge.

TABLE 6.7-10
STATISTICAL ANALYSIS OF LONGMONT WWTP
INFLUENT BODT LOADING BY DAY
(BODT lb/day Influent)

	AVERAGE	STANDARD DEVIATION	MAXIMUM	MINIMUM	RANGE
DAILY	10,750	2,210	17,390	4,400	12,990
Sunday	10,140	2,440	16,340	5,690	10,660
Monday	11,280	2,110	15,870	8,010	7,850
Tuesday	10,760	2,340	15,510	4,400	11,110
Wednesday	11,090	2,570	17,390	5,690	11,700
Thursday	10,290	1,880	13,490	6,910	6,580
Friday	10,800	1,710	15,370	7,000	8,370
Saturday	10,860	2,290	16,680	7,010	9,670

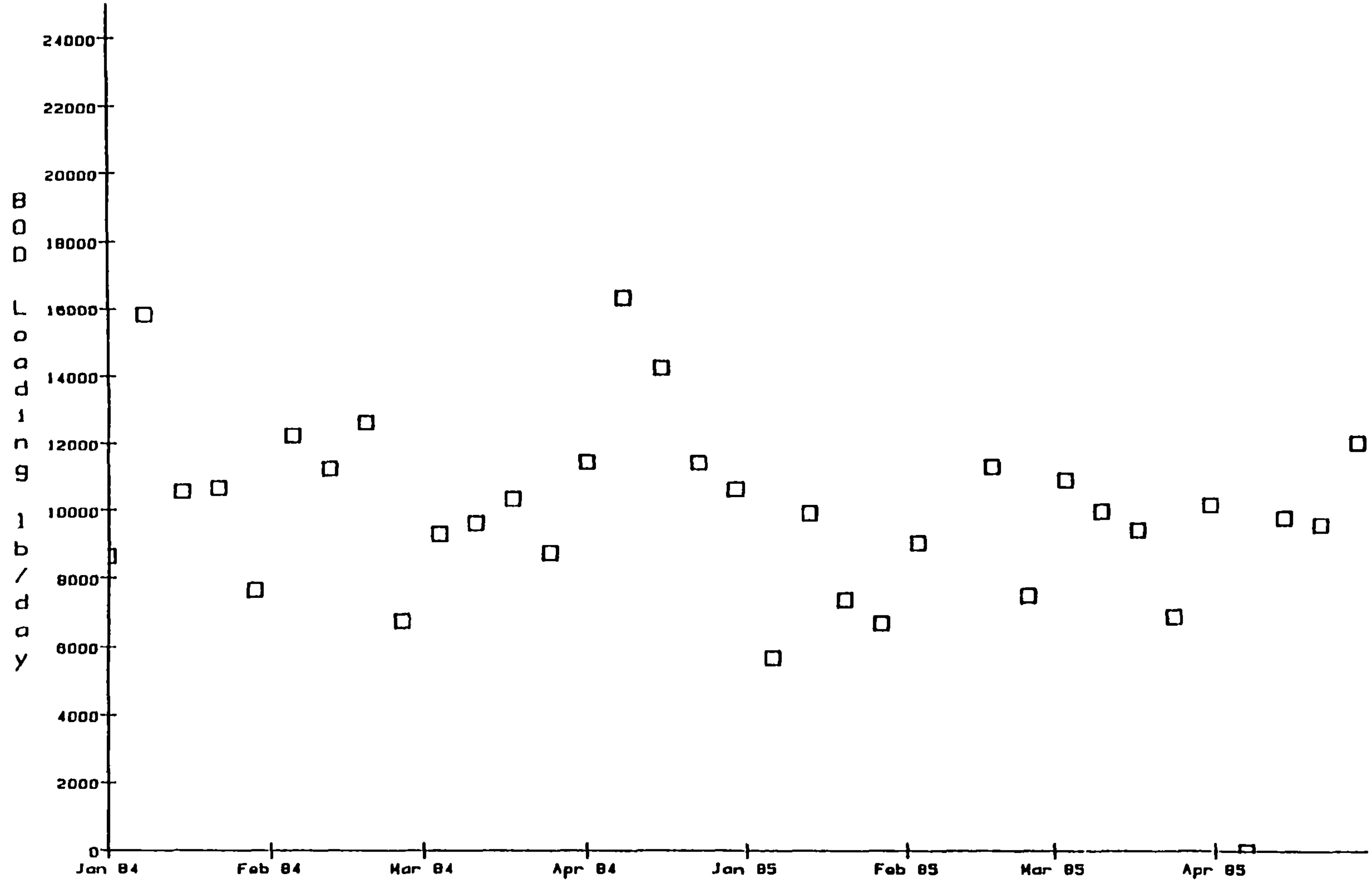


Fig. 6.7-2 Influent Plant BODT Load
Sundays Only

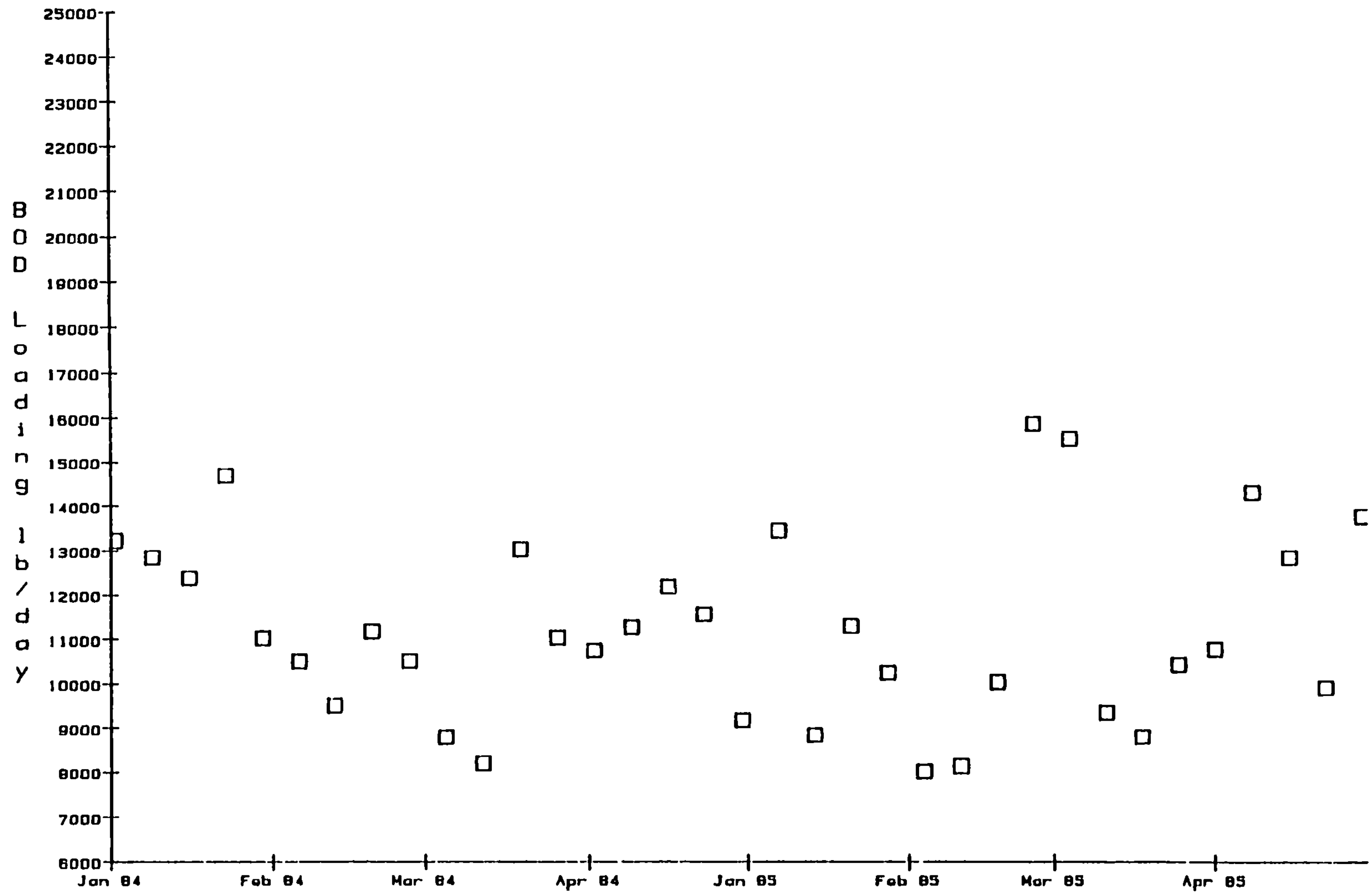


Fig. 6.7-3 Influent Plant BODT Load
Mondays Only

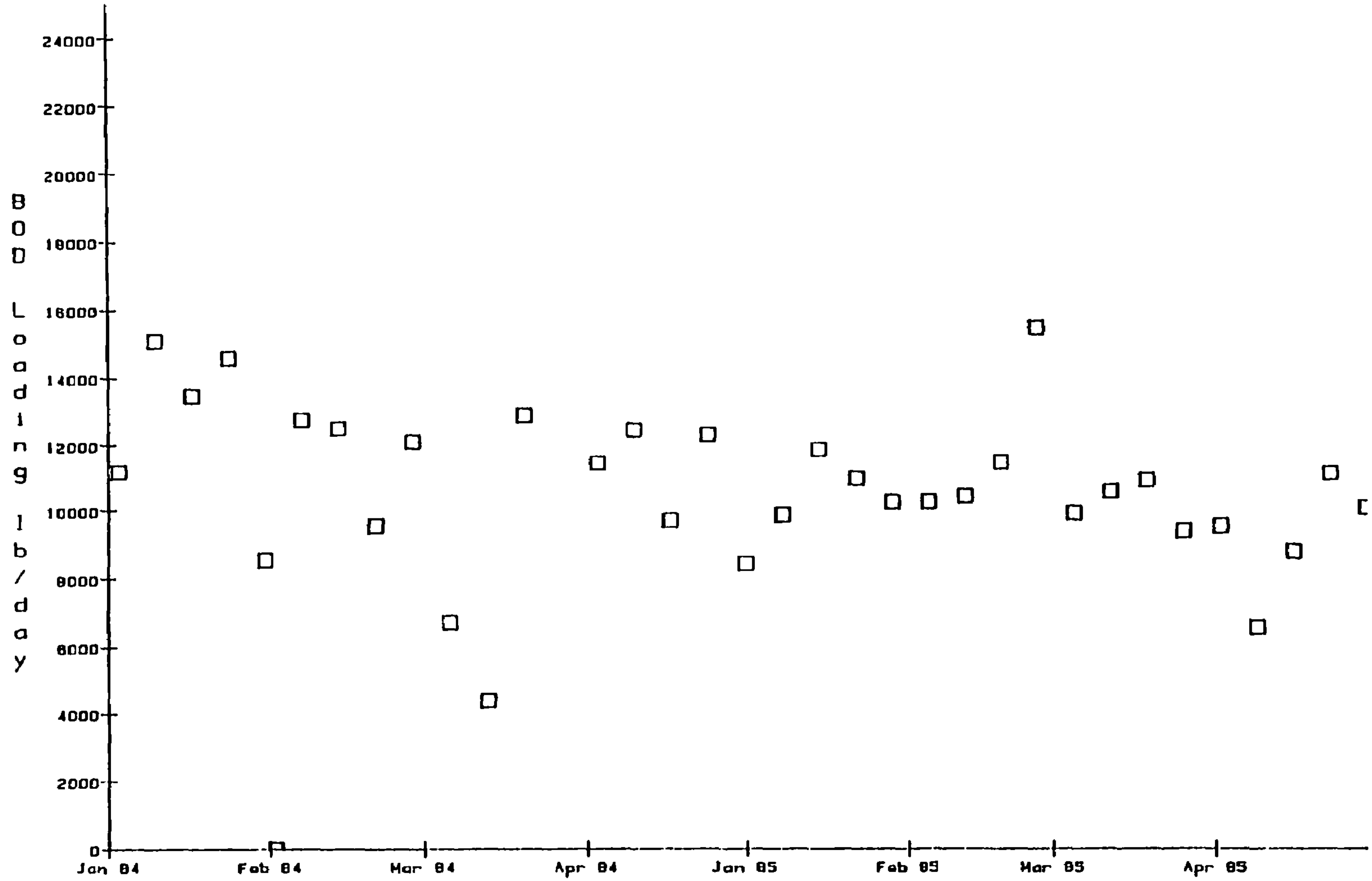


Fig. 6.7-4 Influent Plant BODT Load
Tuesdays Only

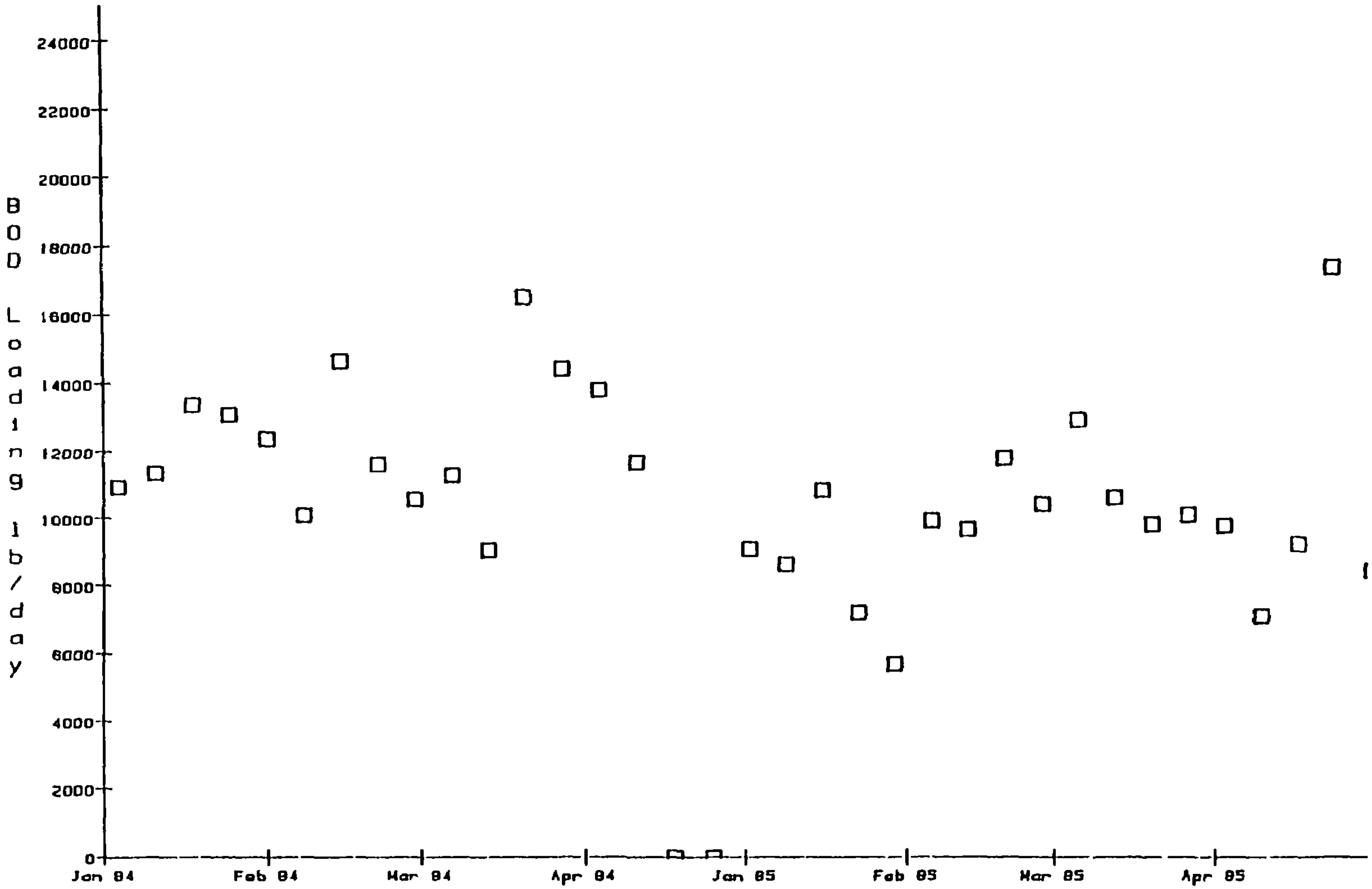


Fig. 6.7-5 Influent Plant BODT Load
Wednesdays Only

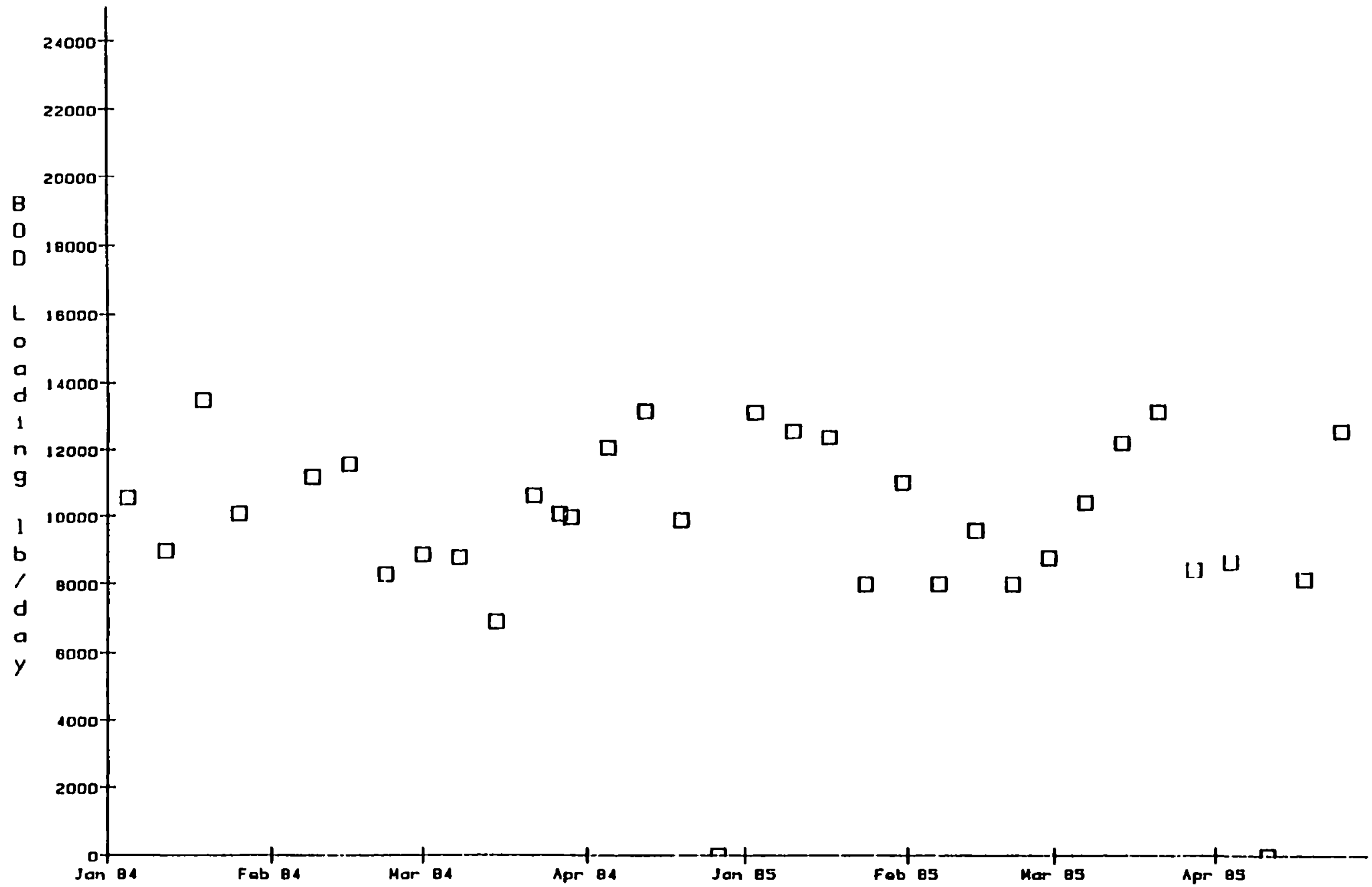


Fig. 6.7-6 Influent Plant BODT Load
Thursdays Only

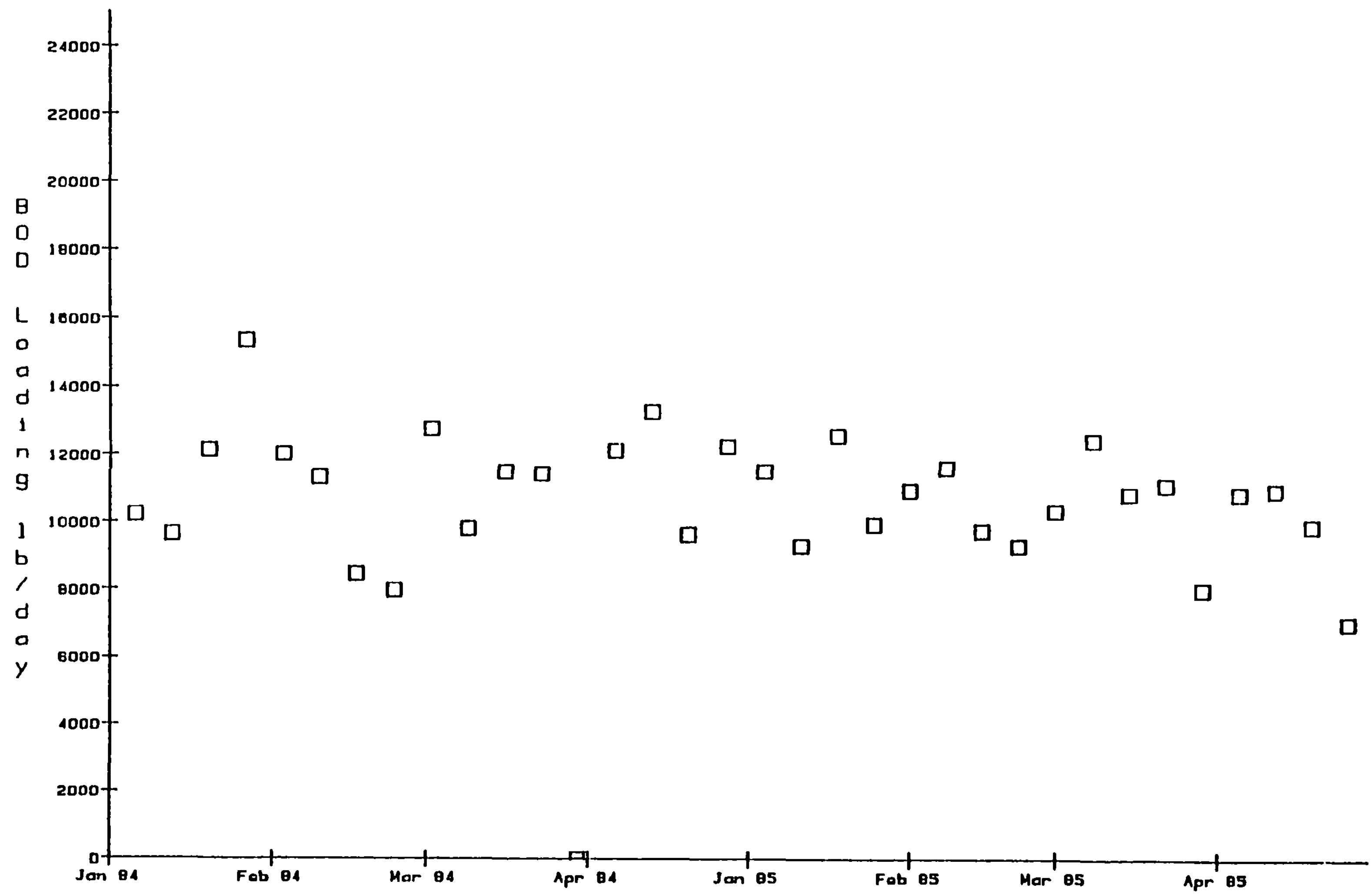


Fig. 6.7-7 Influent Plant BODT Load
Fridays Only

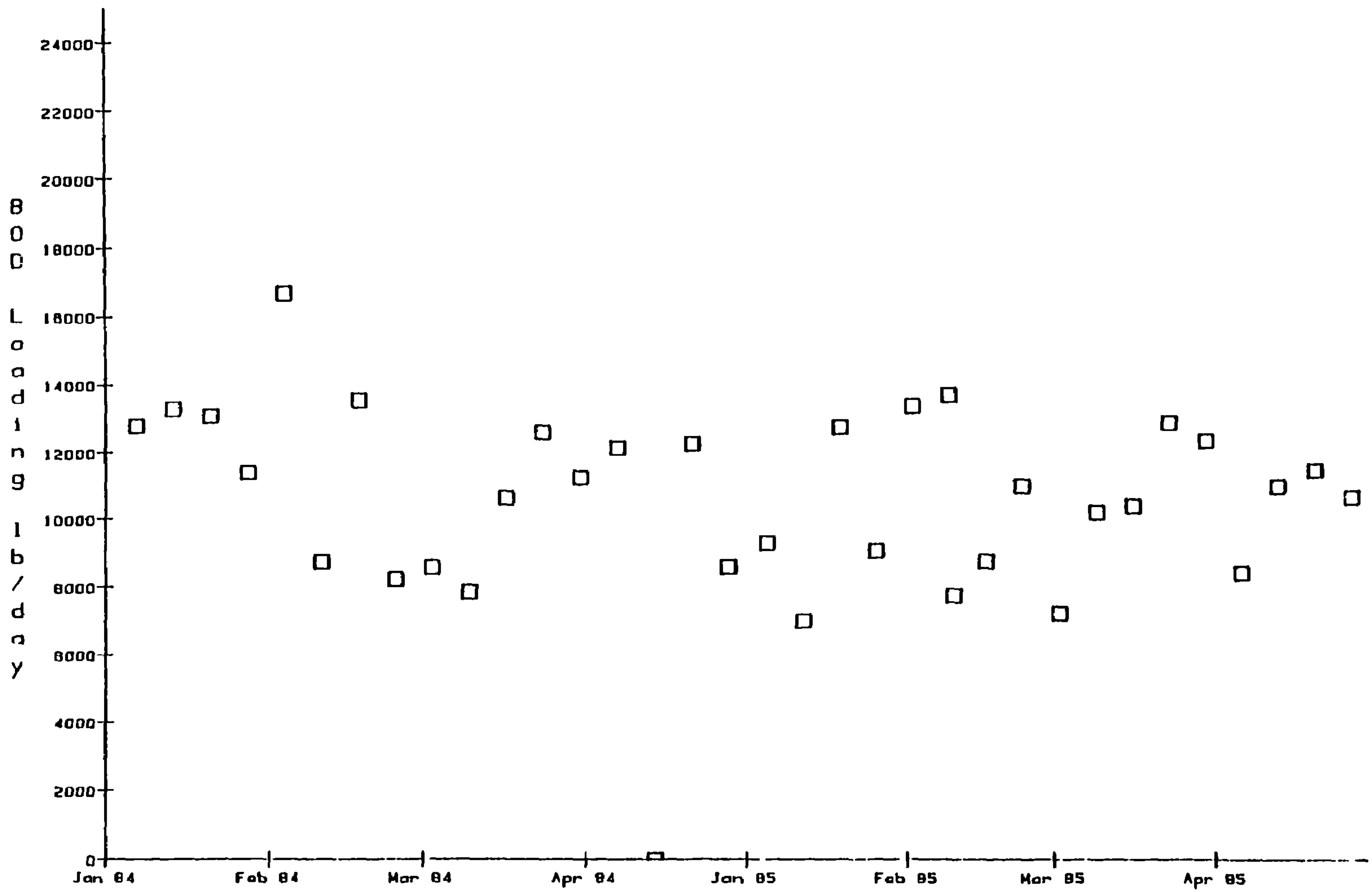


Fig. 6.7-8 Influent Plant BODT Load
Saturdays Only

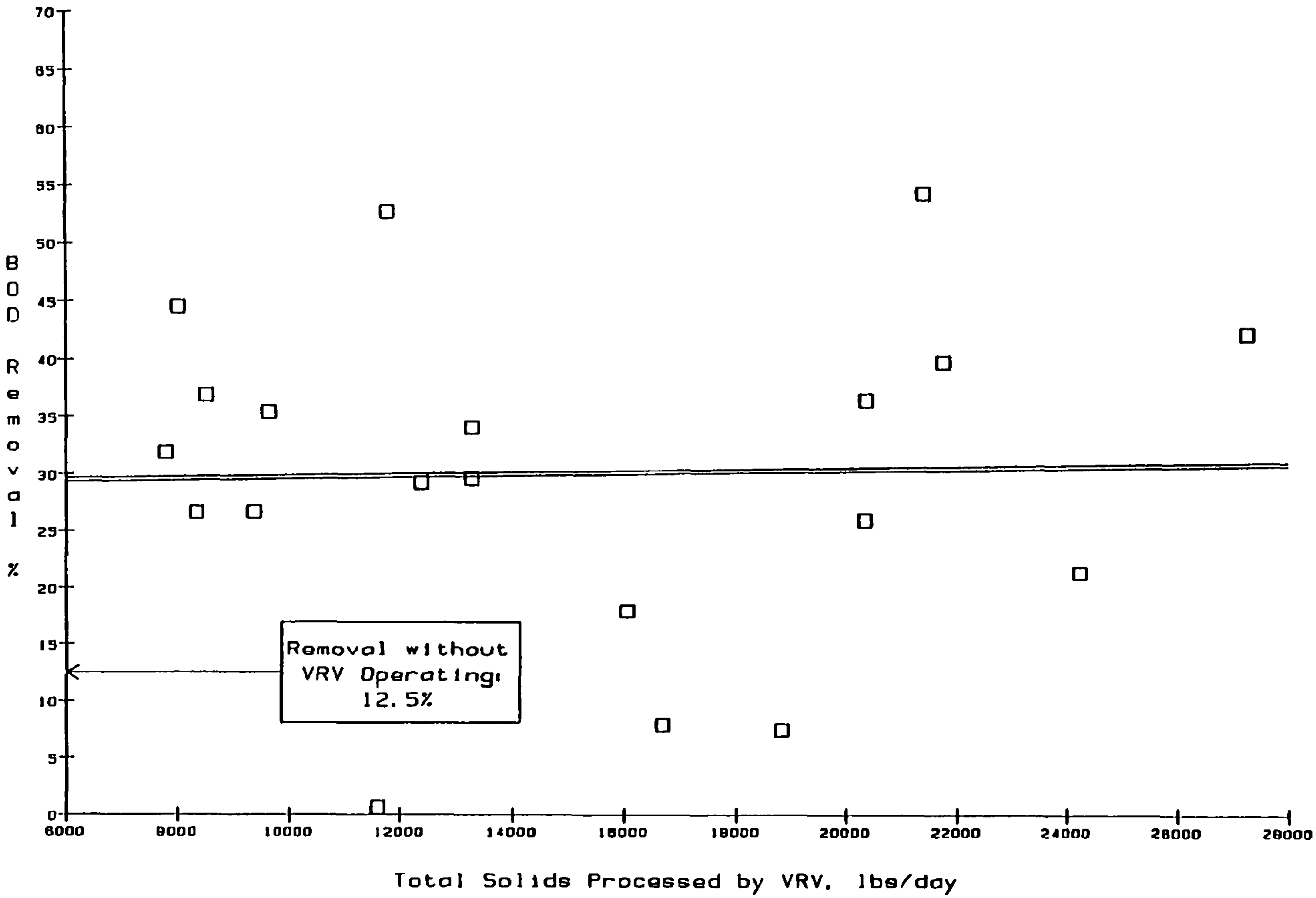


Fig. 6.7-9 Trickling Filter Efficiency
Friday Operation Only

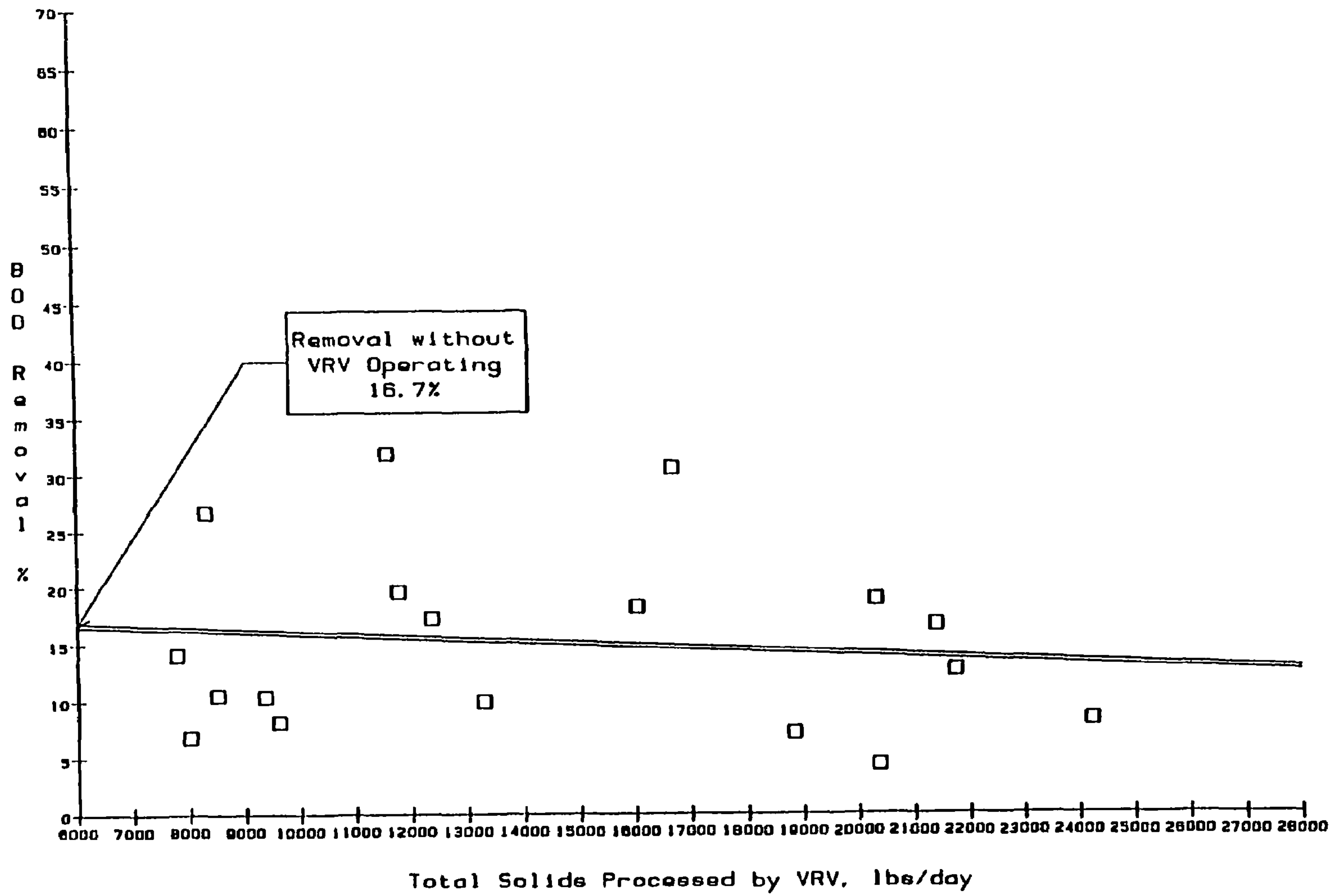


Fig. 6.7-10 Rotating Biological Contactor Efficiency
Friday Operation Only

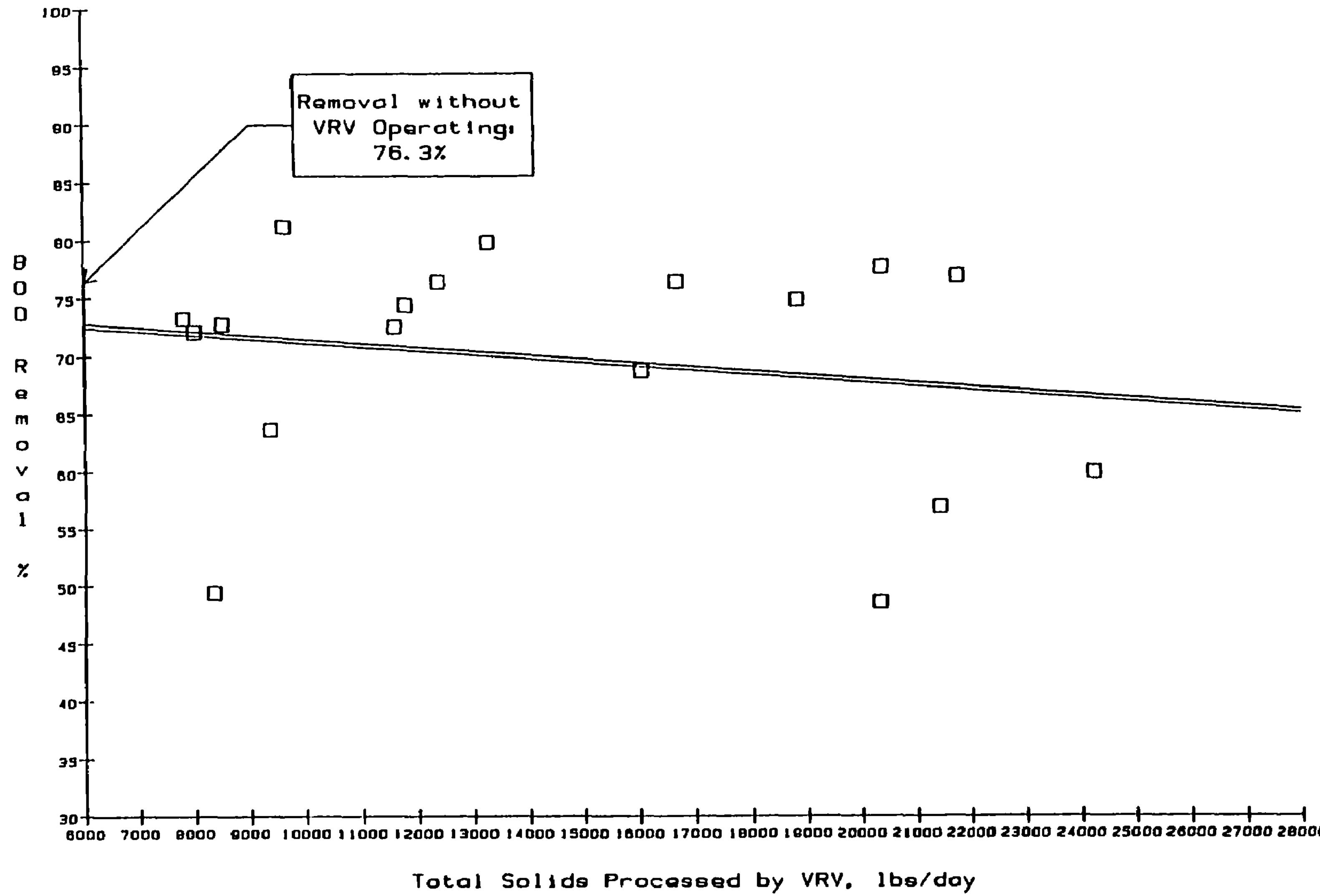


Fig. 6.7-11 Final Clarifier Efficiency
Friday Operation Only

6.8 ACID WASHES

6.8.1 Effect of Inorganic Scaling

Inorganic scale forms in the VRV. If present in the sludge feed, elements such as calcium, magnesium, and aluminum form inorganic salts which plate out on the VRV walls. The inverse solubility of these components causes them to deposit at the higher temperature levels, near the bottom. Because of the relatively low liquid velocity, deposits can accumulate as thick as 1-2 cm before there is an appreciable pressure drop associated with the scale.

Scale reduces heat transfer in the VRV. If the VRV is operated for an extended period without an acid wash, scale build-up increases the temperature difference between the downcomer and upcomer streams across the divider tube.

6.8.2 Removing Inorganic Scale Materials

A proprietary procedure for scale removal was developed which efficiently removed the scale from the VRV, restoring it to initial conditions. A nitric acid solution is used to clean the VRV, removing all of the scale and restoring the heat transfer capabilities. Table 6.8-1 summarizes the amount of acid solution used each month, and the amount of scale removed. The acid solution was neutralized in the acid wash pits before returning to the Longmont WWTP.

TABLE 6.8-1
ACID WASHES

YEAR	MONTH	ACID SOLUTION (Gallons)	SCALE REMOVED (lbs)
1984	June	1,695	---
	July	4,170	4,280
	August	2,220	2,030
	September	1,830	4,700
	October	1,800	8,010
	November	955	7,840
	December	3,560	10,880
1985	January	2,160	8,280
	February	1,410	7,290
	March	3,060	4,120*
	April	4,390	16,740*
	May	2,070	8,050
	August	700	3,080
	September	920	3,690

*Total includes one acid wash with no scale removal data.

6.9 AMMONIA

6.9.1 The Effect of the VRV System on Ammonia/Nitrogen Discharge Levels

The operating conditions during aqueous-phase oxidation converted the major portion of organically bound nitrogen in the biological sludge to soluble TKN and ammonia.

6.9.2 Effluent Recycle Effects

As shown in Tables 6.9-1 and 6.9-2, lower ammonia concentrations were observed during recycle. When recycling, an average of 0.026 kg ammonia nitrogen per kg sludge processed was returned to the WWTP. Effluent recycling increased overall organic nitrogen removal and reduced the overall ammonia nitrogen returned to the WWTP by as much as 20%. Table 6.9-2 presents NH_3-N produced during autogenous operating periods without oxidation effluent recycle. An average of 0.033 kg ammonia nitrogen per kg sludge processed was returned back to the WWTP.

Average daily analyses of ammonia nitrogen in the Longmont WWTP effluent are shown in Table 6.9-3 and 6.9-4. Increases of 6-7 mg/L NH_3-N during system operating periods correspond to an average of 0.035 kg NH_3-N per kg sludge processed. This agrees well with the average value of 0.033 kg NH_3-N per kg sludge given in Table 6.9-2. Ammonia nitrogen produced is carried through the plant and discharged. Ammonia removal was not addressed in the test program because ammonia limits were not exceeded during system operation. If lower ammonia effluent concentrations are required, steam stripping of the reaction vessel effluent using available heat from the process will reduce effluent concentrations to the lower levels necessary.

TABLE 6.9-1
AUTOGENOUS NH_3-N RETURNED TO WWTP
WITH RECYCLE

Date	SLUDGE FEED lb/hr	SLUDGE FEED kg/hr	NH3-N DISCHARGED lb/hr	NH3-N DISCHARGED kg/hr	kg NH_3-N Returned per Kg Sludge Fed
3/28/85	1466	666	28.7	13.0	0.020
3/31/85	1260	572	37.6	17.1	0.030
4/11/85	1085	493	30.7	13.9	0.028
Average	1270	577	32.3	14.7	0.026

TABLE 6.9-2
AUTOGENOUS NH_3-N RETURNED TO WWTP
WITHOUT RECYCLE

Date	SLUDGE FEED lb/hr	SLUDGE FEED kg/hr	NH3-N DISCHARGED lb/hr	NH3-N DISCHARGED kg/hr	kg NH_3-N Returned per Kg Sludge Fed
3/26-27/85	1437	652	52.1	23.6	0.036
4/1/85	1263	573	40.1	18.2	0.032
4/1/85	1183	537	36.3	16.5	0.031
4/4/85	1198	544	42.0	19.1	0.035
4/5/85	904	410	29.0	13.2	0.032
4/7/85	1342	609	52.6	23.9	0.039
4/7/85	1294	587	35.9	16.3	0.028
4/8/85	832	378	24.8	11.2	0.030
4/10-11/85	1155	524	37.3	16.9	0.032
4/11-12/85	1245	565	39.8	18.1	0.032
Average	1185	538	39.0	17.7	0.033

TABLE 6.9-3
LONGMONT WWTP OPERATION
WITHOUT VRV SYSTEM

MONTH/YEAR	DATA DAYS	WWTP AVERAGE EFFLUENT (m^3/hr)	WWTP AVERAGE EFFLUENT NH3-N(mg/L)	WWTP AVERAGE EFFLUENT NH3-N(kg/day)
December 1984	17	1025	16	394
January 1985	9	1009	17	412
February 1985	3	998	17	407
March 1985	10	978	18	422
April 1985	1	978	17	399

TABLE 6.9-4
LONGMONT WWTP OPERATION
WITH VRV SYSTEM

MONTH	DATA DAYS	AVERAGE EFFLUENT (m^3/hr)	AVERAGE SLUDGE (kg/day)	AVERAGE EFFLUENT NH_3-N (mg/L)	AVERAGE EFFLUENT NH_3-N (kg/day)	AVERAGE NH_3-N INCREASE (kg/day)	kg NH_3-N INCREASE PER kg SLUDGE PROCESSED
Dec.1984	14	1073	5176	22	567	173	0.033
Jan.1985	22	994	3450	23	549	137	0.040
Feb.1985	25	946	3178	23	522	115	0.036
Mar.1985	21	946	4903	25	568	146	0.030
Apr.1985	29	1025	6538	26	640	241	0.037
Average							0.035

6.10 OFF GAS

6.10.1 Major Components

Off-gases produced by the oxidation reaction can be divided into two categories: major and trace components. Major components consisted of carbon dioxide (CO_2), oxygen (O_2), nitrogen (N_2) and carbon monoxide (CO). Relative percentages of these components were largely dependent on whether compressed air or oxygen-enriched air was used. Table 6.10-1 shows off-gas analyses as determined by gas chromatograph sampling for various oxygen concentrations.

TABLE 6.10-1
OFF-GAS ANALYSES - MAJOR COMPONENTS

MAJOR COMPONENTS	OXYGEN CONCENTRATION 21%	42%	63%	100%
N_2	83.90	63.89	47.40	2.92
O_2	8.6	5.65	4.80	2.86
CO_2	4.18	28.84	43.00	90.23
CO	.13	1.62	2.50	3.97

6.10.2 Trace Components

An Industrial Hygiene Survey (See Appendix A) was conducted by Stearns-Catalytic Inc. to determine the type and quantity of trace compounds being emitted in the off-gas. Data presented in Table 6.10-2 were from high concentration oxygen testing. Table 6.10-2 lists chemical compounds identified to any significant level.

TABLE 6.10-2
TRACE OFF-GAS COMPONENTS

	MEASURED EXPOSURE LEVELS (ppm)	ESTABLISHED TLV AND/OR PEL (ppm)
Acetone	5 - 30	750
Furan	2 - 3	50
2-Butanone	3 - 4	200
2-Pentanone	1 - 2	200
1-Hexene	1 - 2	100
1-Heptene	1 - 2	400
Benzaldehyde	4.78	100
Furfural	0.34	2
Carbon Monoxide	5	50

All chemicals identified were in concentrations well below that of established and recognized exposure levels. The carbon monoxide airborne concentrations were not observed within the WWTP. Dispersion of carbon monoxide was rapid and efficient with no detectable quantities outside the VRV System battery limits (See Appendix A.). Sampling procedures and other physical characteristics of the trace components are given in detail in Appendix A.

6.11 ASH

6.11.1 Ash Content of Sludges Tested at Longmont

Several ash samples of Longmont sludge were collected and analyzed. Analysis of crystalline compounds was obtained by X-ray diffraction (XRD) and elemental composition by X-ray fluorescence (XRF). Table 6.11-1 contains the elemental compound percentages found in two different samples.

Sample No. 1 was obtained on June 27, 1984 while processing sludge at 231 °C. Sample No. 2 was obtained on August 8, 1985 while processing sludge at 246 °C. Compositions are similar with the exception of phosphorus (P) and potassium (K).

TABLE 6.11-1
ELEMENTAL ASH COMPOSITION (WT.%)

ELEMENT	SAMPLE NO. 1 June 27, 1984	SAMPLE NO.2 August 8, 1985
Al	16.85	10.7
P	16.43	5.8
Si	4.89	3.4
Ca	5.32	3.4
Fe	2.68	2.4
Mg	ND (1.5%)	1.6
K	5.84	0.5
Cu	0.60	0.5
Ti	0.31	0.3
S	0.18	0.1
Zn	0.12	0.1
Sr	0.12	0.1
Ce	0.05	0.1
Sn	ND	0.04
Pb	ND	0.02
Ni	0.03	0.01
Na	ND (6%)	ND (8%)
TOTAL	53.42%	29.07%

ND = Not detected.

6.11.2 Results of EP Toxicity Tests for Ash

Ash was analyzed for metals on a repeated basis for compliance with EPA's EP Toxicity Test. At all times heavy metal concentrations were lower than the acceptable limit set by EPA, usually by two orders of magnitude. Representative analyses are shown in Table 6.11-2.

6.11.3 Ash Dewatering

Liquid/solids separation at the Longmont plant employed a Lamella separator to concentrate the ash solids and return the clarified overflow back to the Longmont WWTP. Underflow from the Lamella plate separator was discharged into one of the three concrete pits. When a pit became full, supernatant was drained off and the ash allowed to dry by evaporation.

A solid bowl centrifuge was field tested and produced results given in Table 6.11-3. A clear centrate and a cake with 39-77% solids was produced. These were only initial tests, and centrifuge operation was not optimized. Figure 6.11-1 shows the relationship between centrifuge feed rate and percent solids. Further tests would better define the percent solids which would be obtained.

Table 6.11-2
RESULTS FROM EP TOXICITY TESTS FOR LONGMONT ASH (MG/L)

Test	EP Toxicity Test Limit	09/10/84	11/10/84		12/11/84		12/15/84	12/22/84		01/16/85		01/22/84	
		F ONLY	F	T	F	T	T ONLY	F	S	F	S	F	S
As	5.0	ND	ND	0.005	ND	0.003	0.009	0.055	0.007	0.008	0.004	0.032	0.001
				0.002		0.004				0.040	0.004		
Ag	5.0	0.41	0.17	0.08	0.08	0.02	0.03	0.07	0.025	0.1	0.01	0.1	0.02
			0.15	0.02	0.08	0.04				0.1	0.01		
Ba	100.0	0.46	2.6	1.0	0.42	1.0	1.0	0.43	1.0	1.5	1.0	0.72	1.0
			2.1	1.0	0.52	1.0				0.75	1.0		
Cd	1.0	0.08	0.5	0.09	0.05	0.01	0.01	0.05	0.01	0.04	0.01	0.04	0.01
			0.4	0.01	0.05	0.01				0.05	0.01		
Cr	5.0	0.46	2.3	0.55	0.25	0.2	0.2	0.43	0.2	0.26	0.2	0.14	0.2
			0.2	0.02	0.24	0.2				0.25	0.2		
Hg	0.2	ND	ND	0.002	ND	0.001	0.002	0.002	0.004	0.001	0.001	0.002	0.002
				0.001		0.001				0.002	0.001		
Pb	5.0	0.63	0.2	0.2	0.38	0.2	0.2	0.36	0.2	0.37	0.2	0.28	0.2
			0.2	0.2	0.37	0.2				0.43	0.2		
Se	1.0	ND	ND	0.001	ND	0.002	0.002	0.003	0.002	0.004	0.002	0.013	0.001
				0.001		0.001				0.014	0.002		

* Duplicate samples collected from pit.
F Filtrate (supernatant)
S Solids
T Total (solids & filtrate)
ND Not Determined

TABLE 6.11-3
DATA SUMMARY
LONGMONT CENTRIFUGE TESTS

DATE	TIME	CENTRIFUGE FEED RATE l/min	(gpm)	POLYMER	FEED MATERIAL	CAKE WT.% SOLIDS
7/17/85	10:00	23	(6)	No	Ash Pits	47
7/17/85	10:30	95	(25)	No	Ash Pits	53
7/17/85	11:10	91	(24)	Yes	Ash Pits	51
7/17/85	14:24	38	(10)	Yes	Ash Pits	51
7/17/85	15:00	38	(10)	Yes	Ash Pits	42
7/17/85	15:10	19-25	(5-7)	Yes	Ash Pits	46
7/18/85	09:30	45	(12)	Yes	Ash Pits	70
7/18/85	09:50	45	(12)	Yes	Ash Pits	58
7/18/85	10:10	76	(20)	Yes	Ash Pits	60
7/26/85	10:50	38	(10)	Yes	L.U.	64
7/26/85	11:15	57	(15)	Yes	L.U.	65
7/26/85	11:45	87	(23)	Yes	Underflow	70
7/26/85	15:00	57	(15)	Yes	Underflow	69
8/01/85		38	(10)	Yes	Underflow	77
8/01/85		19	(5)	Yes	Underflow	73
8/01/85	15:30	19	(5)	Yes	Underflow	64
8/23/85	12:00	57	(15)	No	Ash Pit	45
8/23/85	11:50	76	(20)	No	Ash Pit	61
8/23/85	11:30	95	(25)	No	Ash Pit	65
8/23/85	12:30	114	(30)	No	Ash Pit	39

L.U. - Lamella Underflow.

6.11.4 Ash Disposal Alternatives

Longmont ash residue met all the EP toxicity limits and was disposed of in landfills. Other disposal alternatives which could have a beneficial use of the ash product were reviewed. Laboratory tests were conducted to determine the feasibility of utilizing ash as a filler material in the manufacture of bricks. The tests concluded that additions of 7-8% ash produced a product with improved physical properties. Details of the test are reported in Appendix B.

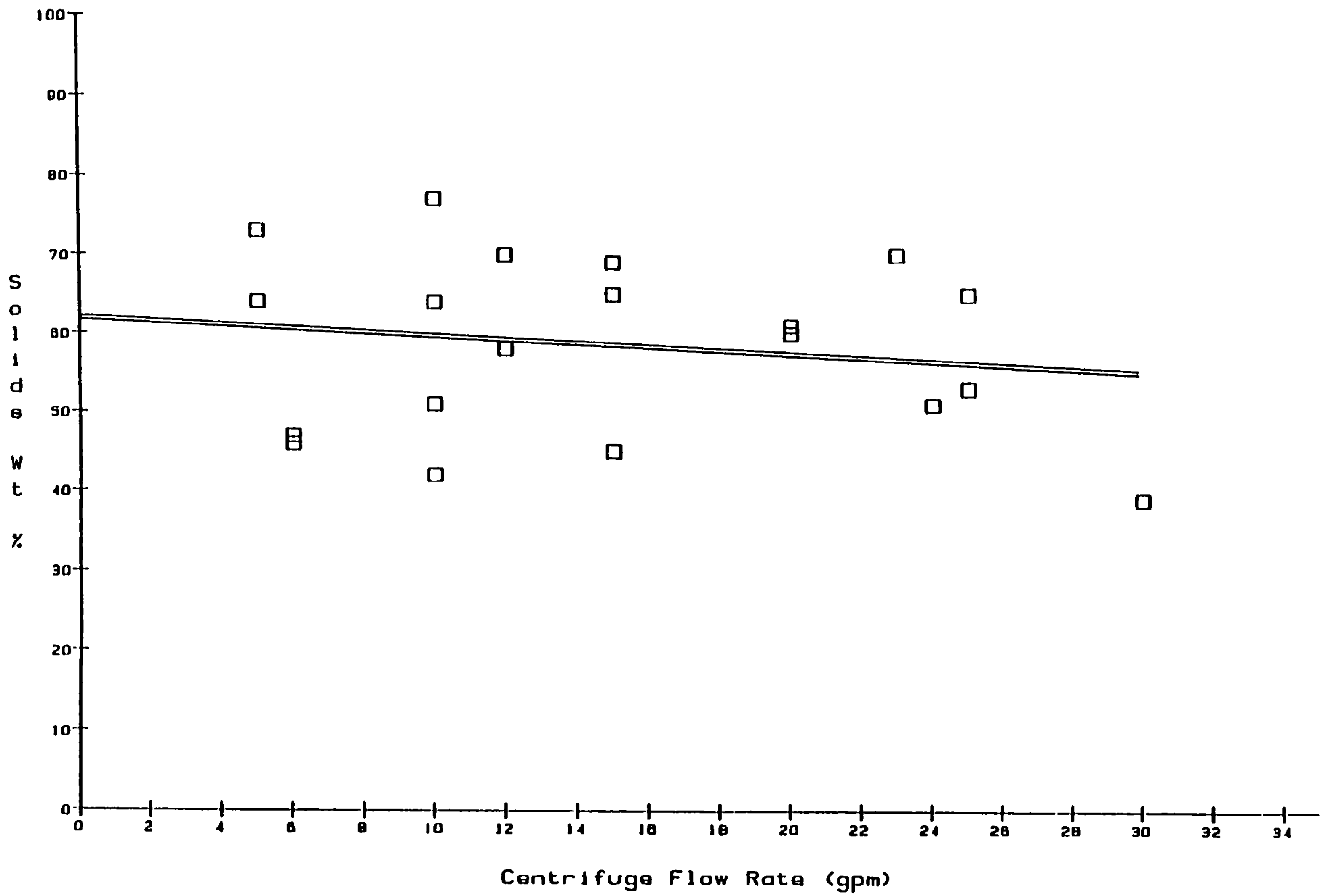


Fig. 6.11-1 Solids Weight Percent vs. Centrifuge Flow Rate

6.12 METALLURGY

High temperature aqueous-phase oxidation of Longmont sludge required the use of corrosion resistant materials. A duplex stainless steel was chosen based on its resistance to stress corrosion cracking, pitting and crevice corrosion. High strength was a necessity for downhole tubulars and reasonable costs were also important factors in the selection.

During operation, corrosive conditions varied to some degree. Operating temperature ranged up to 282 °C (540°F) with varying levels of carbon dioxide, oxygen and chloride. Typical chloride concentrations averaged 100 mg/L. VRV tubulars were exposed to acid during scale removal.

Metal loss during sludge processing was not detectable indicating little or no corrosion. After 15 months of successful operation, it was decided to remove and inspect the inner reaction vessel tubulars to determine the extent and type of corrosion experienced.

Upon removal, each length of pipe was checked for wall thickness and visual defects to verify the actual corrosion. The wall thicknesses of the 7-inch pipe are presented in Figure 6.12-1. It shows a general corrosion from no loss at the surface to a loss of 0.2 MM (8 mils) at the bottom.

Further inspection and laboratory analyses of the VRV tubulars gave the following conclusions:

1. General corrosion is low and consistent with a 20-year service life.

2. No pitting or crevice corrosion occurred on the pipe body.

3. No stress corrosion was found in the VRV tubulars.

4. No erosion was evident within the downhole system.

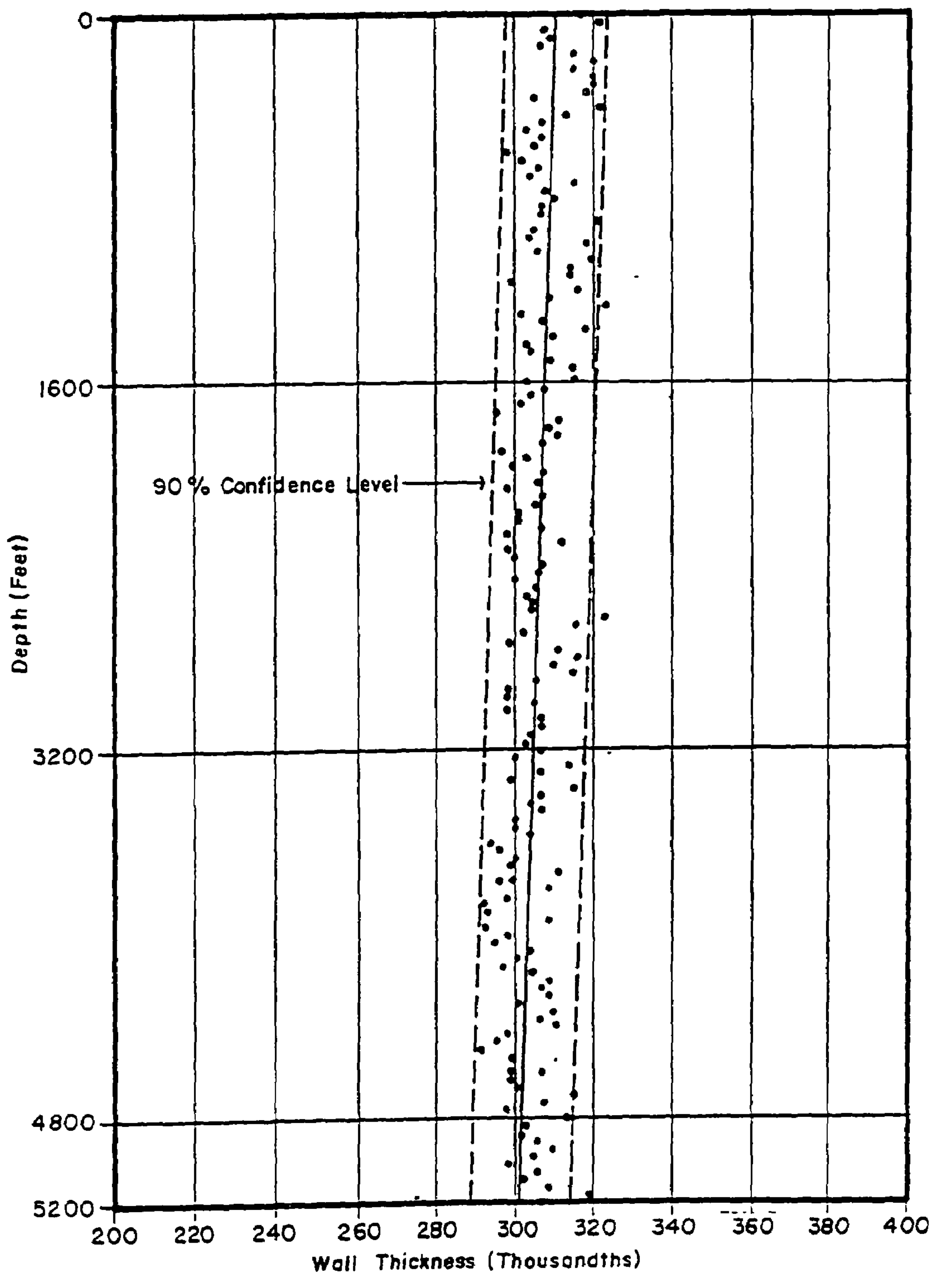


Fig. 6.12-1 Wall Thickness of 7" Pipe

SECTION 7
OPERATING AND CAPITAL COSTS

7.1 VRV SYSTEM OPERATING COST

Operating costs for the VRV System demonstration plant do not reflect the operating costs of a commercial unit. Operating costs for the Longmont facility were higher due to the following:

- Longmont did not operate at maximum capacity
- Chemical consumption was studied and not used at optimal rates
- Oxygen consumption was not optimized
- Maintenance costs were affected by modifications which would be unnecessary in a commercial facility

The operating costs, however, can be accurately calculated based on Longmont experience. Table 7.1-1 gives the operating costs for a Longmont sized reaction vessel. Individual cost factors are discussed in the following sections. It is seen that the operating and maintenance cost is about $113/metric ton and a net operating cost of $95/metric ton with an energy credit.

7.1.1 Labor Cost

VerTech employed four operators to cover the operation twenty-four hours a day, seven days a week. The supervisor covered one eight-hour shift per week plus any sick leave and vacation shifts.

Labor costs can be reduced by more than 50% if the facility is integrated into the Longmont WWTP. One operator will spend less than 50% of his time operating the VRV System.

Table 7.1-1 assumed an operator salary of $22,000 per year and a supervisor salary of $30,000 per year, plus 25% benefits.

Labor costs are calculated as follows:

Supervision	0.1 x $30,000/yr x 1.25	=	$ 3,750/yr
Operators	2.1 x $22,000/yr x 1.25	=	$57,750/yr
TOTAL LABOR			$61,500/yr.

7.1.2 Utilities

<u>Water</u>: Final clarifier effluent has proven satisfactory for all operations at Longmont. In addition, VerTech has used reaction vessel effluent directly for dilution of the influent and demonstrated that it is suitable; therefore the water costs are negligible.

Fuel: The process generates excess heat, which can be exported as steam, hot water or electricity. An energy credit of $171,400/year is calculated in Table 7.1-2 based on 40¢/Therm.

TABLE 7.1-1
OPERATING COST FOR PLANT
UTILIZING A 10" REACTION VESSEL

PLANT CAPACITY 9,100 metric tons, 10,000 short tons/year
PLANT AVAILABILITY 90%

	ANNUAL COST	UNIT COST $/1000 kg
Labor	$ 61,500	6.80
Utilities	39,400	4.30
Oxygen	473,200	52.00
Chemicals	205,700	22.60
Maintenance	120,000	13.20
Ash Removal	125,000	13.70
TOTAL EXPENSES	$1,024,800	112.60
NET ENERGY CREDIT	$ (153,400)	(16.90)
TOTAL	$ 871,400	95.70

TABLE 7.1-2
ENERGY CREDIT

The total available usable energy is calculated based on Longmont experience.

Heat of Reaction	3.27 MW	11.16 MM Btu/HR
Flush Out	(0.56) MW	(1.91) MM Btu/HR
Heat Lost to Rock	(0.94) MW	(3.21) MM Btu/HR
Usable Energy	1.77 MW	6.04 MM Btu/HR

At an average cost of $4/MM Btu, 90% efficiency and 90% availability, the credit is $171,400/year, less start-up fuel requirements of $18,000/year gives a net credit of $153,400.

Electricity: The electrical consumption for a facility which will produce an ash containing 50-70 wt % solids will be about 100 kW at 5¢/kWhr. The annual electrical cost at 90% availability is $39,420/yr.

100 kW x 24 hr/day x 365/day/yr x 0.9 x $0.05/kWhr = $39,420/yr

7.1.3 Oxygen

At Longmont, liquid oxygen was supplied at about $100/1000kg for a leased customer station. The ratio of TCOD/TS was between 1.0 and 1.1. Thus, for an 80% COD reduction and TCOD/TS of 1.0, the cost was $80/1000 kg of TS.

$$0.8 \text{ kgO}_2/\text{kgTS} \times \$100/1000 \text{ kg O}_2 = \$80/1000 \text{ kgTS}$$

Compressed oxygen can be generated from a leased unit including backup for $65 to $90 per 1000 kg. A purchased unit can produce oxygen for $33-40 per 1000 kg. At $65/1000 kg$O_2$, and 80% COD reduction, the cost per 1000 kg of TS is

$$0.8 \text{ kg O}_2/\text{kg TS} \times \$65/1000\text{kg O}_2 = \$52.00/1000\text{kg TS}$$

7.1.4 Chemicals

The chemical consumption depends on the amount of scale components in the original sludge. Longmont's WWTP added aluminum sulfate and thereby increased the amount of scale in the reaction vessel. It has been estimated that the chemical cost will be cut in half after the present redesign of the WWTP is completed. The costs reported are for the actual test period which includes the addition of aluminum sulfate.

During the initial sustained autogenous operation in March 1985, $46.60 per ton of solids were expended for chemicals. Further chemical cost reductions were experienced at Longmont utilizing a new acid wash procedure which reduced costs to $17.60 per ton for Longmont. Gulf Coast chemical costs are 57% of Longmont's.

Chemical costs are:

$17.6/ton	for wash chemicals
3.0/ton	for polyelectrolytes
$20.6/ton	solids

For a Longmont location, chemical cost is estimated at $20.60 per ton solids, or $22.60/1000kg.

7.1.5 Maintenance

Maintenance costs given in Table 7.1-1 include the costs to remove and inspect the VRV every 10 years.

Maintenance costs are thus:	
Labor $/year	45,000
Materials	45,000
Allowance for reactor removal	30,000
TOTAL $/YEAR	120,000

7.1.6 Ash Disposal

At Longmont, the ash was deposited at the local landfill. The ash was also transported to the local cement plant for use as a topping material. Thus the costs were negligible. Costs for disposal of the ash cake are typically $30/wet ton of ash. This results in a disposal cost of $12.50 per ton of processed sludge solids ($13.70/1000 kg).

7.2 VRV SYSTEM CAPITAL COSTS

Final effluent discharge specifications determine the VRV System capital costs. Typical capital costs will vary from $8-10 million for a 254 mm VRV System which will handle 30 TPD dry solids. A system similar to Longmont, integrated into the WWTP, will be closer to $8 million. This cost includes all equipment similar to that shown in Figure 1.4-2, except that centrifuges will be used to dewater the ash instead of ash pits.

7.3 ECONOMIC ANALYSIS

Assuming $10 million capital for a complete system, straight line depreciation over a 20-year period, and 6.5% financing on a 20-year loan, capital costs will be below $100/tonne for a VRV System. Coupled with operating costs below $100/tonne, the total project cost for a VRV System is very competitive with other waste disposal methods.

The Municipality of Metropolitan Seattle completed an evaluation of existing technologies in 1986. The current sludge management program in Seattle produces a product used in silviculture, land reclamation, and composting. Proposed technologies include composting, Carver-Greenfield, Zimpro, and VerTech's aqueous-phase oxidation in a VRV System. The VRV System is within a reasonable range of Seattle's current costs.

REFERENCES

1. "Test Methods for Evaluating Solid Waste," U.S. Environmental Protection Agency, SW-846, 1980.

2. "Methods for Chemical Analysis of Water and Waste," U.S. Environmental Protection Agency, EPA-600/4-79-020, 1979.

3. "Standard Methods for the Examination of Water and Wastewater," 15th Edition, American Public Health Association, American Water Works Association, Water Pollution Control Federation, Washington, DC, 1980.

4. "NIOSH Manual of Analytical Methods," Taylor, D. G., Manual Coordinator, 2nd Edition, Volume 5, Method No. S-17, 1977.

5. "1980 Annual Book of ASTM Standards - Petroleum Products and Lubricants," (II:D116)-D2896, American Society of Testing and Materials, Philadelphia, PA, 1980.

APPENDIX A

Stearns Catalytic

STEARNS CATALYTIC CORPORATION

March 10, 1986

VerTech Treatment Systems
12000 Pecos Street, Suite 3
Denver, Colorado 80234

Subject: Longmont Waste Water Treatment Plant
VerTech Process, Longmont, Colorado
Occupational (Off-gas Health Survey and Study)

Gentlemen:

The following is a summation of the Occupational Off-gas Health Survey and Study performed for VerTech. The study considers the VerTech process operation in conjunction with Longmont Waste Water Treatment Plant (LWWTP) activities. It was concluded from the study that levels of contaminants identified were well below established and recognized exposure levels listed by both American Conference of Governmental Industrial Agencies and Federal Regulations and Recommendations for toxic and/or irritant contaminants.

Specifically, those chemicals identified to any significant level were:

	Established TLV and/or PEL (ppm)	Evaluated Exposure Levels (ppm)
Acetone	750	5 - 30
Furan	50	2 - 3
2-Butanone	200	3 - 4
2-Pentanone	200	1 - 2
1-Hexene	100	1 - 2
1-Heptene	400	1 - 2
Benzaldehyde	100	4.78
Furfural	2	0.34
Carbon Monoxide	50 (20)	<5

Numerous samples were collected from the VerTech facility, the Longmont Waste Water Treatment Plant and from the breathing zones of plant personnel. Analytical procedures used to evaluate these samples were gas chromatography-mass spectrometry (GC/Mass Spec) and Girard-T reagent high pressure liquid chromatrography. Accuracy levels of the various analytic techniques were such that air contaminant concentrations were detectable to less than one part per million for activated charcoal tube collection (GC/MS evaluation), and two parts per million for Girard-T reagent collection for aldehyde determination.

4500 Cherry Creek Drive, P O Box 5888, Denver, Colorado 80217, (303) 758-1122, TLX 45540, TWX 910-931-0453

Normally, National Institute Occupational Safety and Health Procedure S-17 is used for the determination of Furfural; however, because of its complexing nature with other aldehydes, it was also used to determine total aldehyde airborne concentrations. All other organic hydrocarbon collections were done on activated charcoal and were desorbed in the laboratory prior to analyses. The airborne sampling was done using approved EPA analytical procedures.

The analyses of samples taken outside the VerTech facility indicated only trace amounts of organics. Spot check grab samples of transient vapor cloud from the VerTech air separator (S-4 unit) indicate concentrations in the range of 3 to 5 ppm for short periods of exposure, under the worst atmospheric conditions.

Airborne concentration levels of the components identified have never been observed to approach nor exceed the earlier noted permissible exposure levels and/or TLV's published by respective organizations. This includes toxicological information of the effects characterized by these components at lower evaluated levels than those published TLV's and/or PEL's.

Carbon monoxide airborne concentrations were not observed within the LWWTP. Dispersion of any carbon monoxide generation was rapid and efficient with no detectable quantities outside the VerTech facility. Atmospheric conditions influenced dissipation of the heated, moisture laden off-gases. Dispersion was rapid with high local winds, slower during periods of low barometric pressure.

As the data indicates, even accumulative effects of all of the above would be diminished by the evidence of their extremely low or non-existent airborne concentrations.

Very truly yours,

STEARNS CATALYTIC WORLD CORPORATION

Daniel S. Hinds
Assistant Manager of Corporate Safety
and Health
Corporate Industrial Hygienist

APPENDIX B

Kenneth D. Bradford
Manufacturing Consultant
7220 W. Jefferson Avenue, #350
Denver, Colorado 80235

September 28, 1984

Vertech Treatment Systems
2010 W. 120th
Westminster, Colorado 80234

Subject: Physical Testing of Vertech Waste Ash Combined with Clay Brick Mixes.

I. Denver Brick Mix Tests.

Initially a dried sample of pit #4 ash was obtained, ground to pass a 14M screen (retained moisture was 14.5%), additional water added, and the material extruded in 1" x 1" bars. Several samples were dried and fired above 2000°F. In each case, the bars melted. Ash mixed with clay is stable however. Additional tests were run mixing 16.7%, 8.3%, and 6.7% ash with a standard red brick mix from Denver Brick Company. This mix is only semi-plastic. Since the ash, although very fine, is a calcined material, it reduces the mix plasticity and causes tearing at corners during extrusion.

A second more plastic mix of Denver Brick (62T) was selected and 12.5% and 7.1% additive of ash were made. The 7.1% addition (Test #14) extruded well, had .5% less dry shrinkage, .5% more fired shrinkage, and equal absorption. This 7.1 percentage would be a practical addition to this brick mix. Body color is darkened by use of the ash. Further testing is necessary to determine if this darkening is caused by sulfates migrating to the surface. If so it can be controlled with Barium Carbonate in clear burned brick. This would not be necessary with flashed or coated brick.

A seven-day efflorescence test, conducted according to ASTM C-67, was made with sample #14 containing 7.1% ash, Denver Brick's #1 mix, #62T mix, and a #1 mix containing power plant fly ash. All samples are classed as "No Efflorescence." Samples of #14 ash test were subjected to compression and modulus of rupture tests by CTL Thompson laboratory, along with #1 standard brick mix. A formal report by CTL Thompson will be tendered next week.

Results:

Mix	Average Compression	Average M.O.R.
#14 (7.1% Ash)	7035 psi	1877 psi
#1 Brick Mix	6085 psi	1314 psi

ASTM C-62 requires minimum 3000 psi compression to class brick as S. W. (Severe Weathering), its highest classification. The ash sample measures very well compared to the #1 mix and other brick of the local area.

I conclude that waste ash additions up to 10% are safe additions to brick mixes--no distortion or over vitrification. Drying of brick will probably be improved because of lowered dry shrinkage. Fired characteristics are equal or better than standard brick.

An important factor is weight reduction of fired brick. The #14 ash test indicated a reduction in fired weight of 5%. This would be significant since shipping costs are of major concern to brick manufacturers.

II. Colorado Brick Company Mix Tested.

A sample of Colorado Brick standard red mix was obtained and sample bars extruded.

A second sample of ash was also obtained, ground, and mixed with Colorado Red Mix--10% ash to 90% red mix. This level of ash produced a lightly rougher edge in extrusion indicating that 7 to 8% ash addition would be more practical.

Physical results followed those found with Denver Brick mixes; i.e., less dry shrinkage, more fired shrinkage, and 3% less fired weight. Apsorption of the ash test was 1% higher than standard mix but still quite low indicating that compression and modulus of rupture should meet or exceed ASTM standards. A set of #15 (standard red mix) and #16 (10% ash) will be submitted to CTL Thompson for compression and M.O.R.

Color of the ash test was again slightly darker. A sample of both bars along with a copy of specification sheets will be given to Jerry Gunning at Colorado Brick. I will recommend to him that the ash is certainly usable and that a production test be made.

K. D. Bradford

KDB/ce

APPENDIX C

MATERIAL SCIENCE CORP.

10381 E. Berry Drive
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President
P. E. Dempsey

OBSERVATIONS AND CORROSION REPORT

ON

PULLING THE LONGMONT REACTION VESSEL

December 3, 1985

APPENDIX C

SUMMARY OF REACTION VESSEL CORROSION

Readings were taken by the UT thickness gauge to measure the extent of corrosion observed in the reaction vessel tubulars. They were recorded and averaged to give the wall thicknesses plotted in the attached graphs. Corrosion of each individual joint could not be determined since the original wall thickness was not known. It was however possible to measure the wall thickness for several new unused joints of 5" and 7-5/8" available at the site. Wall thickness for the as ordered .300" wall 7-5/8" pipe averaged .310" and for the 5"-.253" wall pipe averaged .263". Measurements of new 5"-220" wall pipe was not obtainable since all of the supplied joints were used in the reaction vessel string.

Based on the above averages for as supplied new pipe and actual measurements of each joint removed from the system; it was apparent that a small degree of general corrosion did occur. Corrosion was not evident at surface but increased with temperature and depth. Corrosion on the 5"-.253" wall pipe varied from 0 to .003". As mentioned above corrosion for the 5"-.220" wall was not obtained. Measurements varied from .249" to .235" which was considerable above the .220" wall ordered. Corrosion on the 7-5/8"-.300" wall pipe varied from 0 at surface to .008" at depth.

In both the 7-5/8" and the 5" pipe, there was no evidence of stress cracking, pitting or crevice corrosion.

GLOSSARY

Anhydrite - A mineral substance containing no waters of hydration; ie, $CASO_4$ consisting of an anhydrous calcium sulfate that is usually massive and white or slightly colored.

Autogenous - Plant operation where no external source of heat is required to maintain process temperatures; self-generated; produced without external influence.

Biochemical Oxygen Demand (BOD) - A measure of the quantity of oxygen utilized in the biochemical oxidation of organic matter in a specified time and at a specific temperature. Commonly referred to as Biological Oxygen Demand. All BOD measures are 5-day unless otherwise noted.

Biochemical Oxygen Demand Total - A measure of the quantity of oxygen utilized in the biochemical oxidation of organic matter, inorganic matter such as sulfides and ferrous iron. It also measures the oxygen used to oxidize reduced forms of nitrogen (nitrogenous demand). Commonly referred to as Biological Oxygen Demand.

Biomass - The mass of biological material contained in a system, consisting of the active biological population and inactive solids.

Biosystem - A treatment plant or system that uses biological activity to remove BOD.

Bottomhole - Refers to the extreme bottom of the reaction vessel.

British Thermal Unit - Quantity of heat required to raise the temperature of one pound of water 1°F-0.55°C equal to 0.95 kJ.

Carbonaceous Biochemical Oxygen Demand (COD) - A quantitative measure of the amount of dissolved oxygen required for the biological oxidation of carbon containing compounds in a sample. An inhibitor is added to prevent oxidation of reduced forms of nitrogen.

Centrate - The liquid discharge from a plant or a piece of equipment, such as a centrifuge.

Centrifuge - A mechanical device in which centrifugal force is used to separate solids from liquids and/or to separate liquids of different densities.

Chemical Oxygen Demand - A quantitative measure of the amount of oxygen required for the chemical oxidation of carbonaceous (organic) material in wastewater using inorganic dichromate or permanganate salts as oxidants in a two-hour test.

Chromatography - The generic name of a group of separation processes that depend on the redistribution of the molecules of a mixture between a gas or a liquid phase in contact with one or more bulk phases. The several types of chromatography are: adsorption, column, gas, gel liquid, ion, thin-layer and paper chromatography.

Colloids - Finely divided solids which will not settle but may be removed from a liquid by coagulation or biochemical action as membrane filtration. In general, particles of colloidal dimensions are approximately 10 to 10,000 Angstroms in size.

Dewater - To extract a portion of the water present in a sludge or slurry.

Diluent - An inert substance used to increase the volume of some other substance or solution.

Dissolved Oxygen - Free elemental oxygen dissolved in water.

Dissolved Solids - Solids in solution that cannot be removed by filtration.

Downcomer - A passageway in which a slurry or liquid is conducted from the top of the reaction vessel or heat exchanger to the bottom.

EP Toxicity Test - Extraction Procedure Toxicity (EP Toxicity); an extraction procedure employing acetic acid at pH5 to determine leachable metals or hazardous organic compounds.

Effluent - A Discharge from a unit operation, such as the final discharge stream from a waste treatment plant.

Electrolyte - A compound which forms charged species in solution. Includes simple electrolytes (coagulants) and polyelectrolytes (flocculants).

Exothermic - Indicating liberation of heat. Also know as exoergic.

Filter Press - A plate and frame press operated mechanically to produce a semi-solid cake from a slurry.

Floc - Collections of smaller particles agglomerated into larger more easily settleable particles through chemical, physical or biological treatment.

Flocculant - A water-soluble organic polyelectrolyte that is used alone or in conjunction with inorganic coagulants, such as aluminum or iron salts, to agglomerate solids present in water or wastewater to form large, dense floc particles which settle rapidly.

Flow Rate - A measure of the volume of water flowing through a system over a period of time, i.e., gallons per day or liters per day.

Foulants - Materials collecting in a system that tend to foul it, causing reduced flow rates or increased pressure drop across the system.

Gallons Per Day - The number of gallons in one day to pass through a plant or system. One gallon is equal to 3.78 liters.

Gas Chromatography - A method of separating a mixture of compounds into its constituents so they can be identified. The sample is vaporized into a gas filled column, fractionated by being swept over a solid absorbent, selectively eluted, and identified.

Gas Chromatography/Mass Spectrometry - The analysis of constituents of water by gas chromatography/mass spectrometry involves isolation and concentration of organics from a sample, separation of the components on a gas chromatograph, and detection and quantification of the compounds with a mass spectrometer.

Grab Sample - A sample taken from a process stream at one time, not a composite sample.

Higher Heating Value - The heat released with the combustion of a substance.

Horse Power - A unit of power equal in the U.S. to 746 Watts and nearly equivalent to the English gravitational unit of the same name that equals 550 foot-pounds of work per second.

Influent - Water, wastewater or other liquid flowing into a treatment plant or treatment process.

Interphase - The interval between the end of one mitotic or meiotic division and the beginning of another.

Kilogram - The basic metric unit of mass and weight equal to 2.2 pounds.

Lamella Solids Separator - A vessel containing inclined plates used to separate solids from liquids and concentrate them.

Mil - A unit of length equal to 0.001 inches or 0.0025 centimeters.

Millimeter - A unit of length equal to 0.001 meters.

Non-Autogenous - Plant operations utilizing an external source of heat to maintain reaction temperatures.

Non-Hazardous - Indicates a condition of no threat to life or limb.

Percent Reduction - The percent of COD destruction in a waste stream. It equals influent COD Minus effluent COD divided by the influent COD.

pH - A measure of the hydrogen-ion concentration in a solution, expressed as the logarithm (base ten) of the reciprocal of the hydrogen-ions concentration in gram moles per liter.

Polyelectrolytes - Complex polymeric compounds, usually comprised of synthetic macromolecules that form charged species (ions) in solution. Water-soluble polyelectrolytes are used as flocculants; insoluble polyelectrolytes are used as ion exchange resins.

Pressure Measurement Lines - Lines that extend deep into the reactor and are purged with a low air flow.

Reaction Vessel - The concentric pipes that form the heat exchanger, downcomer and upcomer in the reactor.

Recirculating - A closed loop circulation of a liquid through a system.

Rotating Biological Contactor - A device for wastewater treatment which is composed of large, closely spaced plastic discs that rotate on a horizontal shaft. The discs alternately move through the wastewater and the air, and develop a biological growth on their surfaces.

Sand Bed - A bed of sand through which water is passed to remove fine suspended particles. Very common in water treatment plants; also used in tertiary wastewater treatment plants and sludge drying beds.

Slurry - A thin, watery mud or any substance resembling it.

Soluble - Capable of being dissolved in a fluid.

Spectrophotometer - An instrument for measuring the amount of electromagnetic radiation absorbed by a sample, as a function of wave length.

Supernatant - The liquid remaining above a sediment or precipitate after sedimentation.

Systeme International d'Units - It is the international system of units of measurement, identified as SI in all languages. It is the modernized metric system, a high refinement of the original metric system.

Total Dissolved Solids - The sum of all dissolved solids (volatile and non-volatile) in a water or wastewater.

Total Kjeldahl Nitrogen - The sum of ammonia nitrogen and organic nitrogen in a sample.

Total Solids - The sum of dissolved and suspended solid constituents in water or wastewater.

Total Suspended Solids - Insoluble solids that either float on the surface of, or are in suspension in water.

Total Volatile Solids - Total materials, generally organic, which can be driven off from a sample by heating, usually to 550°C.

Total Volatile Suspended Solids - That fraction of suspended solids, including organic matter and volatile inorganic salts which will ignite and burn when placed in an electric muffle furnace at 550°C for 60 minutes.

Tubulars - The concentrically placed tubes that form the reaction vessel.

Upcomer - A passageway in which a slurry is conducted from the bottom of the reaction vessel or heat exchanger to the top.

Upflowing - The liquid in the reactor on its way up and out of the reaction vessel.

Vertical Tube Reactor (VTR) - The early developmental stage of the VerTech Treatment System reaction vessel.

Wet-Air Oxidation - A method of sludge disposal that involves the oxidation of sludge solids in water suspension under high pressure and temperature.

X-ray Diffraction - A method of identifying crystalline substances by scattering of X-rays of the constituent atoms to form characteristic patterns.

X-ray Florescence - A non-destructive physical method used for chemical analysis of solids and liquids; the specimen is irradiated by an intense X-ray beam and the lines in the spectrum of the resulting X-ray florescence are diffracted at various angles by a crystal with known lattice spacing. The elements in the specimen are identified by the wave lengths of their spectral lines, and their concentrations are determined by the intensities of these lines.

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15 SUPPLEMENTARY NOTES

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16 ABSTRACT

The overall objective of this study was to provide plant-scale operating data on the wet-oxidation of municipal wastewater sludge utilizing the Vertical Reaction Vessel System and the effect of the return flow from the wet-oxidation process on the operation of the wastewater treatment plant.

The Vertical Reaction Vessel System consists of a series of long concentric tubes placed in the earth using conventional oil field technology. Vertical construction produces a high hydrostatic head at the bottom of the system. The high pressure prevents boiling at temperatures of 250° or higher required for wet-oxidation. By utilizing hydrostatic pressure, the only pumping required is that to overcome frictional losses. Sludge is introduced along with air or oxygen into the multiphase fluid downcomer, where it is heated by hot oxidized sludge rising in the outermost concentric space within the vessel. At the center of the reaction vessel is a tubular heat exchange system which can either extract excess heat or provide heat for startup of the process.

At temperatures above 260°C total chemical oxygen demand reduction of about 80% and total volatile solids reductions of over 90% were consistently achieved. Returning the supernatant liquid from the process to the wastewater treatment system did not significantly affect that system.

17 KEY WORDS AND DOCUMENT ANALYSIS

a DESCRIPTORS	b IDENTIFIERS/OPEN ENDED TERMS	c COSATI Field/Group

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