1981

Alleviating sludge composting moisture problems at the West Windsor sewage treatment plant.

Robert John. Ceschan
University of Windsor

ALLEVIATING SLUDGE COMPOSTING MOISTURE PROBLEMS AT THE WEST WINDSOR SEWAGE TREATMENT PLANT

by

© Robert John Ceschan

A Thesis
submitted to the Faculty of Graduate Studies
through the Department of Geography
in partial fulfillment of the requirements
for the Degree of Master of Arts
in the Environmental Studies Field at
The University of Windsor

Windsor, Ontario, Canada

1981

ABSTRACT

ALLEVIATING SLUDGE COMPOSTING MOISTURE PROBLEMS
AT THE WEST WINDSOR SEWAGE TREATMENT PLANT

by

Robert John Ceschan

With the closing of the Western Sanitary Landfill Site, in the summer of 1973, the City of Windsor began looking toward composting to solve their sludge disposal problem. Since the inception of the Beltsville Extended Aerated Pile Method of Sludge Composting at the West Windsor Sewage Treatment Plant, excessively high moisture levels within the composting piles at the end of the 28 day forced aeration period have caused odour and screening problems.

This study was designed to alleviate the sludge composting moisture problems by employing improved forced aeration methods, such as reduced pipe spacings, enhanced aeration, and larger piping.

The forced aeration method has proved to be a versatile method of sludge composting. Temperatures sufficient for pathogen kill and sludge stabilization were attained with modified aeration, and septic sludge was adequately composted when greater amounts of aeration were provided.

It was found that the increased costs associated with the usage of improved aeration systems did not justify their moisture reduction benefits since all of the aeration systems attained significant moisture reductions. Decreased pipe spacings did not eliminate the presence of wet malodorous pockets and thus,

could not ensure uniform spatial patterns at the end of the composting period. The reasons responsible for this failure were the porosity characteristics of the piles which were greatly affected by the initial variability of the woodchip and sludge inputs, and the inadequately stabilized nature of the compost as denoted by the high temperatures at the end of the composting process. These temperatures were also found to be significantly correlated to moisture levels within a pile. Consequently, the odour and screening problems associated with moist pockets may be predictable before pile breakdown.

ACKNOWLEDGEMENTS

Sincere appreciation is extended to all those who have directly or indirectly contributed to the completion of this thesis.

I would like to especially thank Professor J.P. Hartt, of the Civil Engineering Department for his astute guidance and financial support of this study. My gratitude is also extended to the other members of my advisory committee, Dr. P.D. LaValle and Dr. I. Stebelsky, for their constructive criticism of this research.

I am especially indebted to the City of Windsor and Ministry of the Environment (Experience '79 grant) for their additional financial support provided. For their advice, equipment and manpower essential for the completion of this study, many thanks to the officials at the West Windsor Sewage Treatment Plant, Lou Romano and Bill Newman; and notably, Mr. Michael R. Coulson for his initiation of this study and his invaluable experiences in the sludge composting field.

Finally, a big thank-you to my wife, Pamela, for her invaluable support throughout this study and for the editing and typing of this thesis.

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

Figure		Page
19-21	Spatial Patterns of Studied Variables for Experiment 2	107-109
22-24	Spatial Patterns of Studied Variables for Experiment 3	110-112
25-27	Spatial Patterns of Studied Variables for Experiment 4	113-115
28-30	Spatial Patterns of Studied Variables for Experiment 5	116-118
31-33	Spatial Patterns of Studied Variables for Experiment 6	119-121
34-36	Spatial Patterns of Studied Variables for Experiment 7	122-124
37-39	Spatial Patterns of Studied Variables for Experiment 8	125-127
40-42	Spatial Patterns of Studied Variables for Experiment 9	128-130
43-45	Spatial Patterns of Studied Variables for Experiment 10	131-133

LIST OF APPENDICES

CHAPTER ONE

INTRODUCTION

1.1 The Sewage Sludge Problem

Legislative action prohibiting or restricting water pollution has resulted in the continued expansion and upgrading of sewage treatment plants across Canada and the United States. This has resulted in the increased production of sludge. Sludge is the solid material removed during primary (gravitational), secondary (biological), and advanced (physical, chemical, and biological) waste water treatment (Walker and Willson, 1973). In the United States, the present annual sludge production of about 5 million metric tons (dry solids) is expected to double by 1985 (Dallaire, 1978; Willson et al 1978). In Ontario, approximately 200,000 dry tons of sludge are produced annually from some 40 municipalities (Coulson, 1978). Consequently, the disposal of the ever increasing amount of sludge may create serious environmental and economic problems for many communities. The Canadian practice of sewage sludge disposal has generally resulted in the selection of the most inexpensive method of sewage sludge disposal with little consideration given to the environmental impact of the chosen method (Coulson, 1978).

1.2 An Evaluation of Sludge Disposal Practices

Present sludge disposal practices in Ontario include incineration, lagooning, dumping into sanitary landfills, and land spreading onto farmers' fields (Coulson, 1978). Table 1, which is based on U.S.E.P.A. estimates of the percentages of

TABLE 1

Sludge Disposal Practices

Method	% Total Use in 1972 *	% Total Use in 1975 **	% Change in Use Between 1972-75
Landfill	40	35	-5
Landspreading	20	20	0
Ocean Dumping	15	20	+5
Incineration	25	25	0
Pyrolysis	0	0	0
Composting	0	<1	+1
Thermal De-hydration	0	<1	+1

* source - Dallaire, 1978, p. 110

** source - Willson et al, 1978, p.2

sludge production disposed by various methods, gives an indication of trends in sludge disposal. Most of these disposal methods are expensive, wasteful of energy, esthetically undesireable, harmful to the environment, pose potential health hazards, or some combination of these (Willson, et al 1978).

As can be seen in Table 1, landfilling is the most widely used sludge disposal method in the U.S. It is cheap, requires little capital investment, and can be quickly implemented. Table 1 also indicates that the importance of landfilling as a sludge disposal practice, will decrease over time. The major reason for landfilling's decreasing popularity as a sludge disposal practice is urban growth. This reduces the land available for landfilling adjacent to cities, thus increasing haulage distances and the cost of purchasing land. An additional drawback is establishing a suitable landfill site which would be accepted by the nearby urban community. Poorly located and operated landfills have been found to be responsible for the contamination of local water tables which usually results in the subsequent closing of wells (Foin, 1976; Morse and Roth, 1970).

Incineration, which is the second most popular method of sludge disposal, provides a 90% reduction in sludge volume by removing most of the water and organic solids (Dallaire, 1978). However, the remaining ash residue must be disposed of in some manner, usually by landfilling. An additional drawback which detracts from the use of incinerators as a sludge disposal alternate are the high capital and operating costs associated with the process; notably fuel costs; and legally required air pollution abatement devices such as electro-static precipitators and wet scrubbers (Dallaire, 1978; Erlich and Erlich, 1972; Foin, 1976). Unless care is taken, incineration could merely substitute air pollution for land pollution, and may be wasteful of energy (Erlich and Erlich, 1972; Foin, 1976).

Ocean dumping, which is not practiced in Canada, is perhaps the simplest and least expensive method for disposing of sludge in seaboard communities. This is probably responsible for the increasing popularity of this sludge disposal alternative in the U.S. between 1972 to 1975 (Table 1). However, ocean dumping contaminates shellfish with pathogens and heavy metals, causes beach swimming areas to be infested with pathogens and unsightly wastes, and disrupts marine fisheries (Dallaire, 1978). For these reasons and potentially additional unknown effects on the marine ecosystem, the United States Environmental Protection Agency has ordered all municipalities to cease the dumping of sewage sludge by 1981 (Dallaire, 1978; Foin, 1976; Taffel, 1978, Willson et al, 1978).

Landspreading, which is another major sludge disposal method, is an old practice whereby nutrients, water, and organic matter are added to the soil. However, landspreading of sludge is becoming a major environmental concern since heavy metals and pathogens can be found within the sludge (Bertoldi, Citernesi and Giselli, 1980; Dallaire, 1978; Foin, 1976; Walker and Willson, 1973). The possiblity of groundwater contamination and operational problems associated with the spreading of sludge on frozen or wet soil poses additional concerns that curtail the usage of landspreading as a sludge disposal practice (Dallaire, 1978; Walker and Willson, 1973).

1.3 Composting -- The Sludge Disposal Alternative

The environmental and economic problems associated with the current methods of sludge disposal have prompted research into more acceptable disposal techniques (Coulson, 1978, p.5). One method which has been gaining rapid recognition as a practical solution to the sludge disposal problem is composting. Composting, which is the breakdown or decomposition of organic materials by microorganisms, is an ancient method of waste recycling. Actual processes for composting municipal refuse have been in existence since the 1920's. E.P.A. estimates of 1971 indicated that there were over 2,600 composting facilities outside the U.S. where demands for compost is high (Dallaire, 1978). The Dutch have used compost in land reclamation projects in the Zuider Zee. France and Germany have used compost to control soil erosion within vineyards. Although composting of municipal refuse has been tried in the past by the United States and Canada, few such operations are still in existence today because of high operating costs involved in the separating and grinding of refuse, machinery breakdown, and the difficulty in successfully marketing the product since mineral fertilizers are abundant and readily available.

Only recently has the composting of strictly sewage sludge been tried, although sludge has often been added to refuse before composting. Two methods of sludge composting were developed by the United States Department of Agriculture's

Agricultural Research Service at Beltsville, Maryland, in the mid-1970's. The windrow process composts digested sludge while the aerated pile process composts digested or undigested sludge. Essentially, both methods mix sewage sludge with a bulking material such as woodchips, and the actual decomposition is done by aerobic thermophilic microorganisms (Dallaire, 1978; Epstein, 1977; Gonin, Link and Kundt, 1978). Composting of sewage sludge has been found to compare favourably, in terms of cost , with various other sludge disposal methods as can be seen in Table 2. Although landfilling and ocean dumping are cheaper than composting, they are not as environmentally sound nor do they offer resource recovery benefits. With the implementation of pretreatment programs to control the introduction of toxic substances into municipal treatment plants, composting of municipal sludges should prove to be even more attractive as a sludge disposal practice (Dyer, 1979).

The resource recovery benefits of compost are primarily centred around its ability to improve the physical properties of soil by:

(1) increasing the soil's water content (Dallaire, 1978; Willson et al 1978);

(2) increasing the water retention ability of soil (Crombie, 1979; Dallaire, 1978; Steffen, 1979; Willson et al, 1978);

(3) enhancing soil aggregation (Dallaire, 1978; Steffen, 1979; Willson et al 1978);

(4) increasing soil aeration (Crombie, 1979; Dallaire, 1978; Steffen, 1979; Willson et al, 1978);

(5) improving soil permeability (Bertoldi, Citernesi and Griselli, 1980; Dallaire, 1978; Willson et al, 1978);

(6) increasing the infiltration of surface waters into the soil (Bertoldi, Citernesi, and Griselli, 1980; Dallaire

TABLE 2

**Costs of Various Sludge Disposal Processes
(in 1978 U.S. Dollars)**

Process	$/ Dry Ton
Digested Sludges [1]:	
Ocean Outfall	12 to 42
Liquid Landspreading	24 to 65
Digested and Dewatered Sludges:	
Ocean Barging [2]	37 to 53
Landfilling	28 to 64
Landspreading [3]	31 to 115
Dewatered Sludges:	
Trenching [4]	138 to 161
Incineration [5]	>68 to 112
Heat Drying [5]	74 to 138
Composting [4,5]	42 to 60

1. Costs do not include prior processing -- ie. digestion.
2. This is the cost of disposing of digested and dewatered sludge at sea. Much of the sludge disposed at sea is not dewatered.
3. This is the cost of spreading digested and dewatered sludge on land. Most sludge spread on land is liquid, undewatered sludge.
4. Costs excludes prior processing and transportation of sludge to site.
5. Costs excludes prior processing, cost of removal of residuals and benefits from resource recovery.

Source: Dallaire, 1978, p. 110.

1978; Willson et al, 1978); and

(7) reducing surface crusting (Dallaire, 1978; Willson et al, 1978).

Compost may also be used as a fertilizer (Bertoldi, Citernesi, and Griselli, 1980; Steffen, 1979; Willson, 1978; Willson et al, 1978). Studies conducted with potting and bedding plants (Taffel, 1978), lawn grass (Shell and Boyd, 1970), and red maple seedlings (Gouin, Link and Kundt, 1978) found that the vegetation studied grew profusely because of the nutritional value of compost. Although the landspreading of sludge provides benefits similar to those of compost, sludge emits odours, contains human pathogens, contains higher concentrations of heavy metals, and cannot be spread over land during the entire year (Bertoldi, Citernesi and Griselli, 1980; Council for Agricultural Science and Technology, 1978; Willson et al, 1978).

Given the soil conditioning and fertilizer properties of compost, potential markets for compost include:

(1) landscaping projects as a substitute for topsoil (Crombie, 1979; Dallaire, 1978; Patterson, 1975; Taffel, 1978; Willson, Parr and Casey, 1978; Wolf, 1978);

(2) disturbed lands such as strip mines, gravel pits, road banks, and housing developments for revegetation purposes by mixing compost into the unproductive soils (Crombie, 1979; Dallaire, 1978; Willson et al, 1978); and

(3) horticulture as a commercial soiless potting mixture (Bolan, Nieswand and Singles, 1979; Crombie, 1979; Taffel, 1978; Willson, Parr and Casey, 1978).

Patterson (1975) reported that the Park Service saved over $200,000.00 by using compost instead of buying topsoil for the construction of the Constitution Gardens in Washington, D.C. Wolf (1978) noted that if the Town of Durham, New Hampshire, would use composted sewage sludge for landscaping projects instead of loam which ranges anywhere between $7.00 (unscreened) to $25.00 (screened) a yard, tremendous expenses could be avoided. Taffel (1978) reported that the availability of relatively low cost compost could make possible landscapping projects in the Boston Area possible that would have otherwise been prohibitively expensive. In Durham, tremendous success has been attained in all public work projects which utilized compost (Crombie, 1979). Compost was used for developing new lawns after road construction and for tree plantings in park and cemetary programs.

1.4 Composting at the West Windsor Sewage Treatment Plant-- An Extended Method of Sludge Composting

Towns and cities currently using the Beltsville Aerated Pile Method of Sludge Composting include Durham, New Hampshire; Bangor, Maine; Camden, New Jersey; and Windsor, Ontario (Dallaire, 1978; Epstein, 1977). Windsor decided to try the Beltsville Aerated Pile Method when the Western Sanitary Landfill Site on the City's west side was closed in the summer of 1973. It thus avoided increased haulage and disposal costs to a county sanitary landfill site over 40.2 km. (25 miles) away (Romano and Faust, 1978). Furthermore, with the scheduling of the now defunct Western Sanitary Landfill as a recreational area, topsoil was required for establishing a seedbed for grass and for tree plantings due to the impervious and infertile nature of the clay at the landfill site. Since a tremendous volume of topsoil was needed to provide adequate cover material, Romano and Faust (1978) estimated that $100,000.00 per year over 10 years could be saved if the composted sludge were used as a topsoil replacement. Consequently, composting was perceived as an attractive sludge disposal alternative, since the resource recovery benefits of the compost would offset any additional costs of composting the sewage sludgecake.

The Beltsville Aerated Pile Method has several marked advantages in costs over the Beltsville Windrow Process of sludge composting. Notably, the aerated pile method can utilize raw sludge in the composting process thereby avoiding the additional $9.00 to $15.00/dry ton cost of sludge (Dallaire, 1978) needed for anaerobic digestion of sludge in the Windrow Process (Dallaire, 1978; Epstein et al, 1976; Willson, 1978). In the Windrow Process, sludge must also be turned over often to ensure adequate aeration as opposed to the aerated pile method where air is merely sucked through the pile (Dallaire, 1978). Finally, the aerated pile method has also been found capable of sustaining higher temperatures necessary for destroying pathogenic microorganisms (Epstein et al, 1976; Willson, 1978).

Since the present composting site behind the West Windsor Sewage Treatment Plant encompasses an area of only six acres, the City of Windsor has adopted a modified version of the Beltsville Aerated Pile Method called the Extended Aerated Pile Method as can be seen in Figure 1. The extended pile technique reduces by 50% the mixing pad area, the amount of compost blanket needed for insulation and odour control, and reduces the woodchips needed for the pile base (Dallaire, 1978; Epstein, 1977; Willson et al, 1978). In the Extended Aerated Pile Method, the

SCHEMATIC DIAGRAM OF THE BELTSVILLE EXTENDED AERATED PILE METHOD OF COMPOSTING

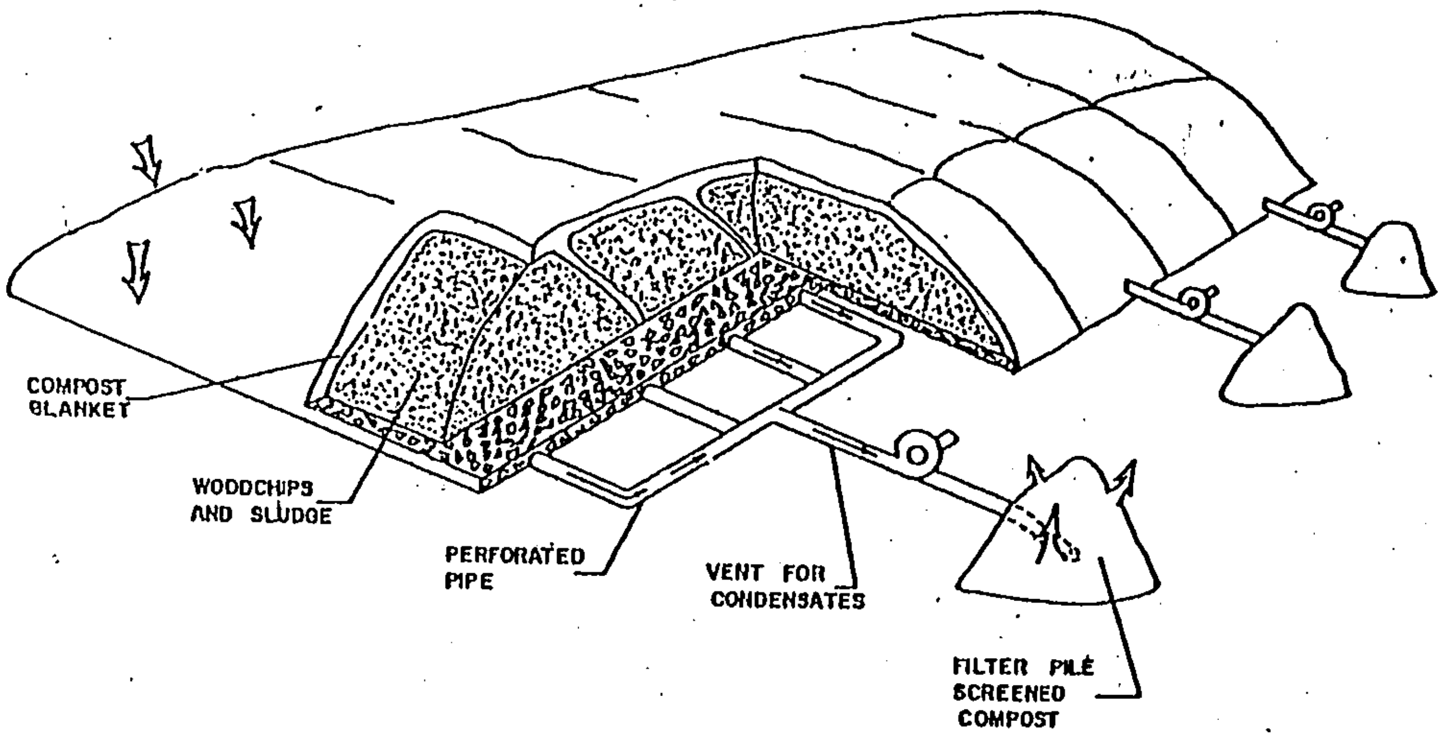


Figure 1

Source - Willson, 1978, p.58.

day's sludge production is mixed with a bulking material and added against the slope of the previous day's pile, thus forming a continuous or extended pile.

During the initial stage of the composting process at the West Windsor Sewage Treatment Plant, the primary and chemically treated sludge (usually lime to suppress odour production) is dewatered to about 26% solids by vacuum filters and a centrifuge (Romano and Faust, 1978). The semi solid dewatered sludge is hauled by a dump truck to a concrete mixing pad in back of the treatment plant and spread over woodchips. Additional woodchips are then spread over the sludgecake by a front end loader (with a known bucket volume) until there is 2.5-3 parts of woodchips to every part of sludge.

In the second stage of the composting process, a tractor with an attached rototiller is used to thoroughly mix the sludge and woodchips. This is the most critical stage in the composting process since the mixing of woodchips with sludge provides structure, texture and porosity to the composting mass which ensures aerobic decomposition, since air could then penetrate and flow freely through the mass (Dallaire, 1978; Epstein, 1978; Haug, 1978; Haug and Haug, 1977; Haug and Haug, 1978; Romano and Faust, 1978; Shea, Braswell and Coker, 1979). By mixing 2.5-3 parts woodchips to every part of sludge ensures that adequate oxygen will be provided to thermophilic organisms for aerobic decomposition. Not enough bulking material or woodchips would result in fewer voids or free air space and hence, limit the quantity and movement of oxygen through the composting pile.

Too much bulking agent would have various detrimental effects:

(1) the pile would become too porous and therefore, it would be unable to retain a sufficient amount of heat necessary for pathogen kill and sludge stabilization; and

(2) the costs of composting increase as greater amounts of material are handled, the expensive woodchip bulking agent would be consumed at a faster rate, and greater land requirements would arise (Haug, 1978).

Prior to mixing, the sludge is often in an aneorobic state due to the initial moist nature of the sludge which displaces void spaces and thus, restricts oxygen transfer. However, by mixing woodchips with sludge, the initial sludge moisture content of 74% has generally been reduced to 50 - 60% moisture after mixing, thereby enhancing void space which ensures aerobic conditions (Epstein, 1978; Haug and Haug, 1977; Romano and Faust, 1978). Haug and Haug (1977 and 1978) have also reported that moisture contents exceeding 60% would result in lower temperature elevations since 75% - 80% of the energy produced through aerobic decomposition is channeled into the evaporation of water. Although Epstein (1978) advises that initially low moisture contents of the woodchip-sludge mixture would be beneficial in processes where woodchips are recovered and re-used, aerobic thermophilic organisms such as bacteria, actinomycetes, and fungi require moisture as well (Epstein, 1978, Hagerty, Pavoni and Heer, 1973; Stanier, Adelberg and Ingraham, 1976; Willson et al, 1978). While Haug and Haug (1978) have stated that complete bacterial metabolism ceases below 10-15%, Epstein (1978) reported that the rate of composting slows down once moisture contents dip below 40-45%. Hagerty, Pavoni and Heer (1973) concluded that moist conditions of about 55% would favour moisture-loving bacteria over fungi or actinomycetes and hence, increase the rate of composting.

The addition of a bulking material, such as woodchips, has also been found by Epstein (1978) and Willson et al, (1978) to improve the initial C/N ratio of sewage sludge of about 10-15/1 to an optimum C/N ratio of 20-30/1. Nitrogen is lost as ammonia at C/N ratios of less than 15/1, while the addition of woodchips to the sludge makes more carbon (C) available for microbial activity and therefore, ensures the conversion of available nitrogen into constituents of the biomass (Epstein, 1978; Willson et al, 1977).

Once the woodchips and sludge are thoroughly mixed into a homogeneous mixture, a front end loader carries the mixture and places it on a previously built section of the aeration base. However, Willson (1977) recommends that the lumps of sludge should not exceed 8 cm. (3 in.) since this would result in a slower decomposition rate.

The initial section of the aeration base consists of 10-16 cm. (4 in.) flexible perforated drainage piping laid out in a "[" shape(approximate total length equal to 20.1 m. (66 ft.) on the ground. Once covered by a 15-20 cm. (6-8 in.) layer of woodchips, the woodchip sludge mixture is piled on the woodchip base and takes on a triangular cross-section appearance with an overall height of about 2.5 m. (7.5 ft.). Additional aeration pipe is then placed on the pad surface parallel to the previously built sections of the pile. The perforated pipe is then connected to a solid plastic pipe that extends beyond the pile base, which is connected to the aerating 1/3 h.p. blower with a 22.9 cm. (9 in.) fan. By the end of the first day's sludge production, a pile with a trapezoidal cross-section is constructed. To prevent the escape of malodorous gases and to provide insulation from the surrounding environment, the completed pile is blanketed with a 30 cm. (12 in.) layer of screened or unscreened compost. The remaining side receives only a thin cover of compost for odour control purposes, since the next day's sludge production when mixed with woodchips is added against the slope of the previous day's pile. After several days, a continuous or extended pile is formed, as portrayed in Figure 2, with pipe spacings at 2.44 m. (8 ft.) intervals. At the completion of a day's pile, the aeration fan with a controlled timer set at 4 minutes on/4 minutes off is turned on and composting begins. The effluent air stream is conducted to an odour filter pile. The filter pile, which is approximately 1.3 m. (4 ft.) high and 2.4 m. (8 ft.) in diameter, is composed of screened compost which absorbs the malodorous gases.

1.5 The Composting Process

Since only mesophilic decomposing organisms, or organisms which grow best at 20°C - 35°C, are originally found in sewage sludge; decomposition of the sludge proceeds at an initially slower rate. The actual rate of composting would be dependent upon the initial chemical nature of the sludge (Epstein, 1978). Sludge, which is primarily composed of organic materials such as sugars, starches and proteins, is characterized by high decomposition rates while compounds of cellulose, certain fats and

CROSS SECTION OF AN EXTENDED PILE

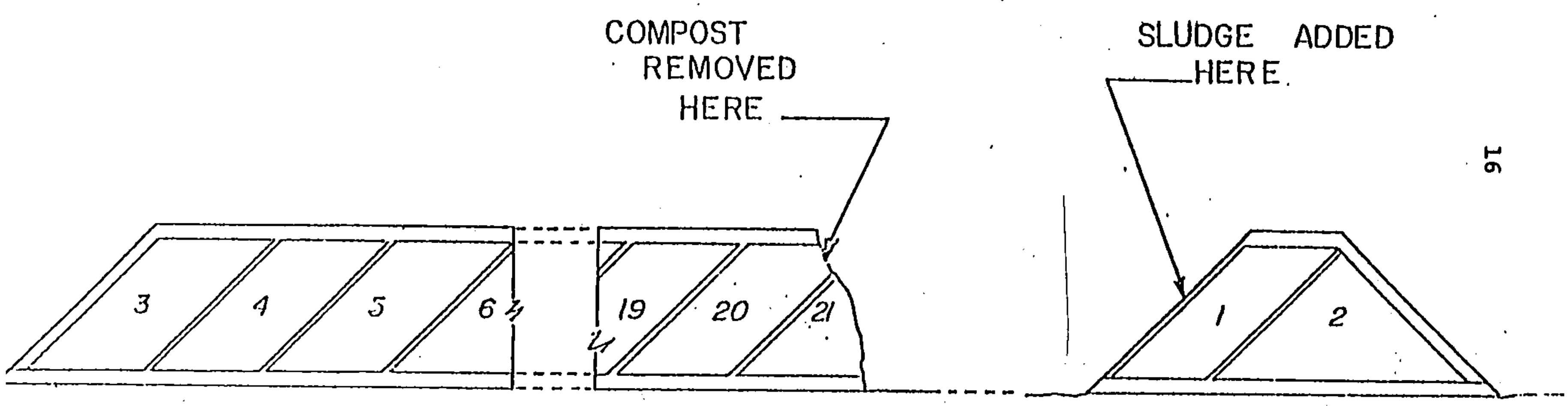


Figure 2

Source - Willson et al, 1978, p. 37.

oils, and other plant constituents, slow down the rate of decomposition (Epstein, 1978).

During the first couple of days of the composting process, heat is released and sludge temperature rises as the mesophilic organisms biologically oxidize the sludge. Once temperatures begin exceeding 45°C, which usually happens in 3 - 4 days, non-pathogenic thermophilic organisms begin to dominate. Further increases in temperature continue at a rate that depends on thermophile numbers, types, and on the characteristics of the organic matter (Willson, Parr and Casey, 1978). Microbial decomposition of the more volatile organic fraction of the sludge eventually raises pile temperature over 60°C (140°F). Temperatures of such a magnitude effectively destroy pathogenic organisms which may cause human diseases. While temperatures of 55°C have been reported sufficient for pathogen kill, temperatures in a composting pile may exceed 80°C (176°F) (Dallaire, 1978; Willson et al, 1978; Willson, Parr and Casey, 1978). Temperatures start to decrease within 16-18 days as the more readily decomposable fraction of the organic matter is consumed by the microflora. Decreasing temperatures, therefore, characterize decreasing biological activity (Dallaire, 1978; Golueke, 1978; Haug and Haug, 1978; Willson et al, 1978). Decreases in microbial activity also indicate that the initial residual sludge has been transformed from a decomposable organic mass to a fairly stabilized compost with many of the characteristics of a fertile pathogenic free soil.

Throughout the composting process, it is critical that aerobic conditions be maintained through the entire pile for rapid, odourless composting. This is attained by maintaining oxygen levels in the composting pile between 5-15% (Epstein, 1978; Romano and Faust, 1978; Willson et al, 1978). A poor distribution or movement of air due to excessive moisture or incomplete mixing is characterized by oxygen levels below 5% (Willson et al, 1978). This results in aneorobic pockets within the pile which will emit odorous gases at the time of pile breakdown. Oxygen levels exceeding 15%, as attained when utilizing higher aeration rates, result in lower temperatures and hence, a slower composting rate. As mentioned earlier, most of the heat islost through moisture evaporation and subsequent transferring of the water vapour to the atmosphere (Haug, 1978; Haug and Haug, 1978; Willson et al, 1978). Furthermore, zones of lower temperatures, within a composting pile, would not be desireable when trying to obtain a pathogen-free compost. Investigations by Epstein (1978) and Willson et al (1978), have shown that intermittent aeration provided the most favourable internal temperature conditions. Cycles are kept short to avoid rapid depletion of oxygen and excessive removal of heat.

At the West Windsor Sewage Treatment Plant, the first two weeks of the composting process are generally directed to providing adequate oxygen through forced aeration to promote organic stabilization and pathogen kill. Oxygen is provided to the aerobic microorganisms by pulling air into the composting pile with a 1/3 h.p. blower which is controlled by a 4 minute on/4 minute off cycle timer. Since substantial portions of a composting pile usually exceed 55°C (130°F), and sludge stabilization is usually attained in 16-18 days, aeration is reversed (air is injected into the pile) and increased for the final two weeks of the composting process. This encourages additional moisture removal from the pile before screening. Haug (1978) reported that additional moisture can be picked up when air is heated. Consequently, given the hot nature of a composting pile, aeration can have valuable drying benefits during the composting process. Note that the quantity of air needed for drying is substantially greater than air needed for promoting organic stabilization of the sludge.

1.6 Justification and Purpose of the Study

At the end of the 28 day composting period, compost piles are torn down and screened. However, removal of the compost from the aerated piles has resulted in the production of excessive odours. Numerous complaints have been received by the City of Windsor from the nearby residential areas surrounding the compost site. The main cause of the odour problem at the time of pile breakdown is the high moisture content within the piles after the 28 day forced aeration period. These high moisture areas which are characterized by inadequately stabilized sludge, may be attributed to excessively high moisture contents prior to composting, and/or the heterogenous as opposed to homogenous nature of the original woodchip-sludge mixture which would restrict oxygen transfer. This would result in anaerobic pockets and insufficient levels of oxygen necessary for proper aerobic decomposition.

An additional problem associated with high moisture content of the composting piles at the end of the forced aeration period are the difficulties encountered in separating the wood-chips from the composted material during the screening process. Similar problems have been identified by Crombie (1979) in Durham, and Willson (Personal Communication, 1979) at Beltsville. Willson (1978) has stated that the production capabilities of the screens at Beltsville sharply decrease when the moisture content of the unscreened compost exceeds 45-50%. Although a newer Liwell screen at Beltsville has been found capable of processing compost at 5-10% higher moisture contents, this would only result in sending wetter bulking material back to the start of the compost process, thus contributing even further to higher moisture contents, and odours to the next composting batch (Willson, Personal Communication, 1979).

One method which has been used to reduce the moisture content of the composting piles is to step up the rate of aeration thereby the rate of evaporation (Golueke, 1978; Willson et al, 1978). Willson (Personal Communication, 1979) has found that higher aeration rates may reduce the moisture content of compost an additional 3-5%.

Oxyten transfer through a composting pile may occur by convective forces, the pressure gradient created by aerating blowers, and by diffusion. However, unlike the pressure gradient created by the aerating blower or convective forces, diffusion does not rely on the resistence of various possible oxygen pathways for movement since the oxygen merely moves from an area of high concentration to an area of low concentration (Willson, Parr and Casey, 1978). Diffusion may be altered by the arrangement of the aeration pipes at the pile base and therefore, may play an important role in moisture reduction since it promotes uniform oxygen movement and hence, evaporation regardless of oxygen pathways. Consequently, Willson, Parr and Casey (1978) reported that distances between aeration pipes under extended piles had little effect on temperatures so long as it did not exceed pile height. Furthermore, oxygen levels were noticeably lower between pipes and consequently, incomplete stabilization occurs at pipe spacing greater than pile height at the end of the 21 day composting period.

Given the promising results of Willson (Personal Communication, 1979) in decreasing moisture contents of composting piles by utilizing high rate aeration, and the success of Willson, Parr and Casey (1978) in composting sewage sludge through closer pipe spacing without detrimentally affecting pile temperatures, the purpose of this investigation was to test the feasibility of reducing high moisture contents of composting piles at the West Windsor Sewage Treatment Plant by employing a more effective piping system and by increasing the rate of aeration during the forced aeration period. Furthermore, by attempting to alleviate the moisture problems associated with the Beltsville Extended Pile Method of Sludge Composting, it is hoped that this sludge disposal method will be continued as opposed to other methods which are not as environmentally and/or economically feasible, and do not have resource recovery benefits.

CHAPTER TWO

METHODOLOGY

2.1 The System Models

Haug (1978) has classified the composting of wet organic sludges as a problem of moisture control. A systematic approach based on speculative theoretical relationships, as established in the introduction, should be utilized when developing a composting moisture control model.

The composting process can be considered as an open controlled system. Although an operator has some level of control over the inputs into the system, energy and matter exchanges between the system and the environment are not totally restricted. The amount of energy exchange between the system and its surroundings is dependent upon temperature differences. Through precipitation, some degree of moisture will penetrate into the protective compost cover material. The by-products of bacterial metabolism such as carbon dioxide, water and heat energy, and evolved gases such as ammonia are also lost to the environment. The controls in this study included the woodchip-sludge mixture to be composted, and the oxygen input as determined by fan or blower operation.

The composting system is highly dependent upon the aeration rate and the porosity of the pile. However, as shown in Figure 3, from the perspective of a moisture control model, the composting system can be divided into two sub-systems with different aeration and porosity requirements:1) a sub-system designe

PROCEDURAL MODEL

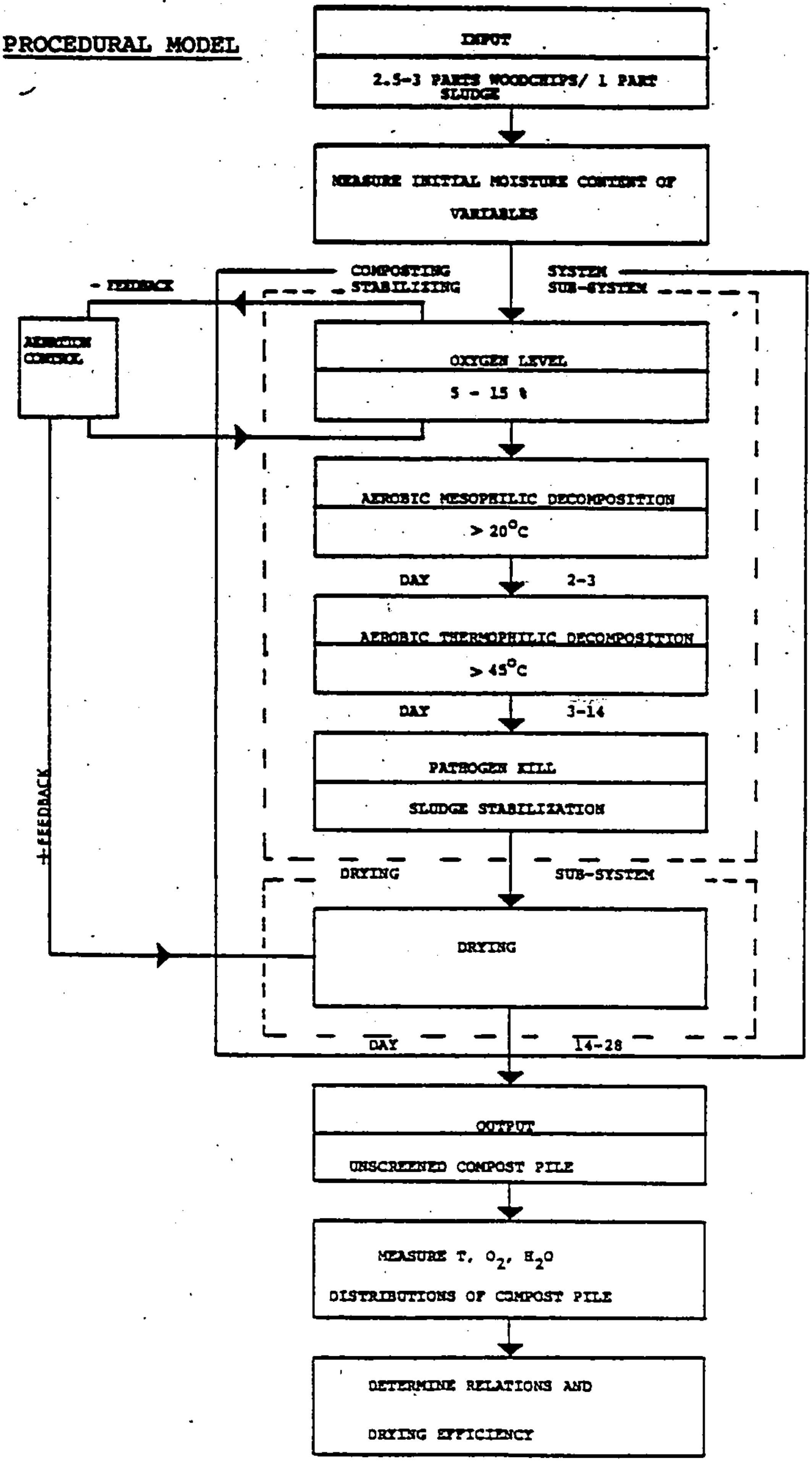


Figure 3

to achieve the primary goal of the composting system, that being pathogen kill and sludge stabilization and 2) an ancillary sub-system designed for moisture reduction purposes prior to pile screening and subsequent to sludge stabilization and pathogen kill.

Within the first sub-system, the usage of a 2.5-3 parts of woodchips to every 1 part of sludge mixture has been found to provide optimum porosity without excessive heat loss which is necessary for pathogen kill and sludge stabilization. The actual levels of oxygen within the composting pile play an important role as shown by Figure 4. Excessively high oxygen levels result in considerable heat loss while low oxygen levels promote odorous anaerobic conditions. Consequently, a negative feedback control system was implemented by regularly monitoring the composting pile. This aided in regulating oxygen levels between 5 and 15 per cent. The oxygen levels were raised or lowered as required, by increasing or decreasing the fan operating time.

Once adequate aeration is maintained, as shown by Figure 3, composting will occur. Temperatures quickly rise as a result of mesophilic decomposition. Thermophilic decomposition, which produces higher temperatures and more efficient decomposition occurs when temperatures exceed 45°C. Within a few days, temperatures sufficient for pathogen kill and sludge stabilization prevail.

Functional Model for the Stabilizing Sub-system

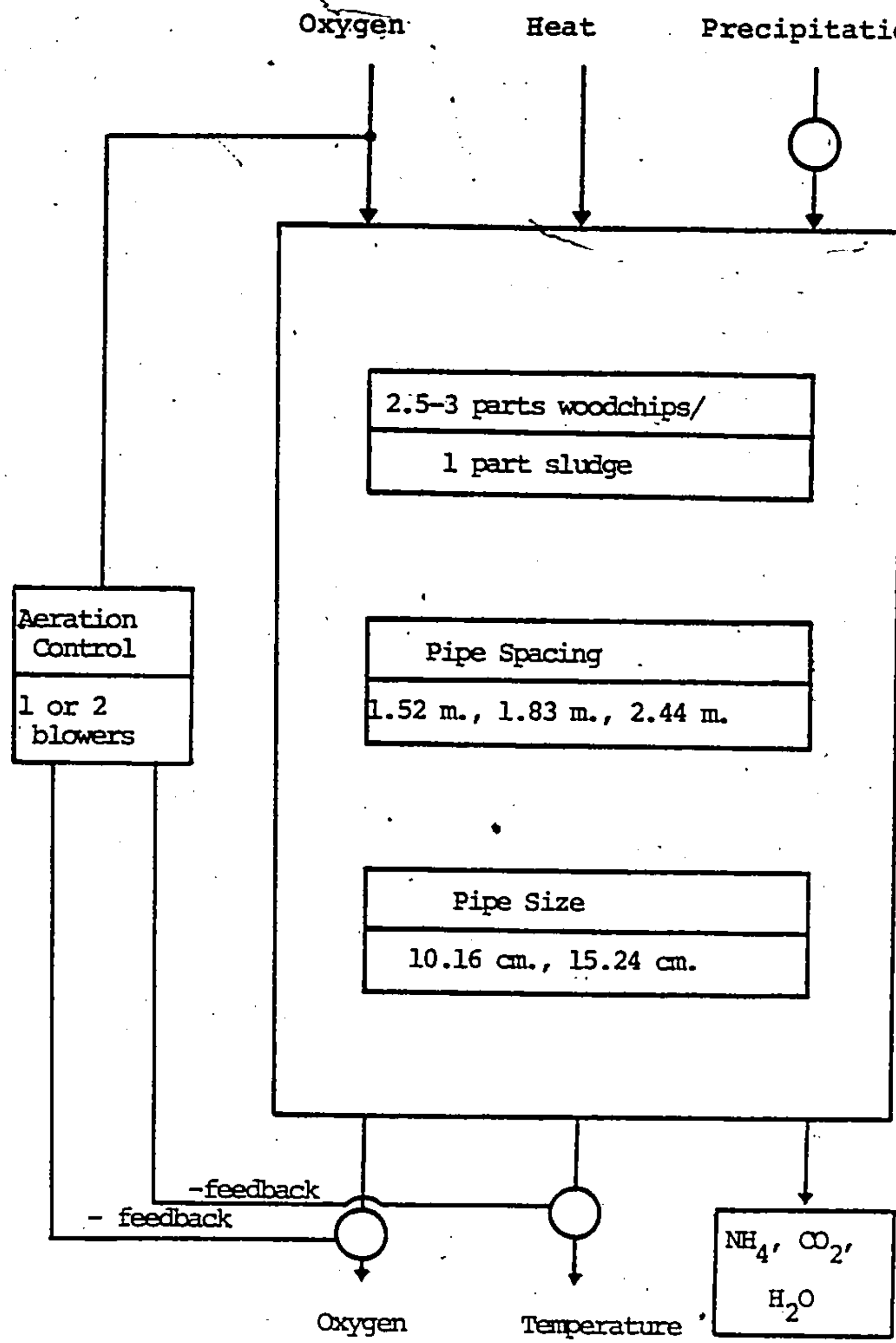


Figure 4

By the end of the second week of composting, a negative feedback controls are no longer needed since pathogen kill and sludge stabilization has been attained. The quantity of air needed for drying is substantially greater than the amount needed for promoting organic stabilization of the sludge. It would be desireable, at this point in time, to step up the rate of aeration. By so doing, higher rates of evaporation are induced and, consequently, a drier compost pile can be attained. As shown by Figure 5, this can be acheived by increasing the oxygen input through the utilization of more blowers, decreased pipe spacing, and increased pipe size thereby ensuring a more uniform oxygen movement. This may result in a reduced number of moist aneorobic pockets, and less resistence to oxygen movement while allowing sufficient room for leacheate drainage. Consequently, this drying sub-system may be responsible for providing an additional moisture reduction benefit during the composting process. However, the success of the drying sub-system in terms of moisture content, may be dependent upon the initial porosity of the woodchip-sludge mixture prior to composting. To ascertain the potential effects of enhanced aeration and decreased pipe spacing on temperatures and oxygen levels within the pile, both are regularly monitored.

The procedural model displayed in Figure 3 was also used to determine the drying efficiency of the various aeration inputs by utilizing stimuli-response relationships. The responses of the composting process to varied aeration inputs can be deduced by monitoring the internal behaviour of the system during and at the end of the process. The drying success of a given aeration

Functional Model for the Drying Sub-system

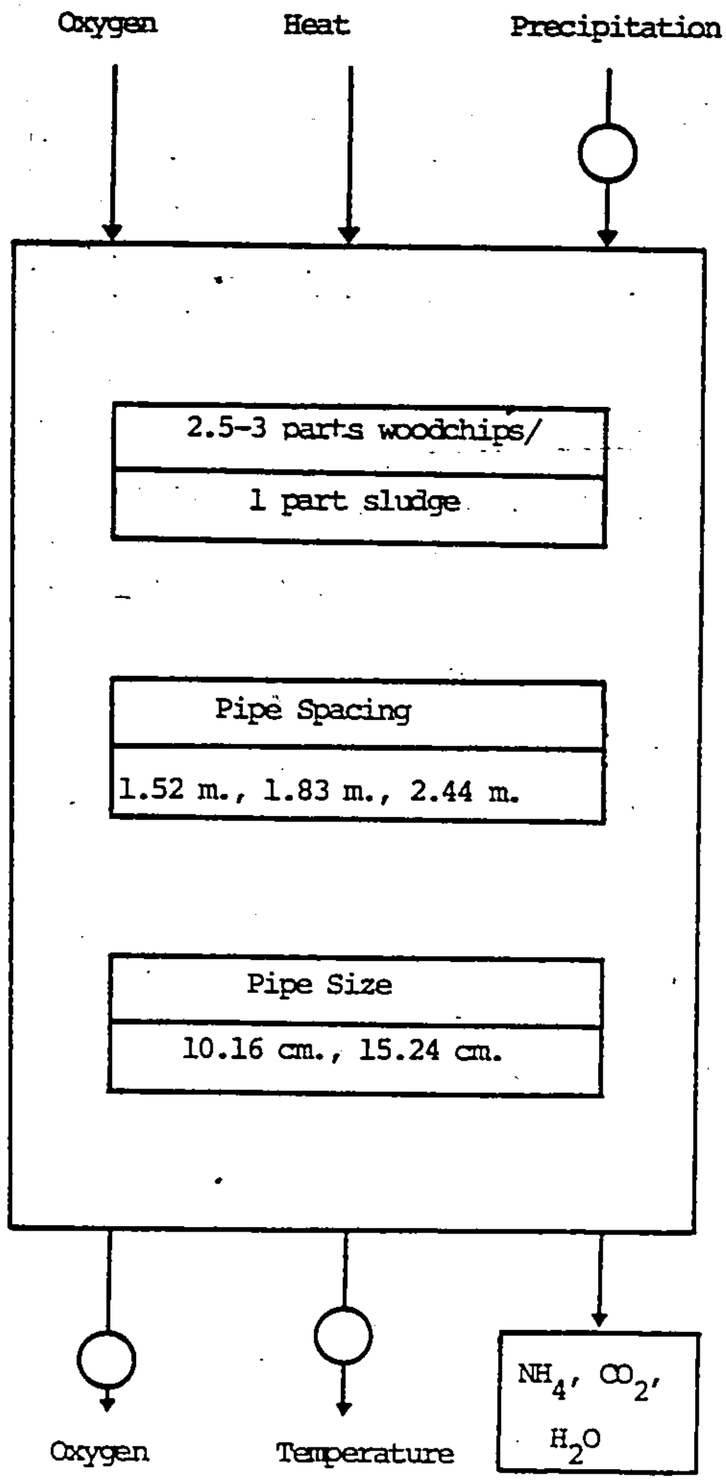


Figure 5

input can be determined at the end of the process through moisture measurements. Actual moisture changes caused by the aeration input could be deduced by comparing the final moisture content of the compost pile with the initial woodchip-sludge mixture.

Since various aeration inputs can be compared to each other when attempting to identify the most efficient moisture control method, precautions are necessary to ensure that alternate and variable sources of moisture to the system are kept constant. Although precipitation, as shown in Figures 4 and 5, has not been found from previous investigations to contribute significant amounts of moisture to a compost system, it is one variable which must be considered in a composting moisture control model. Although little control can be exerted over precipitation, attempts can be made to monitor it and determine if any significant cause-effect relationships exist with the final moisture content at the end of the composting process. If no such relationship exists, drying efficiency could be related to aeration control alone.

Initially high woodchip-sludge moisture contents may also effect the eventual drying efficiency of a pile by a given aeration method. However, by maintaining a constant woodchip-sludge mixture, these differences would be minimal. Furthermore, as Figure 3 indicates, by measuring the moisture content of the initial woodchip-sludge mixture prior to composting, consistent moisture levels can be maintained from pile to pile when attempting to determine the most efficient method of aeration for moisture control purposes.

The utilization of reduced pipe spacings have been found to ensure a more uniform movement of oxygen during aeration control.

Since interrelationships exist between temperature, oxygen and moisture in a composting system, these models also aid in determining the relationships between the three variables and to pipe configuration.

2.2 Models Evaluation

By maintaining constant woodchip-sludge mixing ratios and therefore constant moisture levels prior to composting, and since it is possible to determine any moisture contributions from precipitation through regular monitoring, the models developed in this study were used to assess the drying potential of various modified aeration inputs. The models predict that the drying efficiency of a composting pile utilizing a modified aeration input can be determined by comparing the initial moisture inputs, from the woodchip-sludge mixture, with the final moisture levels attained at the end of the composting process. All of the conducted aeration experiments could then be compared to each other for purposes of determining the optimum moisture reduction method. The moisture spatial patterns should also be uniform or regular, thus minimizing wet malodorous pockets. However, due to the complex nature of the composting process, a given aeration control method must first be capable of pathogen destruction and sludge stabilization during the decomposition stage before drying can occur. This can be monitored by taking temperature and oxygen readings regularly throughout the composting period.

2.3 Experimental Design

In forced aeration systems, air can either be injected (through blowing) or pulled (by suction) into a composting pile. At the composting site at the West Windsor Sewage Treatment Plant, the first two weeks of the composting process is geared toward pathogen kill and sludge stabilization, consequently, air is intermittently pulled into the composting pile by a blower set on a four minute on/four minute off cycle. Suction aeration during this initial two week period of the composting process is desireable over injecting air into the pile, since the odours emitted by the stabilizing sludge can be channeled into the compost scrubber piles via the aeration pipes. However, once adequate sludge stabilization and pathogen kill have occurred, the aerating fan is reversed and set to constant blowing for the final two week dyring period. The marked disadvantage of utilizing the blowing method during the drying phase of the composting process is the resultant moisture layer formed by condensation when the rising water vapour strikes the cooler upper surface layer of the composting pile. Conversely, when air is pulled into a pile by suction, the vapour condenses at the base of the pile in the vicinity of the cold floor as well as the underlying aerating pipes (Dean, 1978). Therefore, the advantage of this aeration method, as opposed to blowing, is that the condensate leachate can be mechanically drawn out of the pile through the aerating pipes as opposed to relying solely upon evaporation for moisture removal purposes. Willson, Parr and Casey (1978) have also shown that the benefits of reversing the direction of aeration were so slight that the extra labour required to reverse the blowers was not justified. Consequently, based on this information, all experiments conducted during this study utilized suction aeration during the final two week drying stage of the composting process.

Since the purpose of this study was to investigate the possibility of employing a more efficient moisture reducing forced aeration system than what is presently being used at the West Windsor Sewage Treatment Plant, several experiments were conducted using modified aeration control systems. All experiments conducted in this study were based on theoretically sound priniciples discussed earlier in the introduction and system models of this study. When attempting to assess the drying efficiency of the various aeration control methods, all other variables which may exert some kind of an effect on moisture levels and distributions were kept constant from experiment to experiment consistent with the composting methods presently used at the West Windsor Sewage Treatment Plant. Some variables included were pile size and shape, the woodchip aeration base, the amount and type of cover material, and the mixing ratio of the woodchip-sludge mixture.

The first set of experiments conducted were specifically designed to ascertain the effect closer pipe spacings would have in aiding the distribution of air and thereby encourage a uniform moisture reduction throughout the entire composting pile. Consequently, the standard aeration input and pipe size used at the West Windsor Sewage Treatment Plan were also utilized. The pipe spacings used were 1.52 m. (5 feet) for Experiment 1, 1.83 m. (7 feet) for Experiment 2, and the standard 2.44m. (8 feet) for Experiment 3. Constant suction as opposed to injection was used during the final 2 weeks of composting after sludge stabilization and pathogen kill had been attained. The initial cycle suction phase was set in accordance with temperature and oxygen readings.

Since temperatures sufficient for pathogen kill and sludge stabilization usually occur during the initial two weeks of the composting process, the final two weeks is geared toward drying the compost mass. Therefore, it would be desireable to draw in as much air as possible into the pile and hence, encourage the rate of evaporation. Consequently, the second set of experiments conducted in this study were designed to determine the effects of enhanced aeration, when combined with closer pipe spacing, would have on the distribution of air and reduction of moisture. A second fan was employed in these experiments in an attempt to increase the aeration rates of the composting system. The fans were both operated off the same timer while aeration cycles during the initial two weeks of the composting process were set in accordance with the oxygen and temperature readings taken. Pipe spacings utilized were 1.52 m. (5 feet) for Experiment 4, 1.83 m. (7 feet) for Experiment 5, and the standard 2.44 m. (8 feet) for Experiment 6. Standard pipe size was also used.

During several occasions at the Treatment Plant, leachate has been found responsible for clogging the aerating pipes and consequently, obstructing the flow of air into the pile. Therefore, a third set of experiments was designed to improve the distribution of air and reduce moisture levels throughout the composting pile by employing a larger 15.24 cm. (6 inches) pipe size instead of the standard 10.16 cm. (4 inches), which would improve leachate drainage and encourage air movement through the aerating pipes. These experiments were conducted in a similar manner to the previous experiments. Pipe spacings were set at 1.52 m. (5 feet) for Experiment 7, 1.83 m. (7 feet) for Experiment 8, and 2.44 m. (8 feet) for Experiment 9.

For the purposes of comparison, a tenth experiment or "control experiment" was conducted utilizing the present standard forced aeration system at the West Windsor Sewage Treatment Plant. This system utilizes 10.16 cm. (4 inches) piping placed at 2.44 m. (8 feet) intervals which are connected to one aerating fan. The initial four minutes on/four minutes off aeration cycle is designed to promote pathogen kill and sludge stabilization.

After two weeks, the aerating fan is reversed and a constant air supply is injected into the composting pile for drying purposes. A summary of the experiments conducted during this study can be found in Table 3.

2.4 Sampling Design and Measurement of Study Variables

To determine the initial moisture content of the woodchip-sludge mixture prior to composting, five samples were analyzed as outlined in Appendix 1. Since wet woodchips or a moist sludge-cake may be responsible for higher moisture levels than recommended for optimum composting, an additional five woodchip and sludge

TABLE 3

A Summary of Conducted Experiments

Name	Pipe Spacing Interval	Aeration Rate	Pipe Size
Set 1 Experiments:			
Experiment #1	1.52 m. (5')	* 1 Fan	*10.16 cm. (4")
Experiment #2	1.83 m. (7')	* 1 Fan	*10.16 cm. (4")
Experiment #3	*2.44 m. (8')	* 1 Fan	*10.16 cm. (4")
Set 2 Experiments:			
Experiment #4	1.52 m. (5')	2 Fans	*10.16 cm. (4")
Experiment #5	1.83 m. (7')	2 Fans	*10.16 cm. (4")
Experiment #6	*2.44 m. (8')	2 Fans	*10.16 cm. (4")
Set 3 Experiments:			
Experiment #7	1.52 m. (5')	2 Fans	15.24 cm. (6")
Experiment #8	1.83 m. (7')	2 Fans	15.24 cm. (6")
Experiment #9	*2.44 m. (8')	2 Fans	15.24 cm. (6")
Control Experiment:			
Experiment #10	*2.44 m. (8')	*1 Fan	*10.16 cm. (4")

* - indicates a standard method used during the composting process at the West Windsor Sewage Treatment Plant.

Note - All experiments except for Experiment 10 utilized constant suction aeration during the final 2 weeks of the composting process.

samples, prior to mixing, were analyzed for moisture content. Willson (Personal Communication, 1979) found that odours associated with composting are proliferated when wet woodchips are mixed with sludge prior to composting.

Regular temperature and oxygen readings were taken throughout the four week composting period. Two readings were taken at the ends of the pile where lower temperatures predominate, and five additional readings were taken across the top of the composting pile. To ensure pathogen kill and sludge stabilization, fan cycles were regulated according to these readings for all experiments conducted. The final two weeks of readings were used to determine the effect of full cycle aeration on the composting piles. The instruments used to measure these variables are described in Appendix 2.

With the assistance of a front end loader, a cross-section through the middle of the composting pile, but perpendicular to the aerating pipes, was dug out at the end of the four week composting period. A 2.44 m. (8 ') by 2.44 m. (8 ') sampling grid was used to collect 48 stratified random samples at approximately 0.61 m. (2') intervals throughout the exposed face of the cross-sectioned pile. The usage of such a large sample size is necessary when attempting to determine the spatial patterns of the measured variables, and in identifying relationships or correlations that may exist relative to each other and to pipe configuration.

Since a given aeration system would be disrupted during the cutting of a cross-section, the oxygen levels attained would actually be a measure of the oxygen diffusing into the compost. Investigations by Willson, Parr and Casey (1978), however, have found that these levels are equivalent to those attained during aeration. Both are a function of the porosity and rate of oxygen consumption within the pile. Furthermore, given that temperature variation within a plane are minimal (Coulson, 1978), temperature and oxygen readings could therefore be taken immediately at the site. The temperature and oxygen probes were inserted horizontally, about 0.75 m. (2-3 feet) into the exposed face of the experimental pile and the readings were taken accordingly. In addition, samples were taken to the lab and analyzed for moisture content (see Appendix 1).

Since the experimental piles were constructed from June, 1979 through to November, 1979, different experimental piles would be subjected to varying precipitation levels. Consequently, to deduce the potential impact precipitation would have on the pile moisture levels at the end of the 28 day composting period, incoming precipitation was continuously monitored by utilizing the Balour Rain Guage located at the West Windsor Sewage Treatment Plant. This was one of several guages operated throughout Essex County by the University of Windsor's (Department of Geography) Precipitation Network.

2.5 Hypotheses and Statistical Analyses Utilized

Based on the system's model and experimental design, the following hypotheses were evaluated:

Hypothesis 1.

Given that a constant woodchip-sludge mixture will be used throughout all composting experiments, the average initial moisture content of the experimental piles should not be significantly different.

To simultaneously test this hypothesis, (statistically, this is a null hypothesis) if indeed the initial moisture content of the experimental piles were not significantly different, a One-Way Analysis of Variance can be employed. Furthermore, should this analysis produce significant results, a Two-Way Analysis of Variance could then be utilized to determine if these significant differences were found in the experimental piles utilizing modified aeration (standard, enhanced, or larger pipe size), and/or various pipe spacings (1.52 m., 1.83 m., and 2.44 m.), and/or some combination of both. Finally, student's t-tests could then be utilized to ascertain individual difference between two experimental piles. However, the following assumptions must first be met before conducting any of the above mentioned parametric tests:

(1) the sample variances must be equal or homoscedastic and

(2) the sample data must be normally distributed.

These can be evaluated by utilizing the Hartley F-max Test for equal variances, and the Kolmogorov-Smirnoff Test for normality. When comparing three or more independent samples for equal variances the Hartley F-max Test is the preferred statistic (Harshbarger, 1977).

Hypothesis 2.

Since the porosity and, hence, drying efficiency of a given experimental pile is directly related to the homogeneous nature of the original woodchip and sludge inputs (which are independent of aeration control), significant differences in the average moisture content of these inputs should not occur between the experimental piles.

By employing parametric student's t-tests, insignificance can be mathematically demonstrated when the observed values do not exceed the critical value at a given level of probability and degrees of freedom (df.) of $(n_1-1) + (n_2-1)$. As described in Hypothesis 1, the assumptions of normality and equal sample variances must first be met.

Hypothesis 3.

Temperature and oxygen levels sufficient for pathogen kill and sludge stabilization can be attained in all experimental piles despite using different aeration control methods.

Hypothesis 4.

Given the insulating properties of the cover material, and the moisture reducing benefits of aeration control, an insignificant cause-effect relationship will occur between the total amount of precipitation received and the average moisture level of the experimental piles at the end of the composting period.

This relationship can be tested by utilizing Correlation-Regression Analysis whereby the dependent variable -- average moisture content of the piles at the end of composting -- is regressed against the independent or causal variable -- total amount of precipitation received by each experimental pile -- provided that the data is normally distributed as determined by the Kolmogorov-Smirnoff Test (K.S.-Test) for normality.

Hypothesis 5.

Since drying is an important sub-system component of sludge composting systems, significant moisture reductions will occur over all experimental piles.

Parametric student's t-tests were utilized to determine if significant reductions occur between the initial and final moisture content of each experimental pile provided the assumptions of normality and equal variances are met. Since only two independent samples were being compared, the Variance-Ratio Test for homogeneity of variances was utilized for each experimental pile.

Hypothesis 6.

Given that the moisture levels of the experimental piles are found to be independent of other modifying inputs, progressively greater moisture reductions will occur as more efficient aeration systems are utilized.

Statistical tests similar to those outlined in Hypothesis 1 were used to test the significance of this hypothesis. The dependent variable, however, was the moisture content of the experimental piles at the end of the composting process. Furthermore, significant differences may then be related to the type of aeration used or pipe spacing, and/or some combination of both.

Hypothesis 7.

Given the inter-relationships of temperature, oxygen, and moisture within a composting system, significant inverse relationships will occur between the spatial patterns of temperature (measure of biological activity) and oxygen (function of the level of activity provided adequate aeration is provided), and moisture (displaces oxygen voids) and oxygen. Conversley, a significant positive relationship exists between temperature and moisture (adequate levels are needed for decomposition).

Provided that the data is normally distributed, Correlation-Regression Analysis were utilized to evaluate these relationships.

Hypothesis 8.

The temperature, oxygen, and moisture profiles of the experimental piles should approach uniformity as a more efficient (reduced) pipe spacing is utilized thereby decreasing the possibility of producing wet malodorous pockets.

The spatial patterns of these variables were evaluated through the computer mapping program Symap Version 5.19/5.20 and its trend surface option. Trend surface attempts to breakdown each observation of a spatially distributed variable into two components, a regional trend component and a local effect component (Unwin, 1975). This is attained by progressively fitting higher order geometric surfaces (more complex polynomial equations) to the observed data. The regional effect component is described by the best fitting surface, whereas the residual values (observed minus expected) are assigned to the local component (local departures from the regional component). Consequently, by separating these local and random variations or "noise effects" from the spatial pattern of the observed variable, a variable may be identified as exhibiting some sort of a regular or clustered pattern as opposed to a confusing non ordered random pattern.

Although six trend surfaces are available in this computer package, only four surfaces were utilized: linear, quadratic, cubic, and quartic given that each variable has only 48 recorded observations. Unwin (1975), has stated that far more observations are needed than are terms in a trend surface equation. A good rule of thumb is that the number of observations should at least be equal to p+30 where p is equal to the number of terms in the fitted trend surface.

Three major assumptions associated with trend surface analysis are:

(1) the data must be continuous,

(2) the most significant fitted trend surface should be decided, and

(3) the data should not be clustered since this can create distorted results.

In this investigation, the studied variables exhibited continuous patterns, while the significance of each trend surface level and the amount of increased fit over a previous level were tested with the variance ratio F-test. Consequently, the highest order surface which is significant in both of the above mentioned cases was chosen to describe the spatial pattern of a study variable. Finally, by using a stratified random sampling scheme with the assistance of a sampling grid, undue data point clustering was avoided. In fact, nearest neighbour analysis indicated that the sampling points of the study variable tended to be random with a moderate tendency toward uniformity (point distribution coefficient = 1.81).

Since autocorrelated residuals, as evidenced by the clustering of similar residual values, may strongly bias the F-tests to the extent of wrongly rejecting the null hypothesis of no trend (Unwin, 1975), the residuals were tested for autocorrelation by plugging in their values into the trend surface analysis.

CHAPTER THREE

ANALYTICAL FINDINGS

3.1 Pre-Experimental Results - The Woodchip-Sludge Input

Prior to the construction of each experimental pile, five samples of the woodchip-sludge mixture were collected and analyzed for moisture content. An examination of Table 4 indicates that, in general, the moisture content of the experimental piles varied, ranging from a high of 56.1% for Experiment 7 to a low of 51.5% for Experiments 3 and 4, prior to composting. To determine if these differences were mathematically significant, an approximate One-Way Analysis of Variance was conducted since the assumption of homoscedastic variance, as seen in Table 5, was not met despite the data being normally distributed. Since the assumptions of parametric statistics can be relaxed when testing against a null hypothesis (Norcliffe, 1977), the loss in efficiency of the test was compensated for by establishing a higher acceptable probability level. An Examination of Table 6 reveals that the F-observed values did not exceed the F-crit (0.01) value of approximately 2.90 at 9 and 40 degrees of freedom; consequently, the inital moisture contents of the experimental piles were not significantly different. Therefore, the results of this analysis support Hypothesis 1 (or null Hypothesis 1), that similar initial moisture contents prior to composting are maintained when utilizing a constant woodchip-sludge mixture. Furthermore, the drying efficiency of a given pile could then

TABLE 4

Descriptive Characteristics of the Initial Input Variables

Variable	Average Moisture Content (in %)	Standard Deviation	Coefficient of Variability (in %) (s.d./x̄)
Experiment #1-			
Sludge	76.4	1.8	2.3
Woodchips	37.9	4.2	11.1
Mixture	53.9	2.5	4.5
Experiment #2-			
Sludge	74.3	2.0	2.7
Woodchips	42.1	2.3	5.5
Mixture	52.9	5.4	10.1
Experiment #3-			
Sludge	76.2	1.2	1.5
Woodchips	38.7	6.8	17.6
Mixture	51.5	3.4	6.5
Experiment #4-			
Sludge	71.6	2.8	3.9
Woodchips	36.6	6.1	16.8
Mixture	51.5	1.4	2.8
Experiment #5-			
Sludge	77.7	1.1	1.4
Woodchips	37.3	5.5	14.8
Mixture	53.6	3.4	6.3
Experiment #6-			
Sludge	78.3	1.4	1.8
Woodchips	38.9	3.0	7.6
Mixture	53.0	4.7	8.9
Experiment #7-			
Sludge	71.6	3.0	4.2
Woodchips	40.5	3.4	8.6
Mixture	56.1	8.0	14.3
Experiment #8-			
Sludge	78.9	3.1	3.9
Woodchips	38.7	5.3	13.8
Mixture	53.9	4.5	8.4

TABLE 4 (continued)

Variable	Average Moisture Content (in %)	Standard Deviation	Coefficient of Variability (in %) (s.d./x̄)
Experiment #9-			
Sludge	76.2	3.2	4.1
Woodchips	37.8	7.2	18.9
Mixture	54.5	6.1	11.2
Experiment #10-			
Sludge	71.2	3.1	4.4
Woodchips	42.3	3.8	9.0
Mixture	55.1	2.6	4.8

TABLE 5

Kolmogorov-Smirnoff Test of Normality and Hartley F-max Test of Equal Variances for the Input Moisture Content Data

Variable	D-max	F-max
Sludge Moisture Content		
Experiment #1	0.255	
Experiment #2	0.298	
Experiment #3	0.233	
Experiment #4	0.294	
Experiment #5	0.234	8.06
Experiment #6	0.167	
Experiment #7	0.219	
Experiment #8	0.149	
Experiment #9	0.227	
Experiment #10	0.282	
Woodchip Moisture Content		
Experiment #1	0.247	
Experiment #2	0.238	
Experiment #3	0.419	
Experiment #4	0.220	
Experiment #5	0.295	9.51
Experiment #6	0.253	
Experiment #7	0.272	
Experiment #8	0.306	
Experiment #9	0.312	
Experiment #10	0.277	
Moisture Conent of the Mixture		
Experiment #1	0.330	
Experiment #2	0.228	
Experiment #3	0.162	
Experiment #4	0.268	
Experiment #5	0.196	*31.18
Experiment #6	0.292	
Experiment #7	0.232	
Experiment #8	0.304	
Experiment #9	0.209	
Experiment #10	0.278	

D-max must exceed D-crit (0.05)=.565 to reject the variable as being normally distributed.

*Significantly different variances when F-max exceeds F-crit (0.05)=26.5.

TABLE 6

Approximate Analysis of Variance of Initial Moisture Content Between the Experimental Piles

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F
Between Experiments	95.748	9	10.638	[x]0.504
Within Experiments	843.932	40	21.098	
Total	939.680	49		

[x] not significant

be solely attributed to the utilized aeration control method.

Since the drying efficiency of a given aeration control method could be altered by the homogenous nature of the original woodchip-sludge mixture, five woodchip and sludge cake samples were collected prior to mixing and analyzed for moisture content. As illustrated in Table 4, the average moisture content of the sludge cake samples were found to be highly variable between the experimental piles ranging from 71.2% for Experiment 10 to 78.9% for Experiment 8. A parametric student's t-test was conducted to determine if these differences were significant since the data was normally distributed and their variances were homoscedastic (Table 5). An examination of Table 7 reveals that significantly different sludge cake moisture contents occurred in 21 of the 45 cases looked at. Conversely, the day's sludge production for an experimental pile tend to be fairly homogenous as shown by the coefficients of variability given in Table 4. The woodchip bulking material, in fact, was responsible for altering the homogenous nature of the sludge cake to a more heterogenous woodchip-sludge mixture as shown by the high coefficients of variability given in Table 4. Note that the woodchip bulking material did not differ significantly among the experimental piles (Table 8).

Given that significantly different sludge moisture levels did occur between the experimental piles, and that a high degree of moisture variability was found in the woodchip bulking material prior to mixing, Hypothesis 2 (statistically null hypothesis 2) was rejected. It will be recalled that Hypothesis 2

TABLE 7

Matrix of "t-observed" Values for Sludge Samples

	Sludge Samples									
	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
1. Experiment #1	-									
2. Experiment #2	1.66	-								
3. Experiment #3	0.17	-1.86	-							
4. Experiment #4	*4.25	1.52	*3.77	-						
5. Experiment #5	-1.01	*-3.69	*-3.66	*-3.94	-					
6. Experiment #6	*-4.49	*-3.63	-2.08	*-7.18	-0.52	-				
7. Experiment #7	*2.91	*5.63	*3.05	-0.03	*4.49	*4.48	-			
8. Experiment #8	-1.72	-2.18	-1.53	*-3.65	-0.75	-0.42	*-2.97	-		
9. Experiment #9	0.11	-2.44	0.01	-2.06	1.29	1.18	*-5.61	1.06	-	
10. Experiment #10	*3.68	1.51	*3.00	0.28	*3.68	*6.10	0.16	*5.11	2.07	-

* Significant at 2-tailed 0.05 level of significance, df=4- t-crit = 2.78.

TABLE 8

Matrix of "t-observed" Values for Woodchip Samples

Woodchip Samples

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
1. Experiment #1	-									
2. Experiment #2	-1.63	-								
3. Experiment #3	-0.23	1.04	-							
4. Experiment #4	0.57	1.51	0.70	-						
5. Experiment #5	0.16	1.93	0.34	-0.17	-					
6. Experiment #6	-0.44	*3.25	-0.04	-0.63	-0.46	-				
7. Experiment #7	-1.87	0.97	-0.48	-1.15	-0.81	-1.62	-			
8. Experiment #8	-0.30	1.24	0.02	-0.82	-0.34	0.06	0.65	-		
9. Experiment #9	0.05	1.29	0.16	-0.26	-0.11	0.34	1.15	0.19		
10. Experiment #10	-1.23	-0.10	-1.13	-1.48	*-2.82	-1.54	-0.61	-1.21	-0.98	

*Significant at 2-tailed 0.05 level of significance, df=4 - t-crit=2.78

predicted that the differences and variability in the average moisture content of the sludge and woodchips would be minimal. Consequently, the drying efficiency of an aeration method may be modified by the heterogenous nature, and therefore porosity, of the original woodchip-sludge mixture.

3.2 Performance of the Experimental Piles During the Composting Process

To ensure that temperatures adequate for pathogen kill and sludge stabilization occurred during the initial two weeks of the composting process, all experimental piles were regularly monitored for temperature and oxygen levels. Monitoring was continued into the final two weeks of the composting process to determine the effect of increasing aeration on the composting piles.

To determine the effect of reduced pipe spacing, at the aeration base, on moisture reduction within the composting system, three piles were constructed. The utilized pipe spacings included 1.52 m. (5 ft.) for Experiment 1, 2.13 m. (7 ft.) for Experiment 2, and 2.44 m. (8 ft.) or the standard system utilized by the City of Windsor in Experiment 3. Figures 6 to 8 indicate that temperatures adequate for pathogen kill were attained by the fourth day of composting. Furthermore, active sludge stabilizing was continuing even at the end of the composting process as denoted by the high temperature readings.

The increasing of aeration by switching to constant suction from 4 min. on/4 min. off cycle suction resulted in a subsequent rise in oxygen levels within the piles, except

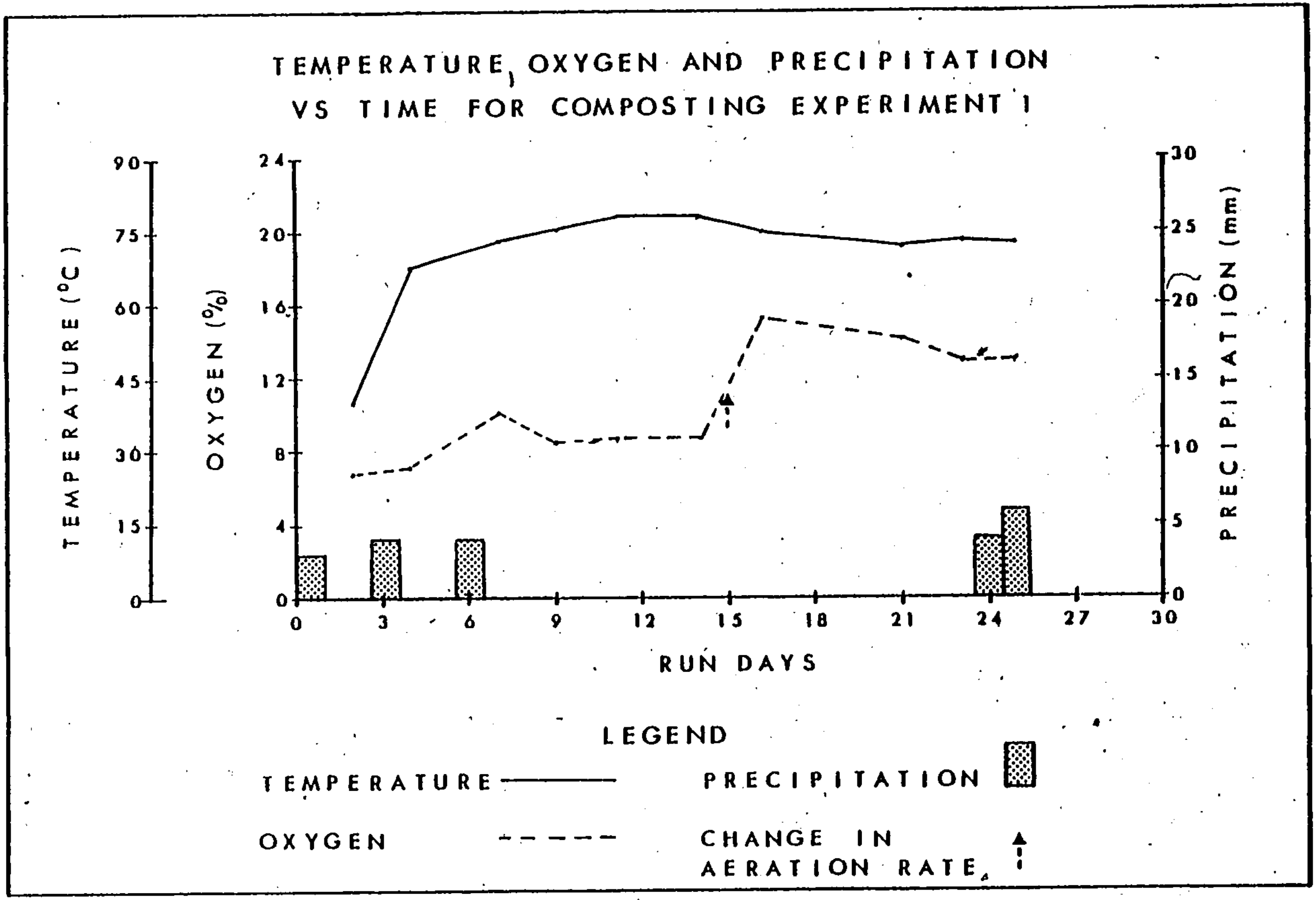

TEMPERATURE, OXYGEN AND PRECIPITATION
VS TIME FOR COMPOSTING EXPERIMENT 1
TEMPERATURE (°C)
90
75
60
45
30
15
0
OXYGEN (%)
24
20
16
12
8
4
0
PRECIPITATION (mm)
30
25
20
15
10
5
0
0
3
6
9
12
15
18
21
24
27
30
RUN DAYS
LEGEND
TEMPERATURE
OXYGEN
PRECIPITATION
CHANGE IN
AERATION RATE

Figure 6

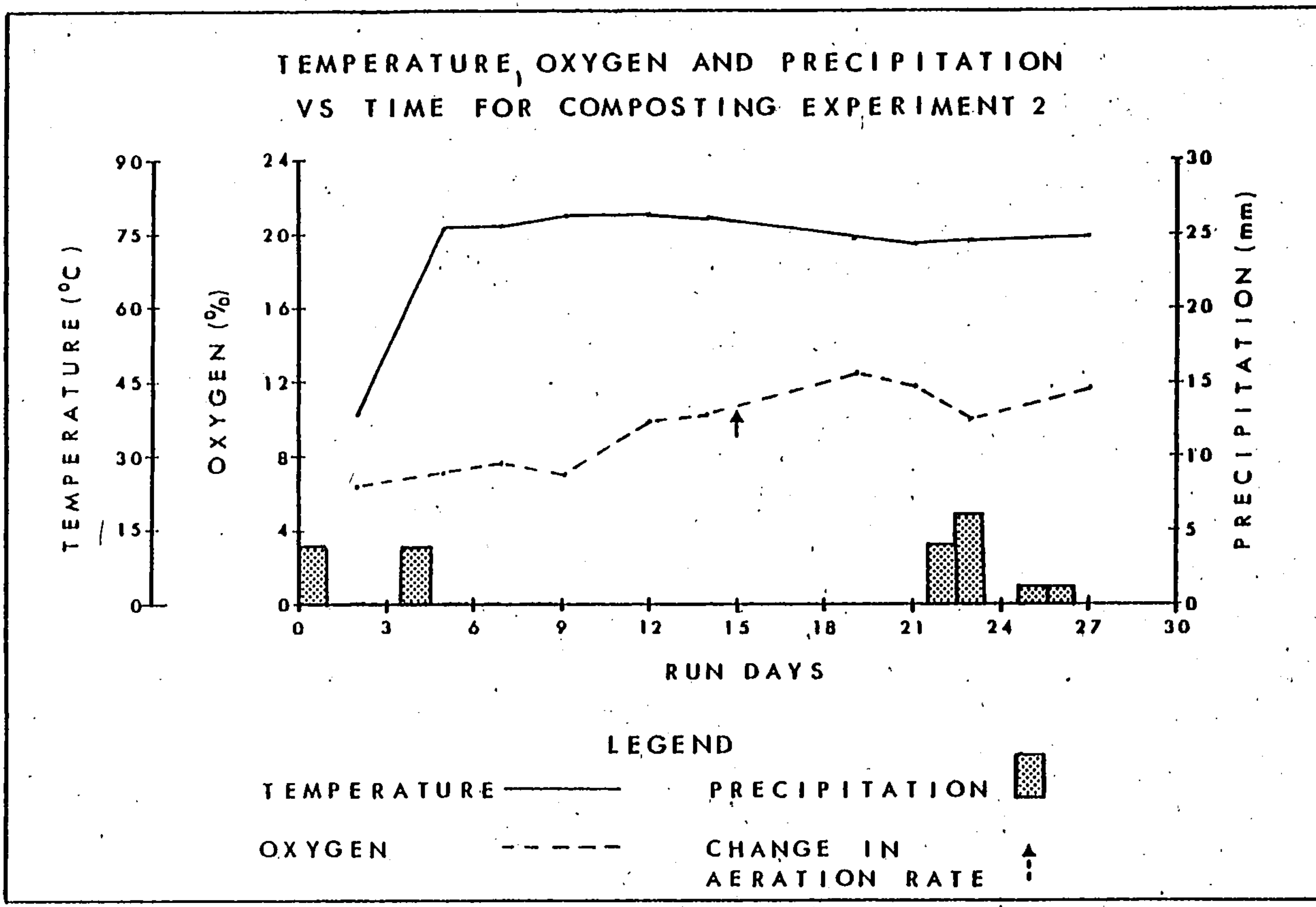

TEMPERATURE, OXYGEN AND PRECIPITATION
VS TIME FOR COMPOSTING EXPERIMENT 2
TEMPERATURE (°C)
90
75
60
45
30
15
0
OXYGEN (%)
24
20
16
12
8
4
0
PRECIPITATION (mm)
30
25
20
15
10
5
0
0
3
6
9
12
15
18
21
24
27
30
RUN DAYS
LEGEND
TEMPERATURE
OXYGEN
PRECIPITATION
CHANGE IN AERATION RATE

Figure 7

TEMPERATURE, OXYGEN AND PRECIPITATION VS TIME FOR COMPOSTING EXPERIMENT 3

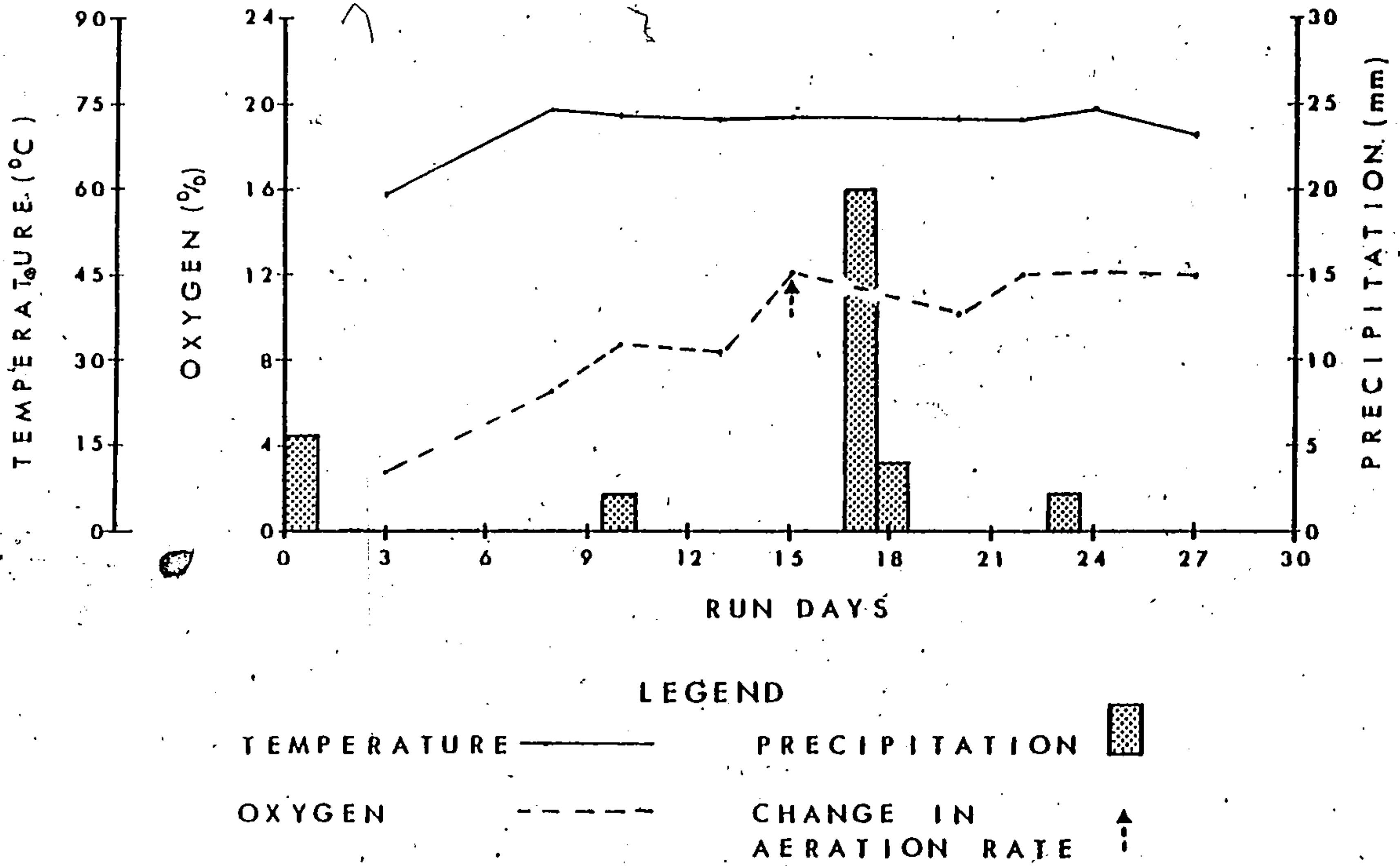


Figure 8

Experiment 3 (Figures 6 to 8). However, the decreasing oxygen levels noted in Experiment 3 may have been attributed to the high amount of precipitation received after enhancing aeration (Figure 8). Only a slight decrease in temperature was experienced by the composting piles subsequent to enhanced aeration. The total precipitation received by the composting piles as indicated in Figures 6 to 8 were respectively 21 mm., 20 mm., and 33 mm.

Given that enhanced aeration would promote a greater rate of evaporation, Experiments 4 to 6 were designed to ascertain the combined effects of enhanced aeration (by employing two aeration blowers), and reduced pipe spacing on the final moisture levels of the composting piles. The pipe spacings utilized were 1.52 m. (5 ft.), 2.13 m. (7 ft.), and 2.44 m. (8 ft.), respectively, for Experiments 4 to 6. Despite using a more efficient and higher rate of aeration, temperatures sufficient for pathogen kill were attained by the fourth to fifth day of composting, as shown in Figures 9 to 11. As delineated by the high temperature levels, vigorous decomposition had persisted up to the last day of composting.

As shown by Figures 9 to 11, the switching of the blowers on the fifteenth day from a 4 min. on/4 min. off cycle to constant suction, produced a subsequent increase in oxygen, and a minimal decrease in temperature levels within the composting piles. Note that on the twelfth day of composting, the aerating blowers were set on a 4 min. on/4 min off cycle when it was realized that one of the aerating blowers was operating on a 2 min. on/6 min. off cycle. The amount of precipitation received,

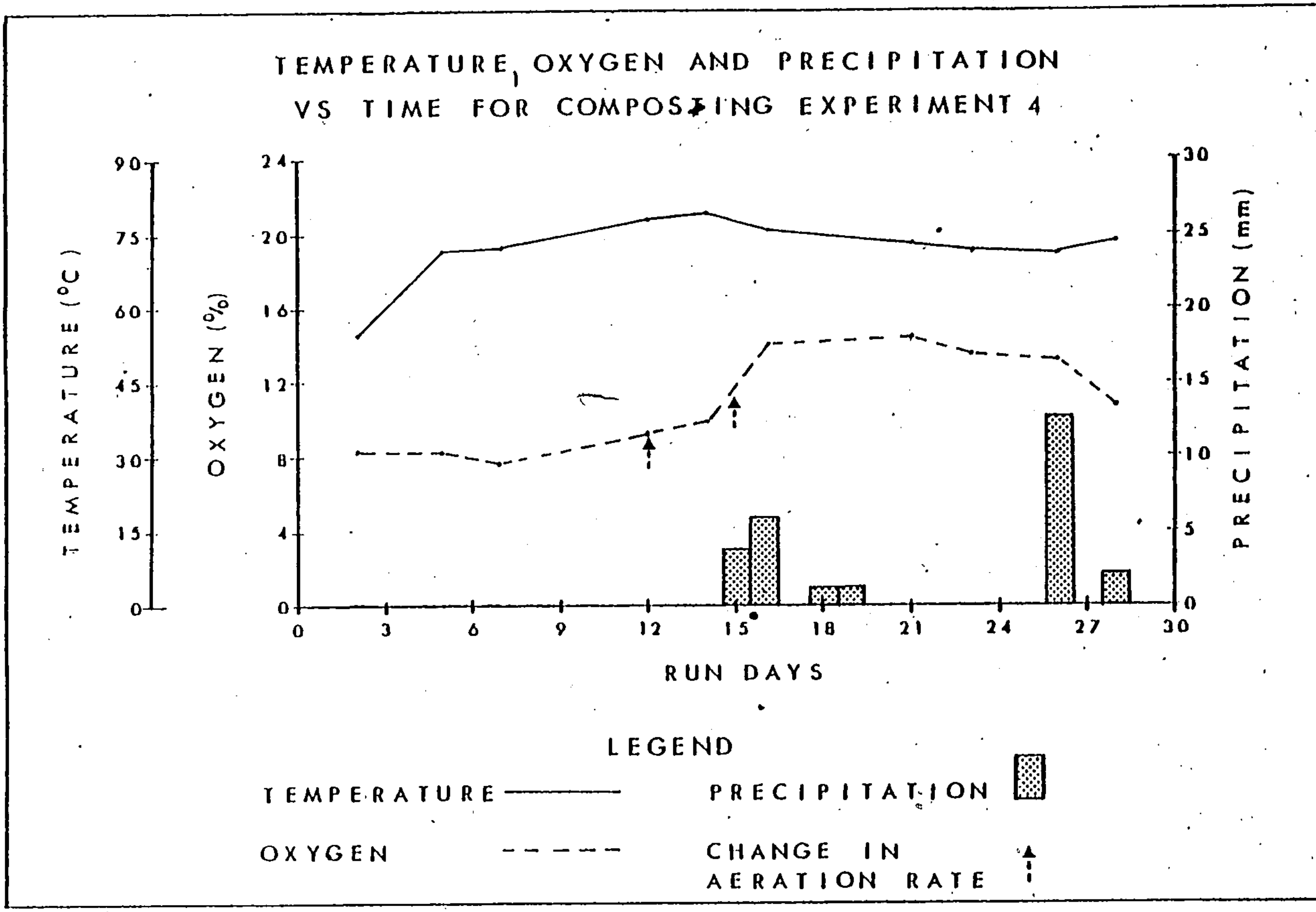

TEMPERATURE, OXYGEN AND PRECIPITATION
VS TIME FOR COMPOSTING EXPERIMENT 4
TEMPERATURE (°C)
90
75
60
45
30
15
0
OXYGEN (%)
24
20
16
12
8
4
0
PRECIPITATION (mm)
30
25
20
15
10
5
0
0
3
6
9
12
15
18
21
24
27
30
RUN DAYS
LEGEND
TEMPERATURE
OXYGEN
PRECIPITATION
CHANGE IN AERATION RATE

Figure 9

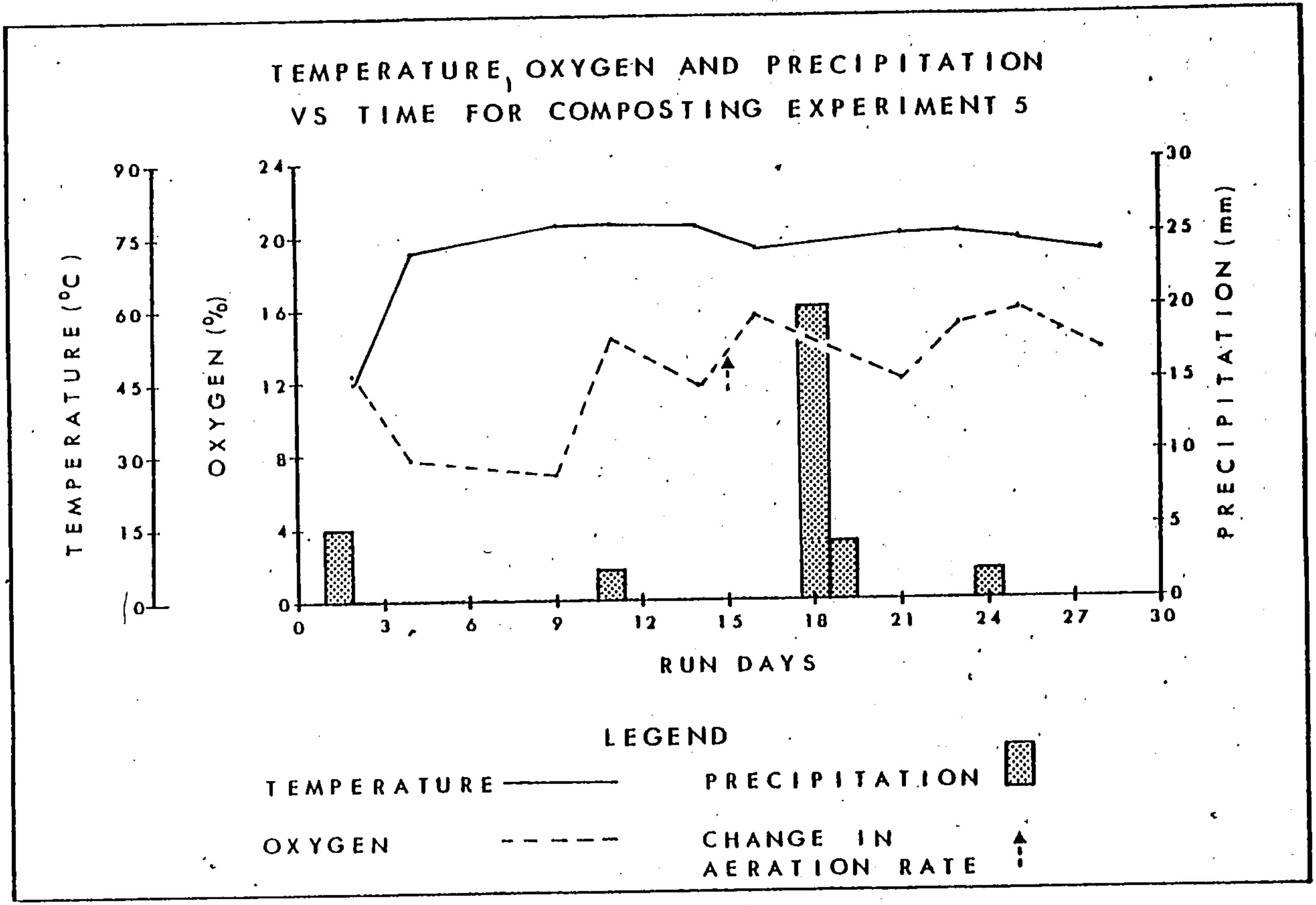

TEMPERATURE, OXYGEN AND PRECIPITATION
VS TIME FOR COMPOSTING EXPERIMENT 5
TEMPERATURE (°C)
0
15
30
45
60
75
90
OXYGEN (%)
0
4
8
12
16
20
24
PRECIPITATION (mm)
0
5
10
15
20
25
30
RUN DAYS
0
3
6
9
12
15
18
21
24
27
30
LEGEND
TEMPERATURE
OXYGEN
PRECIPITATION
CHANGE IN AERATION RATE

Figure 10

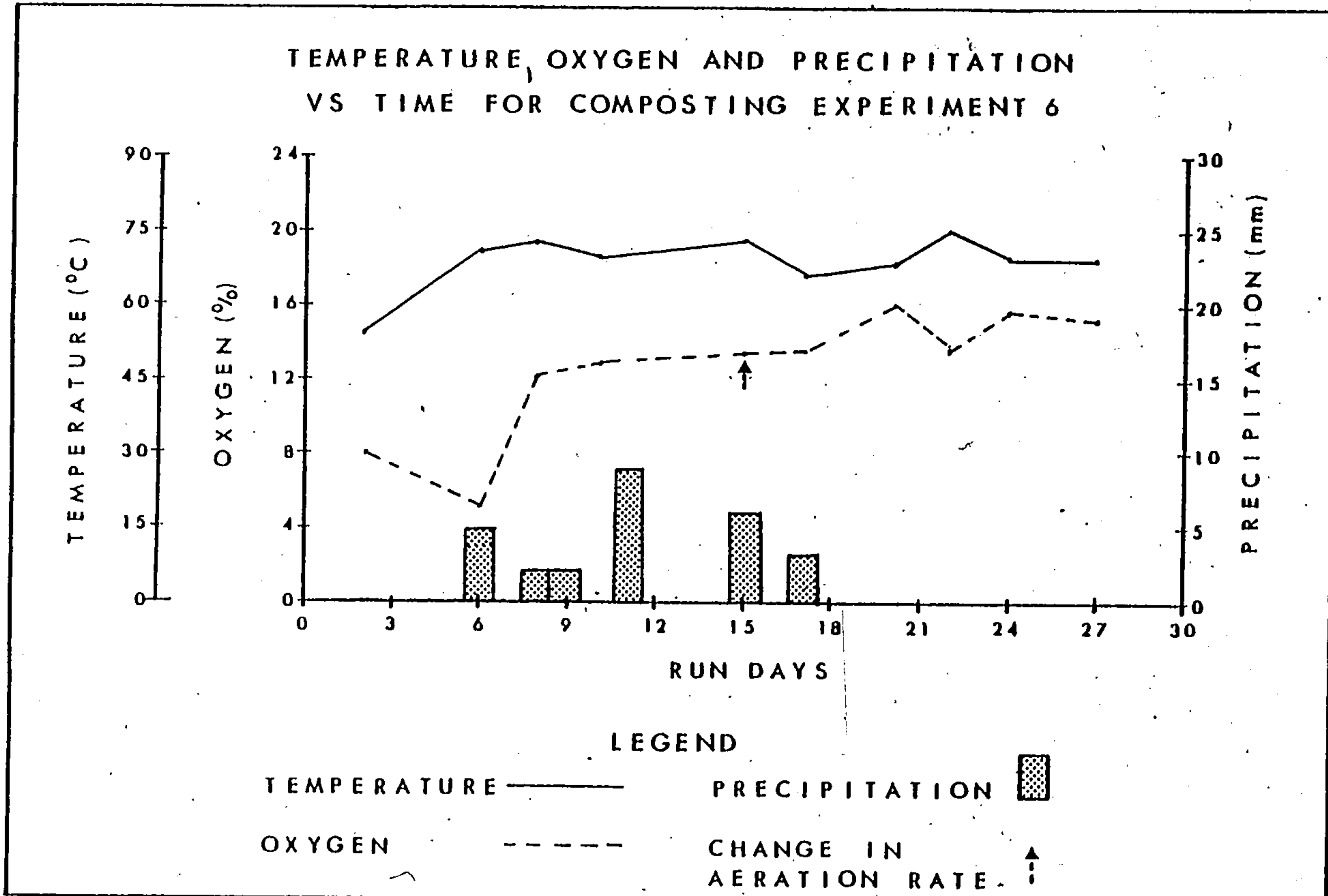

TEMPERATURE, OXYGEN AND PRECIPITATION
VS TIME FOR COMPOSTING EXPERIMENT 6
TEMPERATURE (°C)
90
75
60
45
30
15
0
OXYGEN (%)
24
20
16
12
8
4
0
PRECIPITATION (mm)
30
25
20
15
10
5
0
0
3
6
9
12
15
18
21
24
27
30
RUN DAYS
LEGEND
TEMPERATURE
OXYGEN
PRECIPITATION
CHANGE IN
AERATION RATE

Figure 11

by these experimental piles were 29 mm., 33 mm., and 27 mm. respectively.

During suction aeration, some leachate water usually forms at the aeration base. Since this water may be partially responsible for impeding the smooth flow of air through the aeration pipes, Experiments 7 to 9 utilized larger pipe 15.24 cm. (6 in.) as opposed to standard 10.16 cm. (4 in.) piping. Enhanced aeration and decreased pipe spacings were also utilized. The respective pipe spacings were 1.52 m. (5 ft.) for Experiment 7, 2.14 m. (7 ft.) for Experiment 8, and 2.44 m. (8 ft.) for Experiment 9.

As indicated by Figures 12 and 13, temperature levels sufficient for pathogen kill were attained in Experiments 7 and 8 by the fourth to fifth day of composting. The switching of aeration from a 4 min. on/4 min. off cycle to constant suction, produced subsequent oxygen drops in both experiments followed by a small drop in temperature. Regardless, active decomposition persisted throughout the final two weeks of the composting process as depicted by the high temperatures shown in Figures 12 and 13. The amount of precipitation received by the composting piles was 75 mm. for Experiment 7 and 22 mm. for Experiment 8.

Conversely, temperature levels adequate for pathogen kill were not attained in Experiment 9 until the ninth day of composting as shown by Figure 14. This was attributed to the initial septic nature and corresponding difficulties encountered with dewatering of the sludge prior to construction of this experimental pile. Spillage from the Maple Leaf food processing plant into the City's sanitary sewer was discovered to be

TEMPERATURE, OXYGEN AND PRECIPITATION VS TIME FOR COMPOSTING EXPERIMENT 7

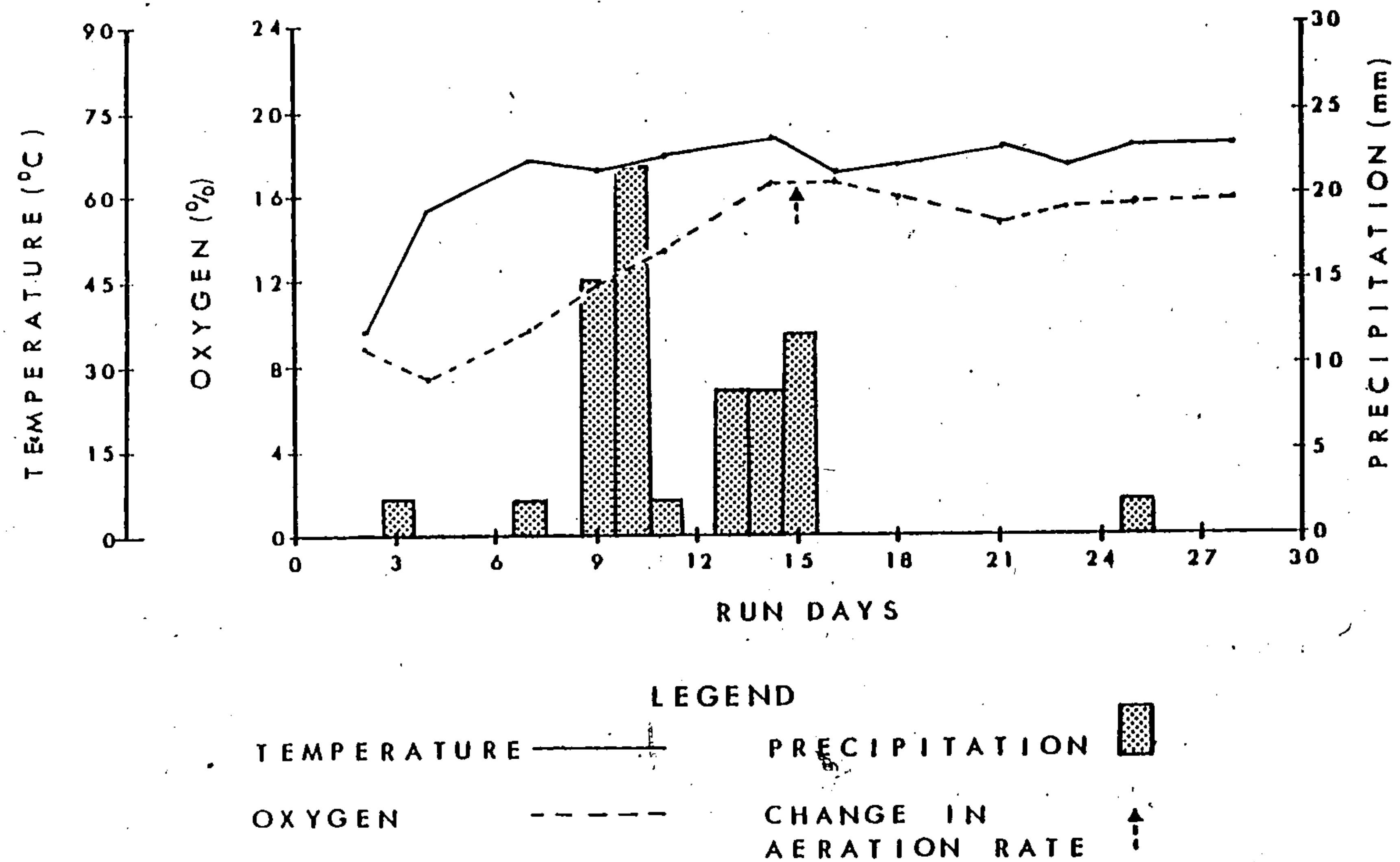


Figure 12

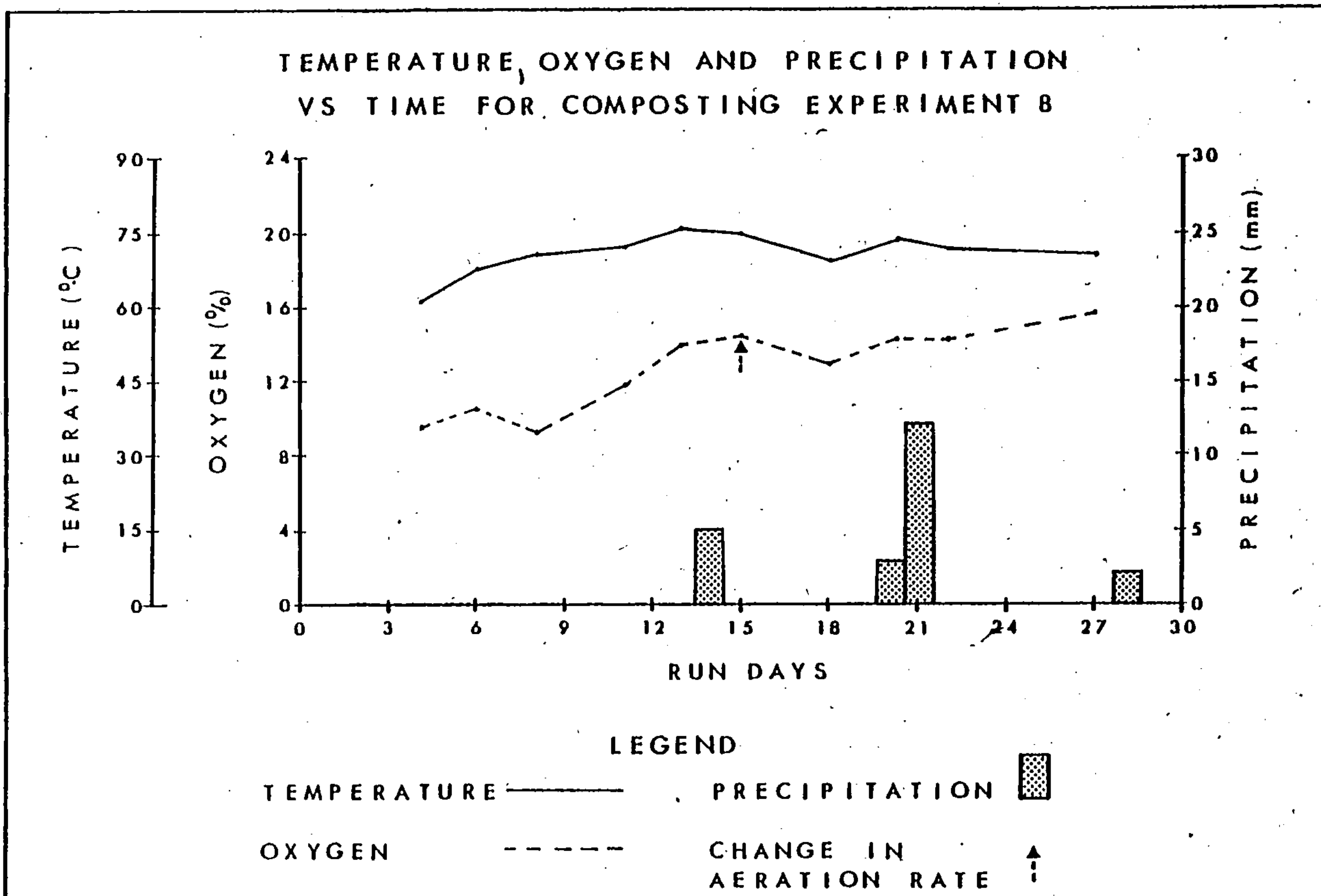

TEMPERATURE, OXYGEN AND PRECIPITATION
VS TIME FOR COMPOSTING EXPERIMENT 8
TEMPERATURE (°C)
90
75
60
45
30
15
0
OXYGEN (%)
24
20
16
12
8
4
0
PRECIPITATION (mm)
30
25
20
15
10
5
0
0
3
6
9
12
15
18
21
24
27
30
RUN DAYS
LEGEND
TEMPERATURE
OXYGEN
PRECIPITATION
CHANGE IN AERATION RATE

Figure 13

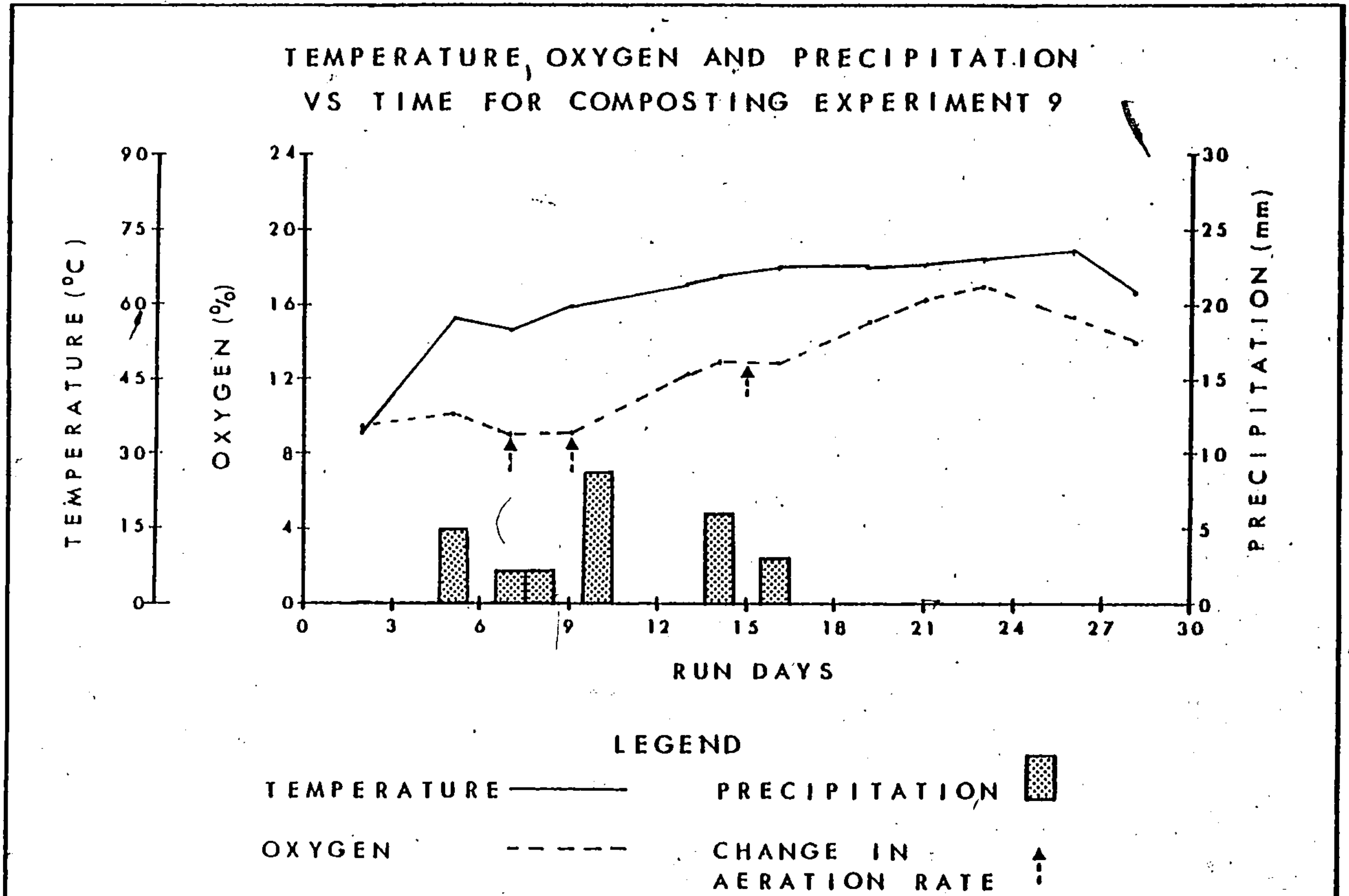

TEMPERATURE, OXYGEN AND PRECIPITATION
VS TIME FOR COMPOSTING EXPERIMENT 9
TEMPERATURE (°C)
90
75
60
45
30
15
0
OXYGEN (%)
24
20
16
12
8
4
0
PRECIPITATION (mm)
30
25
20
15
10
5
0
0
3
6
9
12
15
18
21
24
27
30
RUN DAYS
LEGEND
TEMPERATURE
OXYGEN
PRECIPITATION
CHANGE IN AERATION RATE

Figure 14

responsible for the occurrance of the septic sludge.

As Figure 14 indicates, the aeration cycle was reduced to 2 min. on/4 min. off on the seventh day of composting in an attempt to minimize heat loss. Since the oxygen levels were not excessive, any heat gain was minimal. Consequently, given that a septic aneorobic sludge would be characterized by low temperature and oxygen levels on the ninth day of composting, the aeration rate was intensified to a 6 min. on/2 min. off cycle in an attempt to promote aerobic thermophilic decomposition and related heat gains. This resulted, as shown in Figure 14, in a subsequent increase in oxygen and a corresponding increase in aerobic activity as typified by the temperature levels.

On the fifteenth day of composting, aeration was switched to constant suction. Unlike previously mentioned experiments, the increased aeration rate promoted further beneficial increases in temperature. Consequently, it is apparent that if larger quantitites of air are provided to the composting pile, septic sludge can be properly composted. Note that about 27 mm. of precipitation occurred during the composting process.

To ascertain the drying efficiency of the previously mentioned aerating systems relative to the presently employed system of the West Windsor Sewage Treatment Plant, a tenth or control experiment was conducted. This experiment pile utilized the standard 10.16 cm. pipe size placed at 2.44 m. (8 ft.) intervals while aeration was switched from a cycle aeration of 4 min. on/4 min. off to constant injection or blowing on the fifteenth day of composting.

Figure 15 shows that temperatures sufficient for pathogen kill were attained by the fifth day of composting. The switching of the aeration cycle to constant injection (blowing) resulted in a slight drop of temperatures, however active sludge decomposition, as characterized by the high temperature levels, persisted up to the last day of composting. During the experimental run, approximately 32 mm. of rain fell on the composting pile.

Given that enhanced aeration may be responsible for excessive heat loss from a composting pile, the controlling criteria in any aeration system is to attain temperature levels adequate for pathogen kill and sludge stabilization. It will be recalled that Hypothesis 3 predicted that optimum temperature and oxygen levels needed for pathogen kill and sludge stabilization would be attained by all experimental piles despite modifying aeration control. Based on the previous discussion, this hypothesis is true since temperature and oxygen levels sufficient for pathogen destruction and sludge stabilization occurred during the initial two weeks of the composting process. Consequently, all of the modified aeration systems could be utilized as potentially feasible moisture reduction alternatives to the presently employed forced aeration system used at the West Windsor Sewage Treatment Plant.

3.3 Drying Efficiency of the Experimental Piles

Correlation Regression Analysis was conducted to ascertain if a significant cause-effect relationship existed between the amount of precipitation received (Figures 4 to 13) by the piles

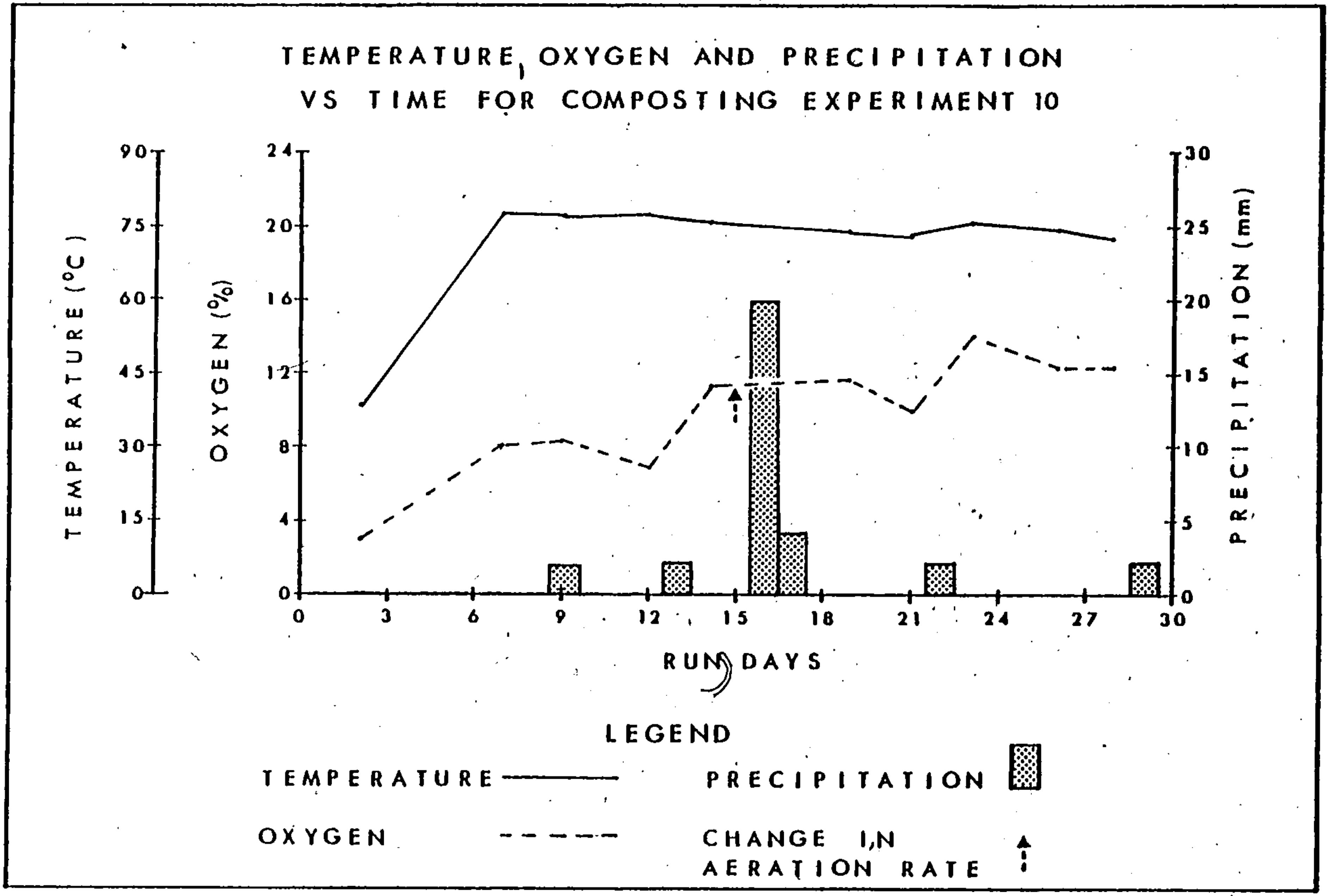

TEMPERATURE, OXYGEN AND PRECIPITATION
VS TIME FOR COMPOSTING EXPERIMENT 10
TEMPERATURE (°C)
90
75
60
45
30
15
0
OXYGEN (%)
24
20
16
12
8
4
0
PRECIPITATION (mm)
30
25
20
15
10
5
0
0
3
6
9
12
15
18
21
24
27
30
RUN DAYS
LEGEND
TEMPERATURE
OXYGEN
PRECIPITATION
CHANGE IN AERATION RATE

Figure 15

and the final moisture content (Table 9) of each pile. Since a prerequisite of any parametric statistical test is that the data be normally distributed, a Kolmogorov-Smirnoff Test of normality was employed. The derived D-max values of 0.3724 for total precipitation, and 0.1360 for average final moisture content of the piles did not exceed D-crit (0.05)=0.410 for 10 cases, consequently, the data was normally distributed. Hypothesis 4 is accepted since an insignificant correlation coefficient of 0.3592 was calculated between the studied variables.To be significant at the 0.05 probability level at 10 cases, a minimum correlation coefficient of 0.564 is required, consequently, Hypothesis 4 holds true. The amount of moisture therefore contributed by precipitation to a composting pile is negligeable.

It will be recalled that Hypothesis 5 predicted that significant moisture reductions would occur over all of the experimental piles since drying is an important sub-system component of sludge composting systems. To determine if the mean moisture content of the initial woodchip-sludge mixtures prior to composting were significantly different from those levels attained at the end of composting, parametric student t-tests were employed since the data was normally distributed and homoscedastic (Table 10). As was predicted and is shown by Table 9, all of the experimental piles had significant moisture reductions.

Table 9, surprisingly and contrary to theoretical expectations, suggests that progressively better moisture reduction in composting piles is not necessarily attainable through improved

TABLE 9

Drying Efficiency of the Experimental Piles

Experiment Ranking (decreasing drying efficiency)	Initial $\overline{x}$ Moisture Content (in %)	Final $\overline{x}$ Moisture Content (in %)	Moisture Content Reduction (in %)	Drying Efficiency-% Change (initial-final)	t-obs.
1. Experiment 1	53.9	39.5	-14.4	-26.7	8.1**
2. Experiment 10	55.1	40.8	-14.3	-26.0	10.1*
3. Experiment 9	54.5	42.4	-12.1	-22.2	4.07*
4. Experiment 5	53.6	42.2	-11.4	-21.2	5.66**
5. Experiment 8	53.9	42.5	-11.4	-21.2	4.42**
6. Experiment 7	56.1	45.5	-10.6	-18.9	2.90**
7. Experiment 6	53.0	44.1	-8.9	-16.8	3.80*
8. Experiment 2	52.9	45.0	-7.9	-14.9	2.99*
9. Experiment 3	51.5	44.6	-6.9	-13.4	3.69**
10. Experiment 4	51.5	46.6	-4.9	-9.5	5.42**

* Significant at 0.05 level of significance, df=51-t-crit=1.671.

** Approximate t-test - Significant at 0.025 level of significance, df=51-t-crit=2.000

TABLE 10

Kolmogorov-Smirnoff Test of Normality and Variance Ratio Test of Equal Variances for Moisture Content Data

Variable	D-max	F-computed
Experiment 1		
initial moisture content	0.330	* 15.5
final moisture content	0.117	
Experiment 2		
initial moisture content	0.228	2.2
final moisture content	0.185	
Experiment 3		
initial moisture content	0.162	5.3
final moisture content	0.217	
Experiment 4		
initial moisture content	0.268	* 9.4
final moisture content	0.114	
Experiment 5		
initial moisture content	0.196	* 7.5
final moisture content	0.200	
Experiment 6		
initial moisture content	0.292	2.0
final moisture content	0.207	
Experiment 7		
initial moisture content	0.236	** 4.0
final moisture content	0.150	
Experiment 8		
initial moisture content	0.304	2.0
final moisture content	0.221	
Experiment 9		
initial moisture content	0.209	1.8
final moisture content	0.181	

TABLE 10 (continued)

Variable	D-max	F-computed
Experiment 10		
initial moisture content	0.278	4.2
final moisture content	0.080	

D-max must exceed D-crit (0.05)=.565 to reject the variable as being normally distributed for inital moisture content data.

D-max must exceed D-crit (0.025)=.214 to reject the variable as being normally distributed for final moisture content data.

* Significantly different variance when F-computed exceeds F-ratio (0.05)=5.63, df=47,4.

** Significantly different variance when F-computed exceeds F-ratio (0.05)=2.61, df=4,47.

aeration control systems. Experiment 7 which supposedly offered the most efficient aeration control system -- enhanced evaporation rates through enhanced aeration, uniform oxygen movement by reducing pipe spacing, and greater free air movement through oversized piping -- ranked sixth for drying efficiency. Drying efficiency can be defined as the change in moisture content of a pile from start to finish expressed as a percent. The following formula was used: drying efficiency (in percent)=

$$\frac{\text{average reduction in moisture from start to finish}}{\text{average initial moisture content of a pile}} \times 100\%$$

Experiment 4, which was expected to rank second to fourth ranked last, and Experiment 10., which typifies the presently employed system at the West Windsor Sewage Treatment Plan had the second highest drying efficiency record despite earlier reported problems with the system.

To determine if the final moisture content of the experimental piles were indeed significantly different, an approximate One-Way Analysis of Variance was conducted since the variances of the moisture contents were not homoscedastic. As shown by Table 11, significantly different moisture contents prevailed after the composting process given that the initial moisture content of the piles were not significantly different (Table 6). However, according to Table 12, these differences were not related to either pipe spacing or the aeration type utilized but some interaction or combination of these variables.

TABLE 11

Approximate One-Way Analysis of Variance of Final Moisture Content Differences Between the Experimental Piles

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F
Between Experiments	77739.697	8	9717.462	* 42.384
Within Experiments	107985.482	471	229.268	
Total	30245.784	479		

* significant at the 0.01 level.

TABLE 12

Approximate Two-Way Analysis of Variance of Final Moisture Content Differences by Aeration Type and Pipe Spacing

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F
Between Aeration Types	120.963	2	60.481	0.957
Between Pipe Spacing Types	35.085	2	17.543	0.758
Aeration Type By Pipe Spacing Interaction	1627.999	4	407.000	*6.439
Residual	26738.988	423	63.213	
Total	28523.039	431	66.179	

* significant at 0.01 level.

To determine which pairs of experiments had significantly different moisture contents, several approximate t-tests were conducted. The results of this analysis are given in Table 13. Experiments 4 and 7 had significantly higher moisture contents than Experiments 1 and 10 which utilized standard pipe size and regular aeration rates. Contrary to expectations, Experiment 7 was also found to have a significantly higher moisture content than Experiment 5 which utilized standard pipe size but more distant pipe spacings. Table 13 also shows that Experiment 10 or the system presently employed by the City of Windsor had a significantly greater moisture reduction than Experiments 2, 3 and 6 which supposedly had more efficient aeration systems.

It will be recalled that Hypothesis 6 predicted that greater moisture reductions would be attained as more efficient aerating systems are used. The results of the t-tests and drying efficiency of the experimental piles indicate otherwise. Consequently, Hypothesis 6 was rejected since there was not a clear indication that such a relationship exists.

3.4 Distributional Inter-Relationships of the Study Variables

The cross-sectional temperature, oxygen and moisture profiles taken at the end of the composting period were mapped and analyzed in an attempt to explain the unanticipated results of this investigation. Visual inspection of the spatial patterns displayed in Appendix 3 would seem to indicate the spatial distributions of the study variables within a given experimental pile tend to coincide. Correlation Regression Analysis was used in an attempt to determine the extent of these inter-relation-

TABLE 13

Matrix of "t-observed" Values for Final Moisture Contents

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
1. Experiment 1	-									
2. Experiment 2	*-4.00	-								
3. Experiment 3	*-3.63	0.51	-							
4. Experiment 4	*-4.39	-1.27	-1.73	-						
5. Experiment 5	-2.18	* 3.66	* 3.11	* 3.11	-					
6. Experiment 6	*-3.76	1.01	0.46	2.16	-1.81	-				
7. Experiment 7	*-3.90	-0.44	-0.77	1.34	*-2.43	-1.12	-			
8. Experiment 8	-1.57	1.59	1.35	* 2.51	-0.22	1.23	1.72	-		
9. Experiment 9	-1.92	* 2.44	2.03	* 3.57	-0.21	1.90	2.16	0.08	-	
10. Experiment 10	-0.79	* 3.66	* 3.26	* 6.00	1.02	* 3.05	* 4.50	1.11	1.44	-

* Significant at 2-tailed 0.02 level of significance, df = 47 - t-crit = 2.42.

ships. Since this is a parametric statistical test, the data was first checked for normality. In most cases, as shown in Table 14, the raw data was normally distributed. Data transformation to the fifth and sixth power were needed to respectively normalize the temperature data for Experiments 2 and 4, while squared transformations were needed for the moisture levels of Experiments 3 and 8, and the temperature levels of Experiment 10.

The data correlation matrix given in Table 15 generally supports the prediction given by Hypothesis 7, that inter-relationships exist between the studied variables within a given experimental pile. Since correlation coefficients of 0.30 or greater are significant, significant positive correlations between temperature and moisture levels therefore prevailed in eight of the ten conducted experiments, while significant inverse correlations existed between temperature and oxygen in seven conducted experiments. Meanwhile, instrument failure may have been responsible for the poor inverse correlations found between oxygen and moisture levels (only three experiments had significant inverse correlations) due to clogging of the oxygen probe when it was inserted into the moist pockets across the face of the compost pile.

Although the drying efficiency index given back in Table 9 does give an indication of the moisture reduction success of a given experimental pile, it is based on averages and consequently statistical description is lost during the process. From the point of view of odour control, the moist malodorous pockets still persistent at the end of the composting process are

TABLE 14

Kolmogorov-Smirnoff Test of Normality for Final Temperature, Oxygen and Moisture Data

Values of D-max

Variable	X	X^2	X^5	X^6	Distribution
Experiment 1					
Temperature	0.1306				normal
Oxygen	0.1612				normal
Moisture	0.1171				normal
Experiment 2					
Temperature	0.2930		0.1968		fifth power
Oxygen	0.0873				normal
Moisture	0.1853				normal
Experiment 3					
Temperature	0.1223				normal
Oxygen	0.1508				normal
Moisture	0.2171	0.1961			squared power
Experiment 4					
Temperature	0.2851			0.2110	sixth power
Oxygen	0.1141				normal
Moisture	0.1499				normal
Experiment 5					
Temperature	0.2032				normal
Oxygen	0.0874				normal
Moisture	0.1999				normal
Experiment 6					
Temperature	0.1966				normal
Oxygen	0.1485				normal
Moisture	0.2066				normal
Experiment 7					
Temperature	0.1969				normal
Oxygen	0.1597				normal
Moisture	0.1501				normal

TABLE 14 (continued)

Variable	X	X^2	X^5	X^6	Distribution
Experiment 8					
Temperature	0.1178				normal
Oxygen	0.1130				normal
Moisture	0.2206	0.1768			squared power
Experiment 9					
Temperature	0.1874				normal
Oxygen	0.1078				normal
Moisture	0.1806				normal
Experiment 10					
Temperature	0.2298	0.2090			squared power
Oxygen	0.0932				normal
Moisture	0.0796				normal

Where: X is the D-max value before normalization

TABLE 15

Data Correlation Matrix for the Experimental Piles

Experiment 1	Temperature	Oxygen	Moisture
Temperature	-	-0.165	0.733
Oxygen		-	0.226
Moisture			-
Experiment 2			
Temperature	-	-0.047	0.794
Oxygen		-	0.031
Moisture			-
Experiment 3			
Temperature	-	-0.347	0.455
Oxygen		-	-0.572
Moisture			-
Experiment 4			
Temperature	-	0.283	0.128
Oxygen		-	0.327
Moisture			-
Experiment 5			
Temperature	-	-0.451	0.659
Oxygen		-	-0.333
Moisture			-
Experiment 6			
Temperature	-	-0.453	0.556
Oxygen		-	-0.254
Moisture			-
Experiment 7			
Temperature	-	-0.509	-0.240
Oxygen		-	0.226
Moisture			-
Experiment 8			
Temperature	-	-0.570	0.589
Oxygen		-	-0.243
Moisture			-

TABLE 15 (continued)

	Temperature	Oxygen	Moisture
Experiment 9			
Temperature	-	-0.332	0.520
Oxygen		-	-0.372
Moisture			-
Experiment 10			
Temperature	-	-0.419	0.331
Oxygen		-	-0.116
Moisture			-

Correlations of 0.30 or greater are significant at 0.05 level based on 48 sample sites.

of equal concern. It will be recalled that Hypothesis 8 predicted that temperature, oxygen and moisture should approach uniformity as reduced pipe spacing is utilized, thereby decreasing the number of wet malodorous pockets. Although the mapping of the recorded data does give an indication of the distributional patterns present in a composting pile, the patterns can be confusing, consequently, difficulties arise when attempting to deduce and assign a general trend or pattern to a composting pile. Consequently, Trend Surface Analyses were conducted on the observed spatial patterns of the composting piles depicted in Appendix III. Autocorrelation of a study variable within a composting pile, which would indicate the presence of a general trend or pattern throughout the composting pile, becomes evident when a trend surface is significantly fitted to an observed spatial pattern since local random departures of the fitted surface are filtered out.

As shown by Table 16, 72.5% of the spatial variation in the temperature profile, 48.0% of the oxygen profile, and 54.6% of the moisture profile in Experiment 1 were significantly describable by quadratic order surfaces. The fitted trend surface, however, indicated an unexpectedly notable clustering within the pile despite utilizing reduced 1.52 m. pipe spacing. High temperature and moisture levels were generally found in the centre of the pile with gradual cooling and drying away from this centre. The distributional pattern of oxygen consisted of low levels in the central left hand side of the pile to gradual increasing levels up to the right hand corner of the pile.

TABLE 16

Trend Surface Analysis of Study Variables for Experiment 1

Source Surface	df	R^2	dR^2	Fr^2	Fdr^2
			Temperature		
Linear	2	0.442	0.442	*17.8	
Residual	45	0.558			
Quadratic	5	0.725	0.283	*20.7	*13.4
Residual	42	0.275			
Cubic	9	0.771	0.046	*14.3	2.0
Residual	38	0.229			
Quartic	14	0.897	0.126	* 2.1	* 8.3
Residual	33	0.103			
			Oxygen		
Linear	2	0.226	0.226	* 7.1	
Residual	45	0.734			
Quadratic	5	0.480	0.214	* 8.0	* 5.9
Residual	42	0.520			
Cubic	9	0.555	0.075	* 5.2	1.6
Residual	38	0.445			
Quartic	14	0.639	0.084	* 4.2	1.6
Residual	33	0.361			
			Moisture		
Linear	2	0.371	0.371	*13.3	
Residual	45	0.629			
Quadratic	5	0.546	0.175	* 9.9	* 5.3
Residual	42	0.454			
Cubic	9	0.587	0.041	* 5.9	0.9
Residual	38	0.413			
Quartic	14	0.741	0.154	*6.6	* 3.9
Residual	33	0.259			

* significant at the 0.05 level.

As shown by Table 17, 89.2% of the spatial variation of the temperature profile in Experiment 2 was explainable by the cubic order surface, while 78.1% of the moisture profile was best explained by the quadratic order surface. Like Experiment 1, the fitted trend surface indicated the presence of clustered spatial patterns within the experimental pile despite using a reduced 1.83 m. pipe spacing. Generally, two pockets of high temperatures prevailed, one on the central left hand side and the other in the central bottom of the pile. Temperatures gradually dissipated away from the pockets toward the pile base and top. A moist pocket was present in the centre of the pile while gradual drier patterns prevailed away from this centre toward the pile base and top. Oxygen can be claimed to exhibit a random pattern because of the inability to fit a significant trend to the observed spatial pattern.

When trend surface analysis was applied to Experiment 3, 80.6%, 28.2%, and 73.9% of the spatial variation in temperature, oxygen, and moisture respectively were described by a cubic, linear and quadratic surface as shown in Table 18. Similar to the previous mentioned experimental piles, a clustered spatial pattern was portrayed by the analysis. Notably, two areas of hot temperatures were evident (central right and left hand side) while temperatures gradually decreased away from these pockets. A moist pocket was also apparent in the bottom central portion of the pile. A steeply decreasing spatial gradient occurred toward the top of the pile and drier compost was also evident in the aeration base. Oxygen

TABLE 17

Trend Surface Analysis of Study Variables for Experiment 2

Source Surface	df	R^2	dR^2	Fr^2	Fdr^2
		Temperature			
Linear	2	0.501	0.501	*22.8	
Residual	45	0.499			
Quadratic	5	0.839	0.338	*42.0	*28.3
Residual	42	0.161			
Cubic	9	0.892	0.053	*33.0	* 4.3
Residual	38	0.108			
Quartic	14	0.906	0.014	*21.6	1.0
Residual	33	0.094			
		Oxygen			
Linear	2	0.056	0.056	1.3	
Residual	45	0.094			
Quadratic	5	0.101	0.045	1.0	0.7
Residual	42	0.899			
Cubic	9	0.298	0.197	1.8	* 2.7
Residual	38	0.702			
Quartic	14	0.340	0.042	1.0	0.4
Residual	33	0.660			
		Moisture			
Linear	2	0.626	0.626	*39.1	
Residual	45	0.374			
Quadratic	5	0.781	0.155	*31.2	*10.4
Residual	42	0.219			
Cubic	9	0.825	0.044	*18.3	2.2
Residual	38	0.175			
Quartic	14	0.842	0.017	*12.0	0.6
Residual	33	0.158			

* significant at 0.05 level.

TABLE 18

Trend Surface Analysis of Study Variables for Experiment 3

Source Surface	df	R^2	dR^2	Fr^2	Fdr^2
		Temperature			
Linear	2	0.202	0.202	* 5.6	
Residual	45	0.798			
Quadratic	5	0.434	0.232	* 7.2	* 5.9
Residual	42	0.566			
Cubic	9	0.806	0.372	*17.9	*18.6
Residual	38	0.194			
Quartic	14	0.827	0.021	*11.8	0.8
Residual	33	0.173			
		Oxygen			
Linear	2	0.282	0.282	* 9.0	
Residual	45	0.718			
Quadratic	5	0.337	0.055	* 4.2	1.1
Residual	42	0.663			
Cubic	9	0.389	0.052	* 2.7	0.8
Residual	38	0.611			
Quartic	14	0.430	0.041	1.8	0.5
Residual	33	0.570			
		Moisture			
Linear	2	0.577	0.577	*32.1	
Residual	45	0.423			
Quadratic	5	0.739	0.182	*24.6	*10.0
Residual	42	0.261			
Cubic	9	0.756	0.017	*14.0	0.7
Residual	38	0.244			
Quartic	14	0.783	0.027	* 8.0	0.7
Residual	33	0.217			

* significant at 0.05 level

tended to follow a diagonal pattern from lower levels at the bottom left hand corner of the pile to the higher levels at the top right hand corner.

As indicated by Table 19, 86.9% of the spatial variation of the temperature profile in Experiment 4 was characterized by a quadratic order surface, while 17.6% of the oxygen profile was explained by a linear order surface. Temperature and oxygen levels gradually increased toward the pile base, thus indicating a clustered pattern. The moisture profile was assumed to be randomly distributed since a trend could not be significantly fitted to the observed spatial pattern.

Quadratic surfaces, as shown in Table 20, successfully accounted for 70.4% and 84.9% of the temperature and moisture profiles in Experiment 5. Both temperature and moisture levels increased toward the pile base. Clustering occurred when a moist pocket was identified in the bottom central portion of the pile. Oxygen was assumed to be randomly distributed since a trend surface could not be significantly fitted to the observed spatial pattern.

In Experiment 6, quadratic surfaces successfully accounted for 54.0% and 68.8% of the temperature and moisture profiles, while the cubic surface explained 54.4% of the oxygen profile as indicated in Table 21. Strong clustering was evident when high temperature and low oxygen levels prevailed in the centre of the pile. Moisture levels also increased toward the pile base.

TABLE 19

Trend Surface Analysis of Study Variables for Experiment 4

Source Surface	df	R^2	dR^2	Fr^2	Fdr^2
		Temperature			
Linear	2	0.659	0.659	*41.3	
Residual	45	0.341			
Quadratic	5	0.869	0.210	*57.9	*23.3
Residual	42	0.131			
Cubic	9	0.885	0.016	*32.7	1.3
Residual	38	0.115			
Quartic	14	0.911	0.026	*21.7	1.7
Residual	33	0.089			
		Oxygen			
Linear	2	0.176	0.176	* 4.9	
Residual	45	0.824			
Quadratic	5	0.224	0.048	* 2.5	0.9
Residual	42	0.776			
Cubic	9	0.309	0.085	1.9	1.2
Residual	38	0.691			
Quartic	14	0.376	0.067	1.4	0.7
Residual	33	0.624			
		Moisture			
Linear	2	0.087	0.087	2.2	
Residual	45	0.913			
Quadratic	5	0.160	0.073	1.6	1.2
Residual	42	0.840			
Cubic	9	0.336	0.176	* 3.9	2.6
Residual	38	0.664			
Quartic	14	0.370	0.034	1.4	0.4
Residual	33	0.630			

* significant at 0.05 level.

TABLE 20

Trend Surface Analysis of Study Variables for Experiment 5

Source Surface	df	R^2	dR^2	Fr^2	Fdr^2
		Temperature			
Linear	2	0.576	0.576	*25.3	
Residual	45	0.424			
Quadratic	5	0.704	0.128	*20.1	*6.1
Residual	42	0.296			
Cubic	9	0.745	0.041	*11.8	1.4
Residual	38	0.255			
Quartic	14	0.750	0.005	* 6.8	0.1
Residual	33	0.250			
		Oxygen			
Linear	2	0.033	0.033	0.8	
Residual	45	0.967			
Quadratic	5	0.168	0.135	1.7	2.3
Residual	42	0.832			
Cubic	9	0.258	0.090	1.4	1.2
Residual	38	0.742			
Quartic	14	0.359	0.101	1.4	1.1
Residual	33	0.641			
		Moisture			
Linear	2	0.652	0.652	*40.8	
Residual	45	0.348			
Quadratic	5	0.849	0.197	*42.5	*16.5
Residual	42	0.151			
Cubic	9	0.878	0.029	*32.5	2.3
Residual	38	0.122			
Quartic	14	0.907	0.029	*21.7	2.0
Residual	33	0.093			

* significant at 0.05 level.

TABLE 21

Trend Surface Analysis of Study Variables for Experiment 6

Source Surface	df	R^2	dR^2	Fr^2	Fdr^2
		Temperature			
Linear	2	0.353	0.353	*12.6	
Residual	45	0.647			
Quadratic	5	0.540	0.187	* 9.8	*5.6
Residual	42	0.460			
Cubic	9	0.639	0.099	* 7.1	2.5
Residual	38	0.361			
Quartic	14	0.679	0.040	* 4.9	0.8
Residual	33	0.321			
		Oxygen			
Linear	2	0.022	0.022	0.5	
Residual	45	0.978			
Quadratic	5	0.410	0.388	* 5.9	*9.2
Residual	42	0.590			
Cubic	9	0.554	0.144	* 5.1	*3.0
Residual	38	0.446			
Quartic	14	0.658	0.104	* 4.7	2.1
Residual	33	0.342			
		Moisture			
Linear	2	0.582	0.582	*32.3	
Residual	45	0.418			
Quadratic	5	0.688	0.106	*19.1	*5.0
Residual	42	0.312			
Cubic	9	0.747	0.059	*11.9	2.1
Residual	38	0.253			
Quartic	14	0.781	0.034	* 8.0	1.0
Residual	33	0.219			

* significant at 0.05 level.

As shown by Table 22, 86.8% of the spatial variation of temperature, 31.7% of oxygen, and 46.3% of moisture were respectively accounted for by a quadratic, linear, and cubic surface in Experiment 7. However, all of these variables exhibted some form of clustered pattern. High temperature and moisture levels were present in the centre of the pile while lower levels prevailed toward the top and base of the pile. Oxygen levels progressively decreased toward the bottom right hand corner of the pile.

When trend surface analysis was applied to the observed spatial patterns of Experiment 8, 55.3% and 49.5% of the temperature and moisture profiles were significantly accounted for by quadratic order surfaces. Table 23 also indicated that 20.7% of the oxygen profile can be significantly explained by a linear surface order at the 0.05 probability level. However, as in previously mentioned experiments, clustering of the spatial patterns are noted. Lower temperature levels occurred toward the bottom right hand corner of the pile. Conversely decreasing oxygen levels occurred toward the bottom left hand corner of the pile. However, the trend surface depicted for the moisture profile did appear to differ from previously conducted experiments. The indicated trend was dry compost from top to bottom of the pile but with progressively wetter compost toward the central right hand edge and the left hand corner of the pile. The presence of these moist pockets, however does indicate some degree of clustering.

TABLE 22

Trend Surface Analysis of Study Variables for Experiment 7

Source Surface	df	R^2	dR^2	Fr^2	Fdr^2
		Temperature			
Linear	2	0.593	0.593	*33.0	
Residual	45	0.407			
Quadratic	5	0.868	0.275	*57.9	*30.7
Residual	42	0.132			
Cubic	9	0.892	0.024	*33.0	2.0
Residual	38	0.108			
Quartic	14	0.909	0.017	*21.6	1.0
Residual	33	0.091			
		Oxygen			
Linear	2	0.317	0.317	*10.6	
Residual	45	0.683			
Quadratic	5	0.417	0.100	* 6.0	2.4
Residual	42	0.583			
Cubic	9	0.514	0.097	* 4.4	1.9
Residual	38	0.486			
Quartic	14	0.604	0.090	* 3.6	1.5
Residual	33	0.396			
		Moisture			
Linear	2	0.055	0.055	1.3	
Residual	45	0.945			
Quadratic	5	0.284	0.229	* 3.3	*4.5
Residual	42	0.716			
Cubic	9	0.463	0.179	* 3.6	*3.2
Residual	38	0.537			
Quartic	14	0.587	0.124	* 3.2	1.9
Residual	33	0.413			

* significant at 0.05 level.

TABLE 23

Trend Surface Analysis of Study Variables for Experiment 8

Source Surface	df	R^2	dR^2	Fr^2	Fdr^2
		Temperature			
Linear	2	0.386	0.386	*13.8	
Residual	45	0.614			
Quadratic	5	0.553	0.167	*10.1	*5.1
Residual	42	0.447			
Cubic	9	0.555	0.002	* 5.1	0.1
Residual	38	0.445			
Quartic	14	0.589	0.034	* 3.5	0.6
Residual	33	0.411			
		Oxygen			
Linear	2	0.207	0.207	* 5.8	
Residual	45	0.793			
Quadratic	5	0.282	0.075	* 3.3	1.5
Residual	42	0.718			
Cubic	9	0.342	0.060	* 2.2	0.9
Residual	38	0.658			
Quartic	14	0.354	0.012	1.3	0.1
Residual	33	0.646			
		Moisture			
Linear	2	0.291	0.291	* 9.7	
Residual	45	0.709			
Quadratic	5	0.495	0.204	* 8.3	*5.7
Residual	42	0.505			
Cubic	9	0.509	0.014	* 4.4	0.3
Residual	38	0.491			
Quartic	14	0.547	0.038	* 2.8	0.6
Residual	33	0.453			

* significant at 0.05 level.

Table 24 shows that 46.3% of the spatial variation in temperature and 68.5% of moisture are significantly accounted by quadratic order surfaces. A linear order surface accounted for 12.7% of the spatial variation of oxygen in Experiment 9. The temperature and oxygen surfaces generally depicted a similar pattern-increasing levels toward the right hand side of the pile, however higher temperature levels at the bottom right hand and higher oxygen levels at the top right hand corner of the pile were observed. A moist layer ran through the centre of the pile with the highest levels occurring in the central edge and bottom left hand corner of the pile.

When trend surface analyses were applied to the control experiment (#10), 78.1% of the variation in temperature, 21.8% of oxygen, and 29.5% of moisture were respectively accounted for by a cubic, linear, and quadratic surface, as shown in Table 25. Reversing aeration during the final two weeks of composting promoted different patterns than those noted earlier. Unlike the previously conducted experiments, temperatures tended to be higher at the top of the pile and lower at the bottom. However, like the other experiments, a very hot central pocket can be noted. Moisture followed a similar pattern, but a high moisture layer prevailed throughout the centre of the pile. The oxygen profile exhibited by this pile was similar to those attained in previous piles with a gradual decrease in level from one side to another.

TABLE 24

Trend Surface Analysis of Study Variables for Experiment 9

Source Surface	df	R^2	dR^2	Fr^2	Fdr^2
		Temperature			
Linear	2	0.337	0.337	*11.2	
Residual	45	0.663			
Quadratic	5	0.463	0.126	* 7.1	*3.2
Residual	42	0.537			
Cubic	9	0.491	0.028	* 4.2	0.5
Residual	38	0.509			
Quartic	14	0.555	0.064	* 3.0	1.0
Residual	33	0.445			
		Oxygen			
Linear	2	0.127	0.127	* 3.3	
Residual	45	0.873			
Quadratic	5	0.186	0.059	2.0	1.1
Residual	42	0.814			
Cubic	9	0.354	0.168	* 2.3	2.5
Residual	38	0.646			
Quartic	14	0.438	0.084	1.8	1.0
Residual	33	0.562			
		Moisture			
Linear	2	0.499	0.499	*22.7	
Residual	45	0.501			
Quadratic	5	0.685	0.186	*17.1	*7.8
Residual	42	0.315			
Cubic	9	0.699	0.014	* 9.7	0.5
Residual	38	0.301			
Quartic	14	0.739	0.040	* 6.6	1.0
Residual	33	0.261			

* significant at 0.05 level.

TABLE 25

Trend Surface Analysis of Study Variables for Experiment 10

Source Surface	df	R^2	dR^2	Fr^2	Fdr^2
		Temperature			
Linear	2	0.377	0.377	*13.5	
Residual	45	0.623			
Quadratic	5	0.652	0.274	*16.3	*11.4
Residual	42	0.348			
Cubic	9	0.781	0.129	*14.5	* 5.3
Residual	38	0.219			
Quartic	14	0.795	0.014	* 9.5	0.5
Residual	33	0.205			
		Oxygen			
Linear	2	0.218	0.218	* 6.4	
Residual	45	0.782			
Quadratic	5	0.311	0.093	* 3.9	1.9
Residual	42	0.689			
Cubic	9	0.410	0.099	* 2.9	1.6
Residual	38	0.590			
Quartic	14	0.608	0.198	* 3.6	*3.3
Residual	33	0.392			
		Moisture			
Linear	2	0.013	0.013	0.3	
Residual	45	0.987			
Quadratic	5	0.295	0.281	* 3.5	*5.5
Residual	42	0.715			
Cubic	9	0.406	0.111	* 2.8	1.7
Residual	38	0.594			
Quartic	14	0.479	0.073	* 2.1	0.9
Residual	33	0.521			

* significant at 0.05 level.

Finally, the residuals of all the conducted trend surface analyses were tested for autocorrelation since strong clustering of these values could strongly bias the conducted F-tests to the point of wrongly rejecting the null hypothesis of no trend. Trend Surface Analysis of these residual values strongly indicated that the residuals were not autocorrelated since correlations of less than 1% were obtained in all of the runs. Consequently, given these results and the results of the Trend Surface Analyses, Hypothesis 8 can be rejected since wet malodourous pockets still persisted by the time of pile breakdown despite employing reduced pipe spacings.

In summary, most of the experiments tended to exhibit similar trends despite using different pipe spacings, except for Experiment 10 which utilized injection aeration. While all of the experiments indicated a presence of a very hot and moist central pocket or layer, different trends toward the top and base of the pile were attained when injection aeration was used during Experiment 10. The suction aeration experiments tended to have a dry and cool upper layer, while the base of the piles were generally moist and hot. This was a complete reversal of the moisture and temperature patterns attained by Experiment 10, as was to be expected. Consequently, since a reversal of moisture and temperature spatial patterns are attainable when changing the direction of aeration, intermittent aeration may prove to be an important method of aeration when attempting to dispose of the clustered spatial patterns presently encountered with strictly suction or injection aeration systems.

The trend surface analyses of the oxygen spatial patterns also lend additional support to the importance of the initial woodchip-sludge mixture during aeration. Although a small percentage of the observed oxygen spatial patterns were accountable by the trend surface equations, they were nevertheless significant. Generally, these trends indicated, in six out of ten experiments, that oxygen patterns tend to vary from one side of the pile to another, in the same direction in which the piles were constructed. Since the porosity of a pile and resultant oxygen levels are dependent upon the initial variability of the woodchip-sludge mixture, indications are that a high degree of variability persists in a given pile, consequently, any benefits derived from aeration will be minimized since air follows the pathway of least resistence.

The inter-relationships of moisture and temperature were also displayed during Trend Surface Analysis since similar spatial patterns generally occurred within a given experimental pile. Consequently, given the similarities in these spatial patterns and the evidence presented earlier in this investigation during Correlation-Regression Analysis, temperature readings may be used as an indicator of the moisture and hence odour status of a composting pile prior to pile breakdown.

CHAPTER FOUR

CONCLUSIONS

4.1 Conclusions

The flexibility of the forced aeration method of sludge composting was demonstrated when temperatures sufficient for pathogen kill and some level of sludge stabilization were attained under nine different conditions. Neither differences in precipitation nor the use of modified forced aeration methods have a significant effect on the final moisture levels of the experimental piles. Interestingly, the versatility of forced aerated sludge composting was also demonstrated when septic sludge was adequately composted when higher aeration rates were employed.

Since significant moisture reductions were also attained in less costly aeration systems, the extra costs associated with employing reduced pipe spacing, increased aeration input, and/or larger expensive piping are justified only if the moist mal-odorous pockets at the time of pile breakdown were eliminated. The results of this investigation, however, clearly demonstrated that clustered and/or random (as opposed to uniform) temperature, oxygen, and moisture spatial patterns, were attained despite employing supposedly more efficient aeration systems, and reduced pipe spacing. One reason for the apparent failure of the improved forced aeration systems in attaining uniform spatial patterns was the variability discovered in the initial woodchip-sludge mixture which, in turn, would affect the porosity characteristics of a pile. The average moisture content of the sludge cakes were found to vary significantly daily, while the woodchip bulking agent varied significantly during a day's operation. Consequently, given the variable porosity characteristics of the piles, any additional benefits derived from improving aeration would merely be channeled along oxygen pathways of least resistence, therefore, by-passing the moist malodorous pockets.

Preliminary evidence presented during this investigation however, suggests that uniform spatial patterns may be attainable if air is alternately pushed (injection) and pulled (suction) through the composting piles. Reversed spatial patterns are attainable when changing the direction of aeration, as was indicated during this investigation. Consequently, the employment of intermittent aeration may eliminate the moist malodorous pockets presently responsible for the odour and screening problems encountered at the West Windsor Sewage Treatment Plant after pile breakdown. Likewise associated zones of dessication along the oxygen pathways of least resistence, where composting activity is regulated, may also be reduced.

Evidence presented in this study also strongly indicates that the encountered odour and screening problems associated with the moist compost may be related to the premature breakdown of the composting piles. During this investigation, all of the conducted experimental piles were still experiencing high temperatures, even at the time of pile breakdown. Consequently, it can be concluded that the malodours generated during pile breakdown are probably attributed to the inadequately stabilized compost, since temperatures are a function of biological activity and hence, decomposition.

Finally, given the significant inter-relationships which were found to exist during this investigation, the level of difficulty which will be encountered at the end of the composting period may be pre-determined based on the oxygen and temperature readings when taken. Notably, high temperatures can be indicative of the moisture condition of a pile and hence odour and screening problems which will be encountered.

4.2 Limitations of the Investigation

Three significant problems were encountered during the course of this study. Firstly, because of time and financial constraints, additional runs of the conducted experiments were not possible. Consequently, it had to be assumed that the conducted run would be representative of similar additional runs had they been conducted. However, the evidence revealed by the other modified experiments did indicate that aeration control and corresponding high oxygen distributional patterns would be highly dependent upon the initial porosity characteristics of the pile.

Secondly, the analysis of the initial woodchip and sludge inputs was based on a relatively small sample size. A more intensive sampling scheme prior to composting is needed to ascertain the potential causal effect the inputs would have on moisture levels at the end of the composting period. This approach would provide valuable information regarding the relationship of a heterogenous woodchip-sludge mixture to the final moisture levels upon completion of the composting process. Once this relationship is quantifiably deduced, definite insights may be attained when analyzing aeration control as a potential moisture reducing method.

Finally, ambiguous readings were often attained from the oxygen probe, probably because of water clogging the air holes, while compiling the oxygen profiles, when the oxygen probe was inserted horizontally into moist pockets. An alternate, less sensitive probe to moisture for oxygen determination should be utilized when compiling an oxygen profile at the end of the composting period.

4.3 Recommendations for Future Research

Given the dependability of forced aeration systems on the initial porosity characteristics of a pile, it is recommended that additional efforts at decreasing the moisture levels presently encountered with the forced aeration method of sludge composting be directed to limiting the variability of the woodchip-sludge mixture. One method would be to employ a more efficient mixing operation.

It is also recommended that attempts be made to assess the degree of organic stabilization and relate it to moisture levels since a definite positive causal relationship may exist between the variables, given the high correlations indentified between temperature and moisture. It should be pointed out that at present, there exists no common agreement on the point at which degrading organic solid waste becomes fully stabilized compost. Should a significant cause-effect relationship be proven it may be possible to utilize moisture levels to determine the degree of organic stabilization as opposed to other more time consuming methods, such as volatile solids or percent ash.

Finally, additional efforts at reducing moisture levels through forced aeration should be directed at using intermittent aeration. Preliminary evidence gained during this investigation suggests that more uniform spatial patterns may be obtainable, thereby limiting the production of wet malodorous pockets and intensively dessicated wells or channels which may well inhibit biological activity.

APPENDIX III

Spatial Patterns of Studied Variables

APPENDIX I

Test for Moisture

Equipment:

Drying oven, large desiccator cabinets, sample containers and covers, and an analytical balance.

Procedure:

Samples of 50 to 100 grams of the organic materials are taken in tared containers and immediately covered. Samples are weighed to the nearest 0.1 gram within one to two hours and dried to a constant weight in a drying oven at 75°C, with lids off or cocked. The samples are then cooled in a desiccator cabinet with the lids on, and are weighed.

Calculation:

$$\%\ \text{moisture} = \frac{100\ (\text{loss in weight})}{(\text{net wet weight})}$$

Reference:

"Municipal Refuse Disposal" U.S. DHEW, Public Administration Service, Chicago, Illinois, 1970, Appendix II, p. 392.

APPENDIX II

Oxygen and Temperature Monitoring Equipment

Oxygen:

A teledyne portable oxygen analyzer, Model 320B IRC, with a range of 0 to 25 per cent oxygen was used for regular measurements. A one meter long, hollow stainless steel probe with an attached squeeze bulb was used to pass through the cover material and penetrate the compost mix, allowing the gas sample to be drawn into the meter.

Temperature:

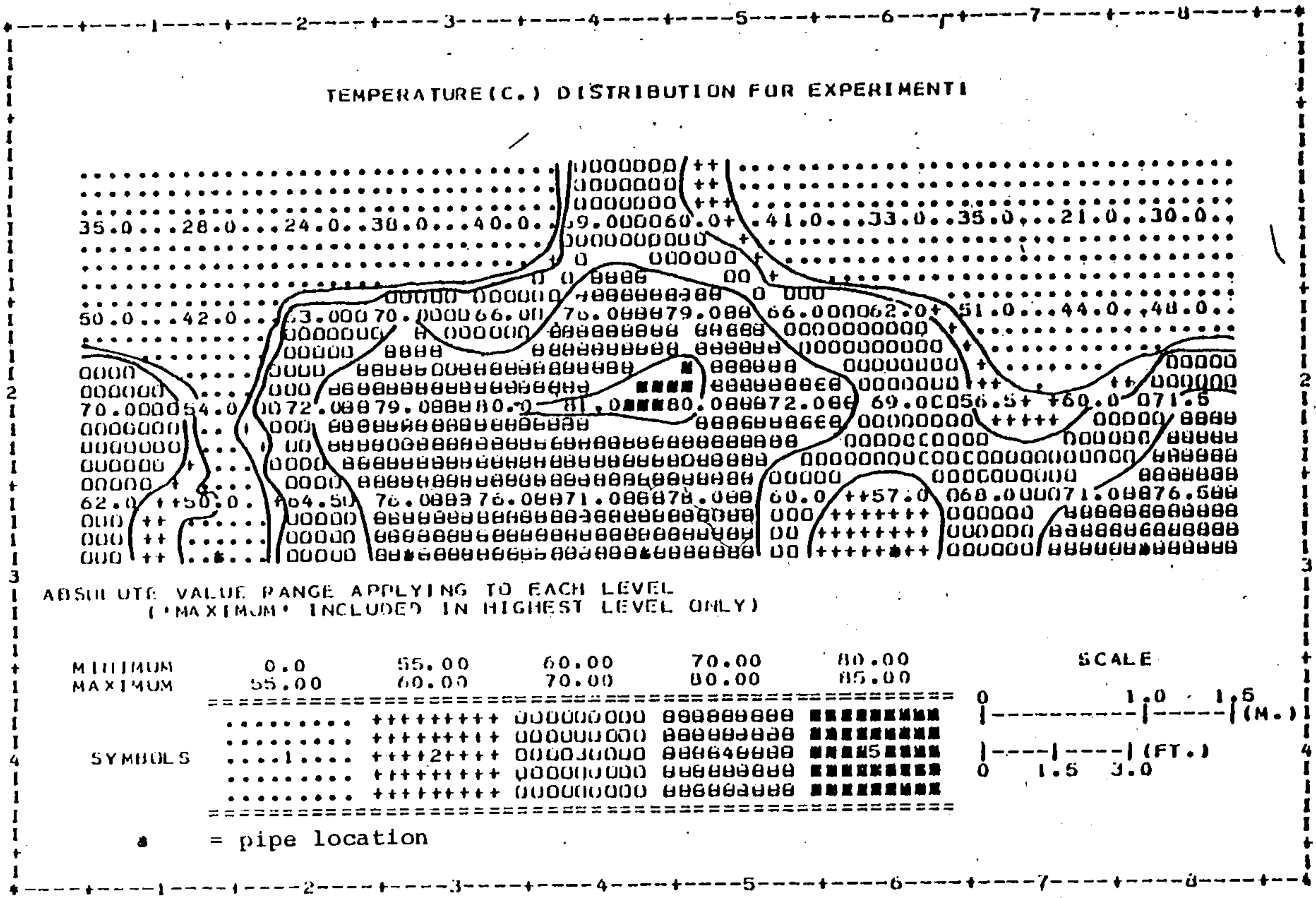
An Atkins, Model 23108-30, temperature meter with a range of 0 to 100°C was used for regular measurements. A one meter probe attached by wires to the meter, was used to pass through the cover material and penetrate the compost.

References:

Coulson, 1978, p. 94.

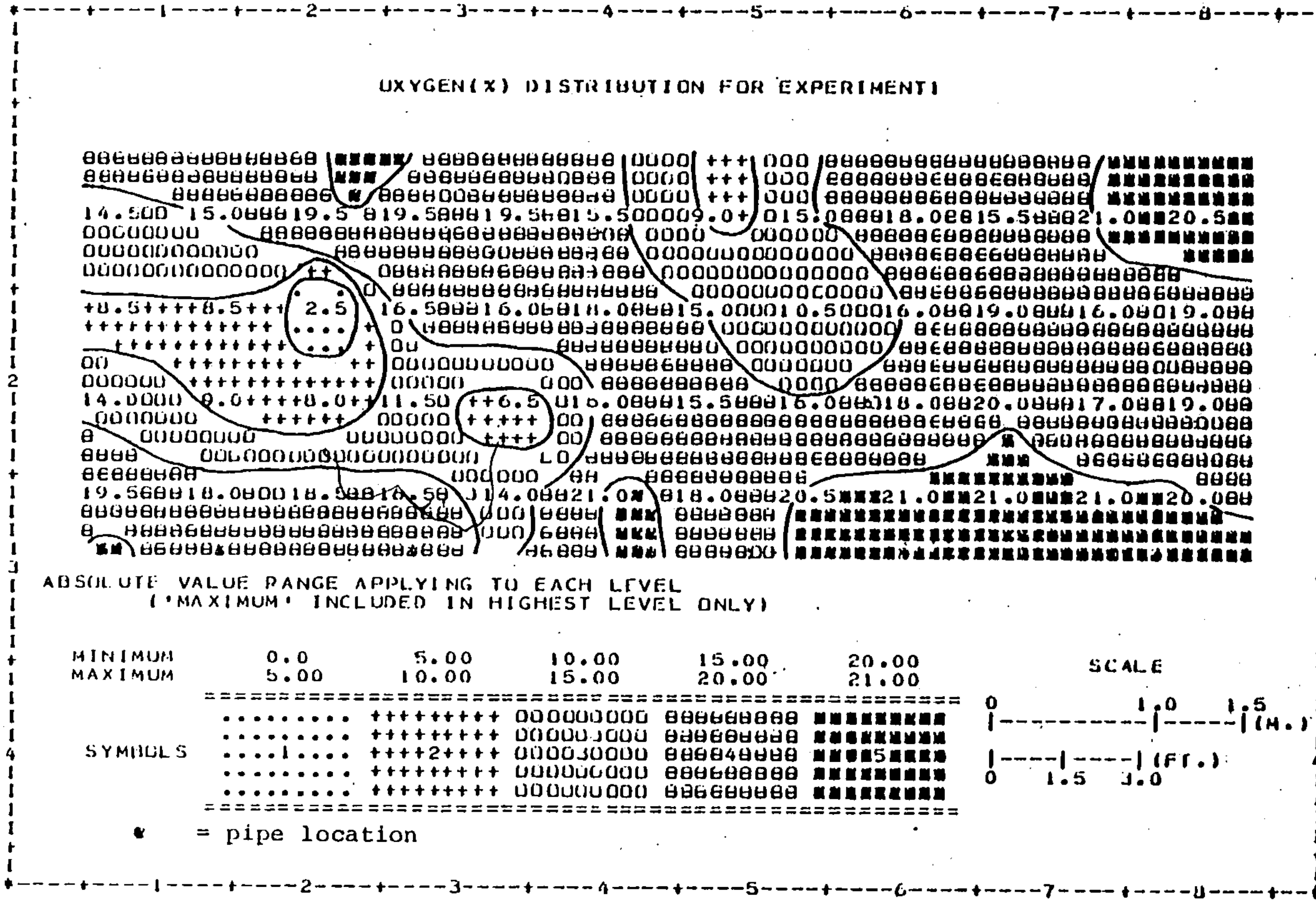
Romano and Faust, 1978, p. 106.

Figure 16



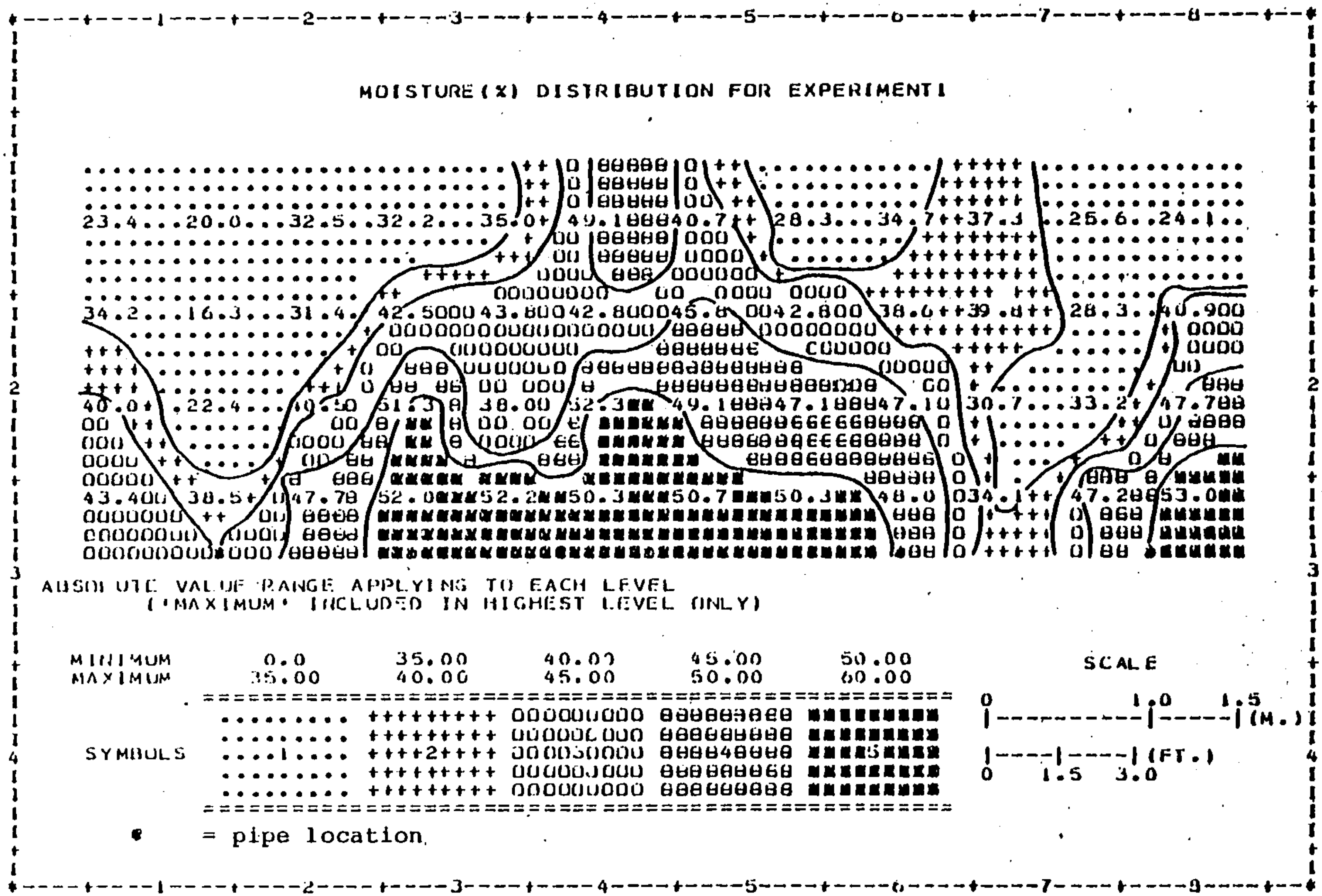
WIDTH WISE CROSS-SECTION THROUGH THE COMPOSTING PILE.
COMPOST PILE #1=10.16 CM. (4 IN.) PIPING AT 1.52 M. (5 FT.) INTERVALS.
AERATION RATE=1 FAN SET AT 2 WKS. CYCLE THEN 2 WKS. CONSTANT SUCTION.

Figure 17



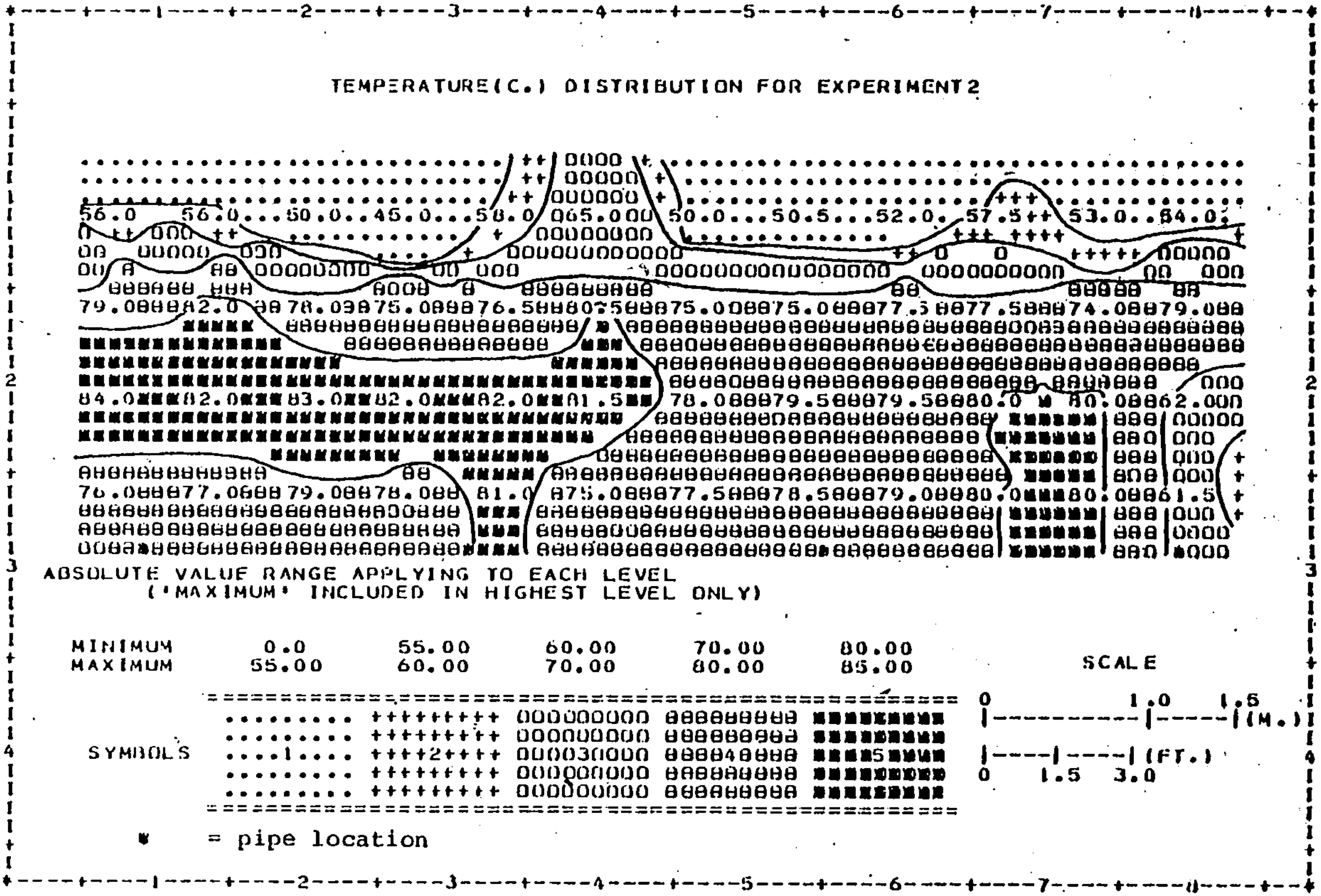
WIDTH WISE CROSS-SECTION THROUGH THE COMPOSTING PILE
COMPOST PILE #1=10.16 CM. (4 IN.) PIPING AT 1.52 M. (5 FT.) INTERVALS
AERATION RATE=1 FAN SET AT 2 WKS. CYCLE THEN 2 WKS. CONSTANT SUCTION.

Figure 18



WIDTH WISE CROSS-SECTION THROUGH THE COMPOSTING PILE.
COMPOST PILE #1=10.16 CM. (4 IN.) PIPING AT 1.52 M. (5 FT.) INTERVALS.
AERATION RATE=1 FAN SET AT 2 WKS. CYCLE THEN 2 WKS. CONSTANT SUCTION.

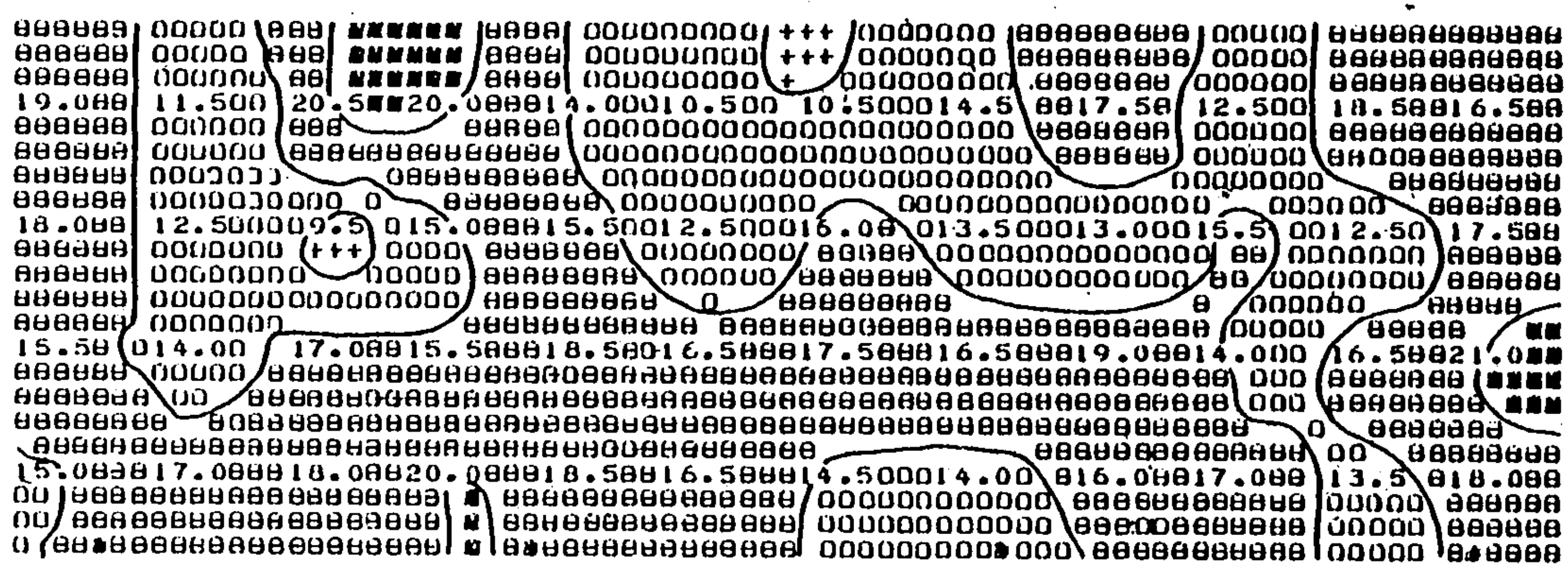
Figure 19



WIDTH WISE CROSS-SECTION THROUGH THE COMPOSTING PILE.
COMPOST PILE #2=10.16 CM. (4 IN.) PIPING AT 2.13 M. (7 FT.) INTERVALS.
AERATION RATE=1 FAN SET AT 2 WKS. CYCLE THEN 2 WKS. CONSTANT SUCTION.

Figure 20

OXYGEN(%) DISTRIBUTION FOR EXPERIMENT2



ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
('MAXIMUM' INCLUDED IN HIGHEST LEVEL ONLY)

MINIMUM	0.0	5.00	10.00	15.00	20.00
MAXIMUM	5.00	10.00	15.00	20.00	21.00
SYMBOLS	....1....	++++2++++	00003000	8888488888	■■■■5■■■■

SCALE

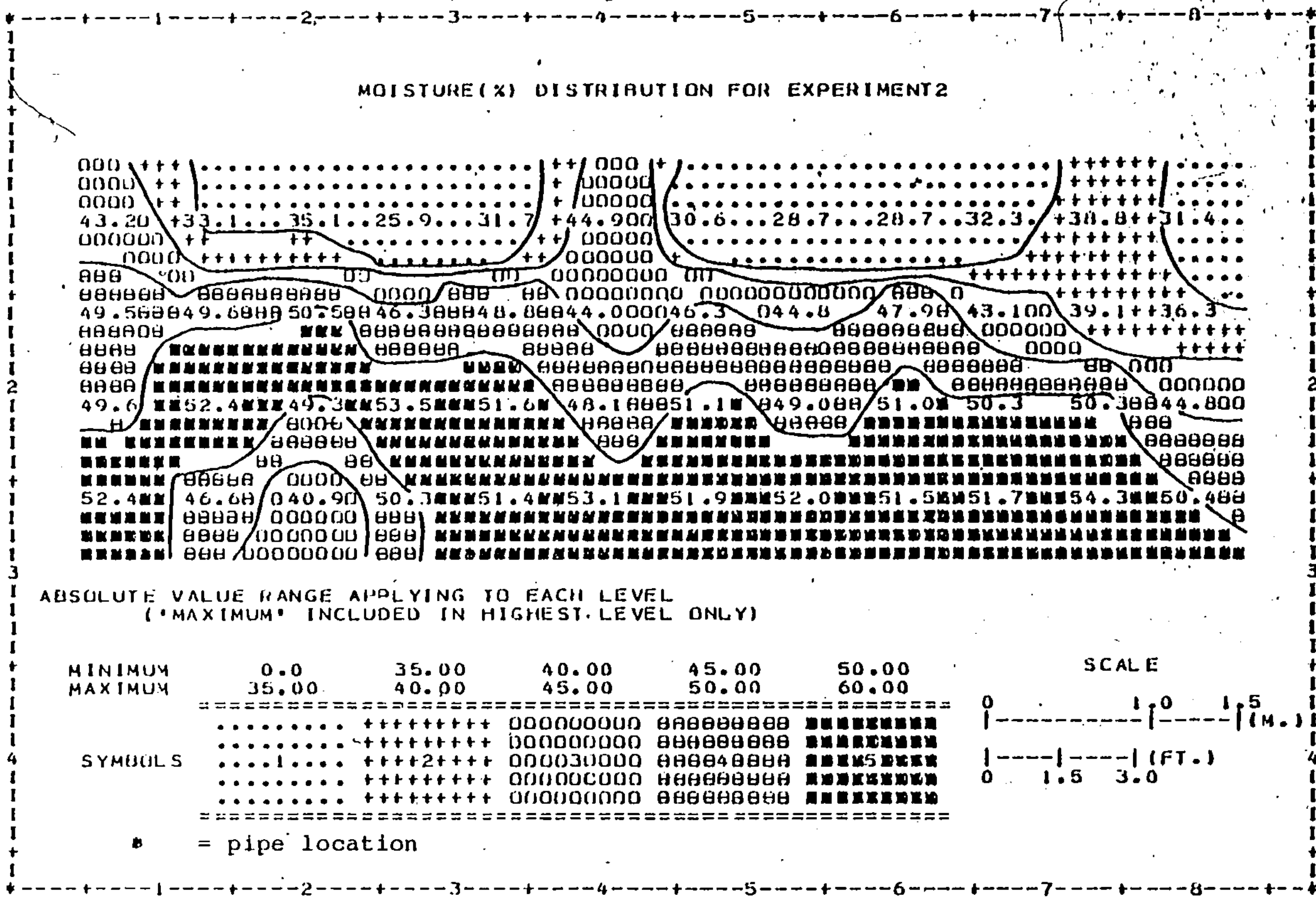
0 — 1.0 — 1.5 (M.)

0 — 1.5 — 3.0 (FT.)

* = pipe location

WIDTH WISE CROSS-SECTION THROUGH THE COMPOSTING PILE.
COMPOST PILE #2=10.16 CM. (4 IN.) PIPING AT 2.13 M. (7 FT.) INTERVALS.
AERATION RATE=1 FAN SET AT 2 WKS. CYCLE THEN 2 WKS. CONSTANT SUCTION.

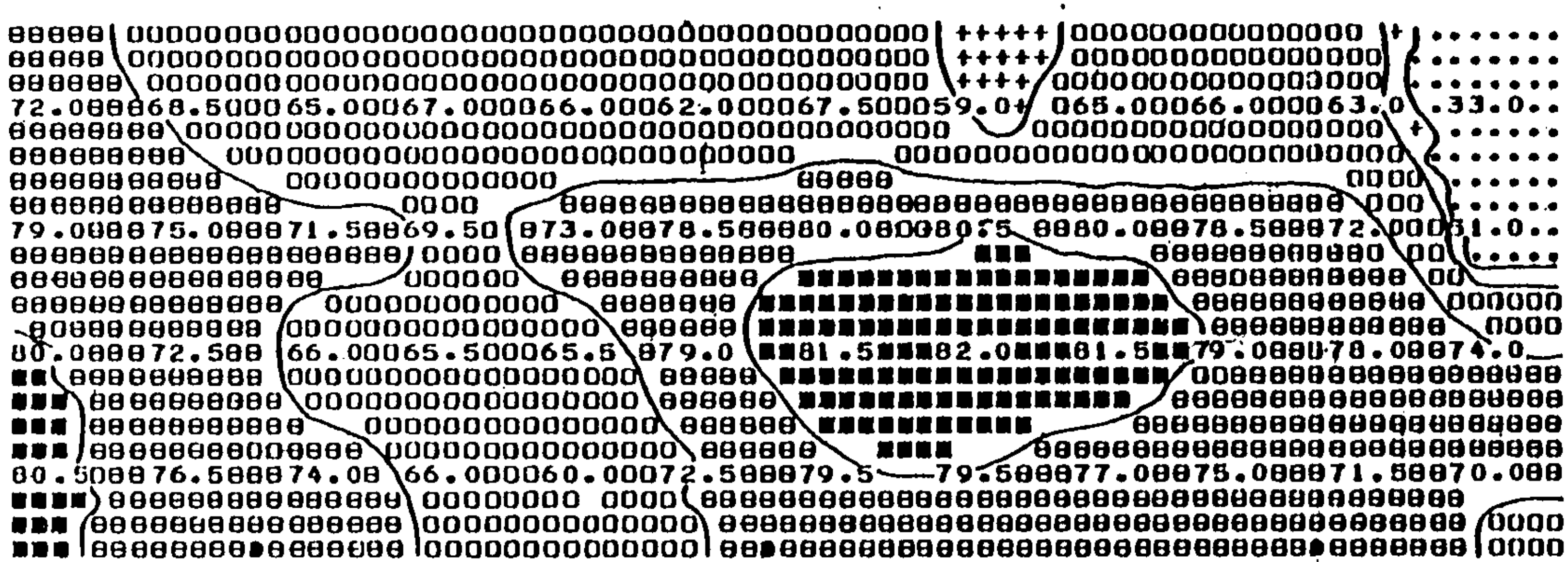
Figure 21



WIDTH WISE CROSS-SECTION THROUGH THE COMPOSTING PILE.
COMPOST PILE #2=10.16 CM. (4 IN.) PIPING AT 2.13 M. (7 FT.) INTERVALS
AERATION RATE=1 FAN SET AT 2 WKS. CYCLE THEN 2 WKS. CONSTANT SUCTION.

Figure 22

TEMPERATURE(C.) DISTRIBUTION FOR EXPERIMENT3



ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
('MAXIMUM' INCLUDED IN HIGHEST LEVEL ONLY)

MINIMUM	0.0	55.00	60.00	70.00	80.00
MAXIMUM	55.00	60.00	70.00	80.00	85.00
SYMBOLS	....1....	+++++++++ +++++++++ ++++2++++ +++++++++ +++++++++	000000000 000000000 000030000 000000000 000000000	888888888 888888888 888848888 888888888 888888888	■■■■■■■■■ ■■■■■■■■■ ■■■■5■■■■ ■■■■■■■■■ ■■■■■■■■■

SCALE

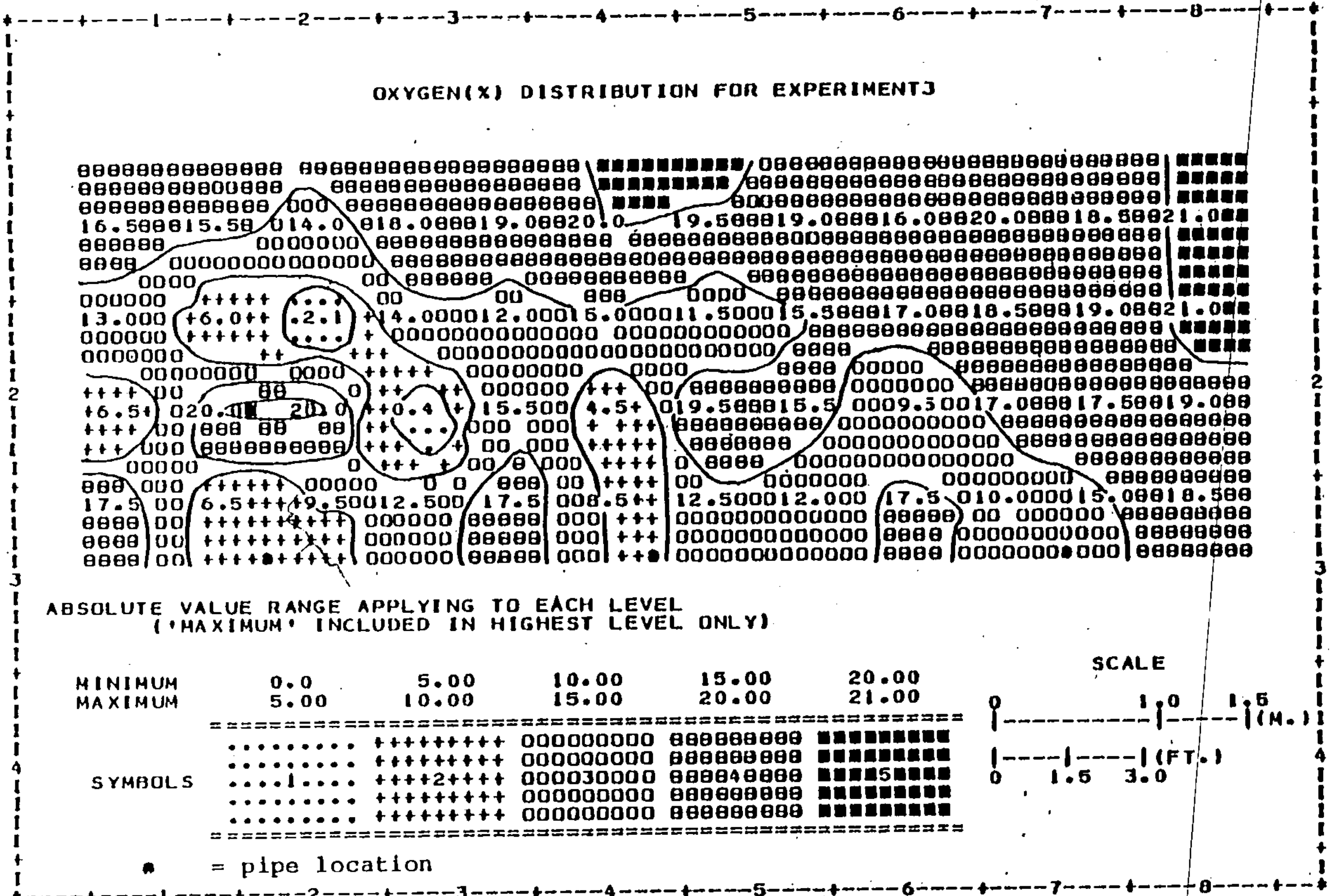
0 — 1.0 — 1.5 (M.)

0 — 1.5 — 3.0 (FT.)

● = pipe location

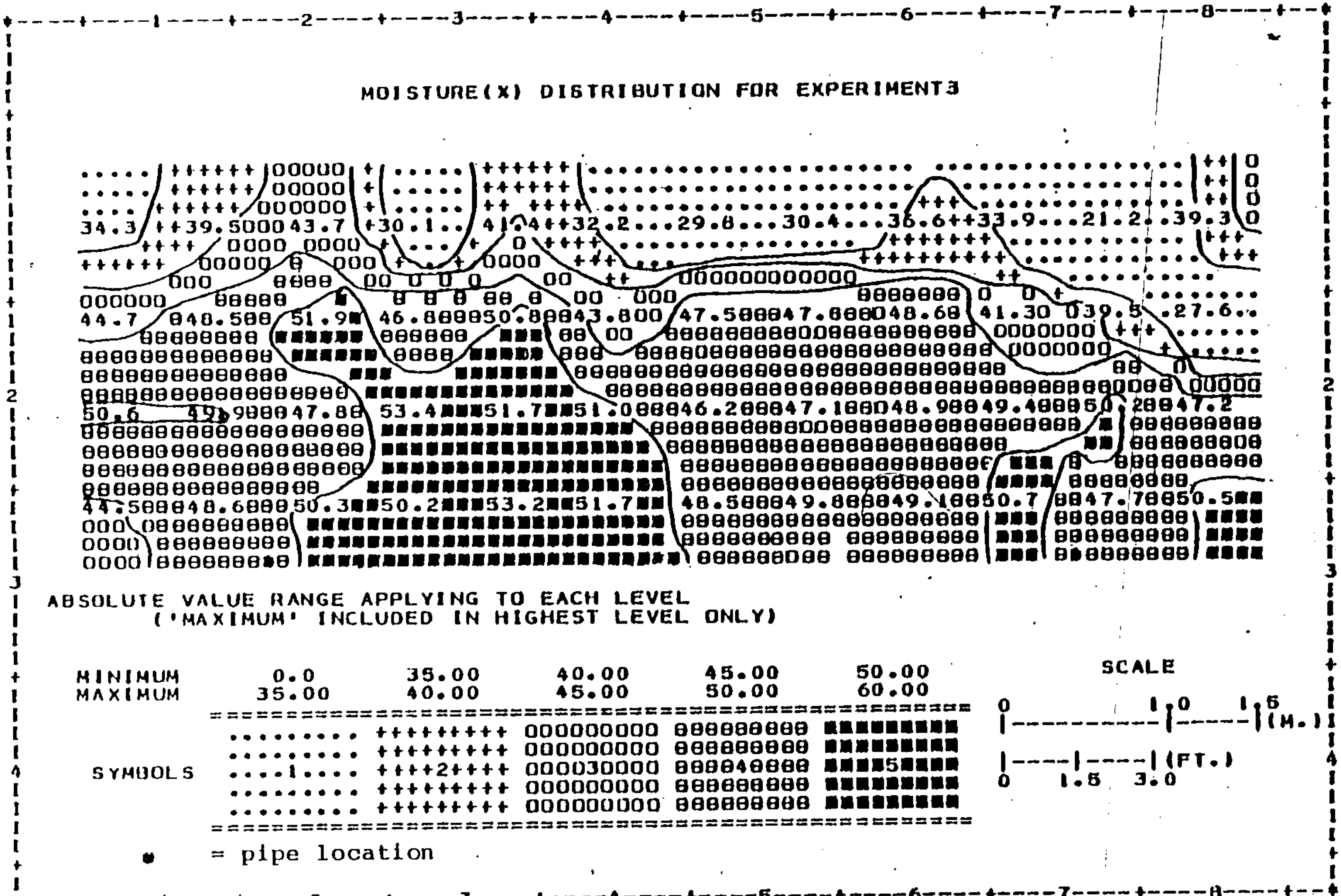
WIDTH WISE CROSS-SECTION THROUGH THE COMPOSTING PILE.
COMPOST PILE # 3=10.16 CM. (4 IN.) PIPING AT 2.44M. (8 FT.) INTERVALS.
AERATION RATE=1 FAN SET AT 2 WKS. CYCLE THEN 2 WKS. CONSTANT SUCTION.

Figure 23



WIDTH WISE CROSS-SECTION THROUGH THE COMPOSTING PILE.
COMPOST PILE #3=10.16 CM. (4 IN.) PIPING AT 2.44 M. (8 FT.) INTERVALS.
AERATION RATE=1 FAN SET AT 2 WKS. CYCLE THEN 2 WKS. CONSTANT SUCTION.

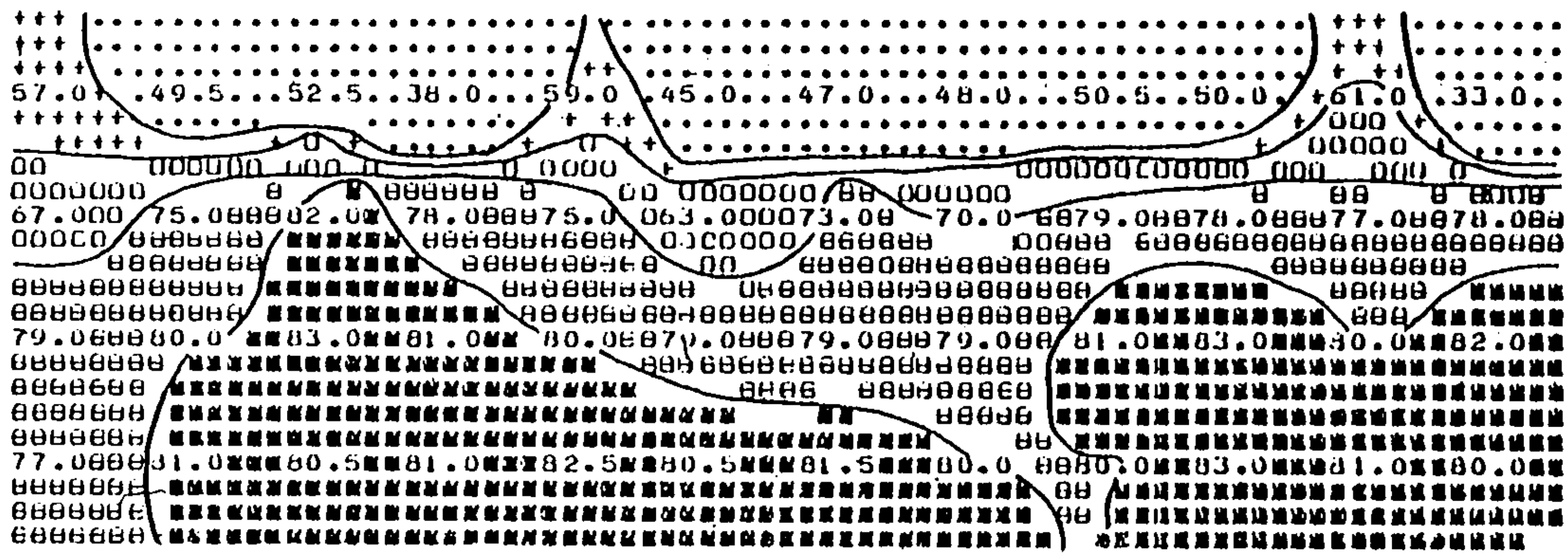
Figure 24



WIDTH WISE CROSS-SECTION THROUGH THE COMPOSTING PILE.
COMPOST PILE #3=10.16 CM. (4 IN.) PIPING AT 2.44 M. (8 FT.) INTERVALS.
AERATION RATE=1 FAN SET AT 2 WKS. CYCLE THEN 2 WKS. CONSTANT SUCTION.

Figure 25

TEMPERATURE(C.) DISTRIBUTION FOR EXPERIMENT4



ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
('MAXIMUM' INCLUDED IN HIGHEST LEVEL ONLY)

MINIMUM	0.0	55.00	60.00	70.00	80.00
MAXIMUM	55.00	60.00	70.00	80.00	85.00
SYMBOLS	....1....	+++++++++ +++++++++ ++++2++++ +++++++++ +++++++++	000000000 000000000 000030000 000000000 000000000	888888888 888888888 888848888 888888888 888888888	■■■■■■■■■ ■■■■■■■■■ ■■■■5■■■■ ■■■■■■■■■ ■■■■■■■■■

SCALE

0 — 1.0 — 1.5 (M.)

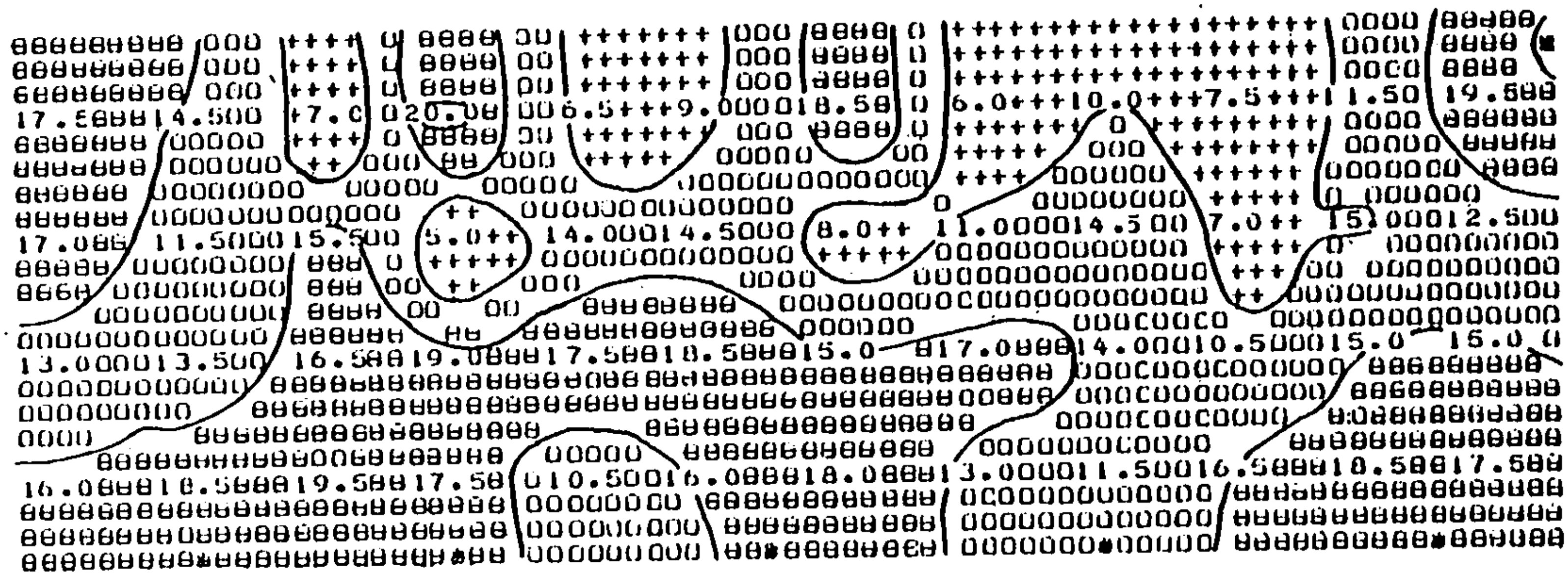
0 — 1.5 — 3.0 (FT.)

● = pipe location

WIDTH WISE CROSS-SECTION THROUGH THE COMPOSTING PILE.
COMPOST PILE #4=10.16 CM. (4 IN.) PIPING AT 1.52 M. (5 FT.) INTERVALS.
AERATION RATE=2 FANS SET AT 2 WKS. CYCLE THEN 2 WKS. CONSTANT SUCTION.

Figure 26

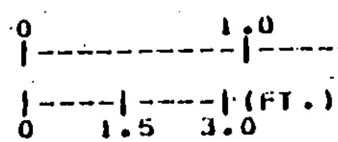
OXYGEN(%) DISTRIBUTION FOR EXPERIMENT4



ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
('MAXIMUM' INCLUDED IN HIGHEST LEVEL ONLY)

MINIMUM	0.0	5.00	10.00	15.00	20.00
MAXIMUM	5.00	10.00	15.00	20.00	21.00
SYMBOLS	....1....	+++++++++ +++++++++ ++++2++++ +++++++++ +++++++++	000000000 000000000 000030000 000000000 000000000	888888888 888888888 888848888 888888888 888888888	████████ ████████ ████5████ ████████ ████████

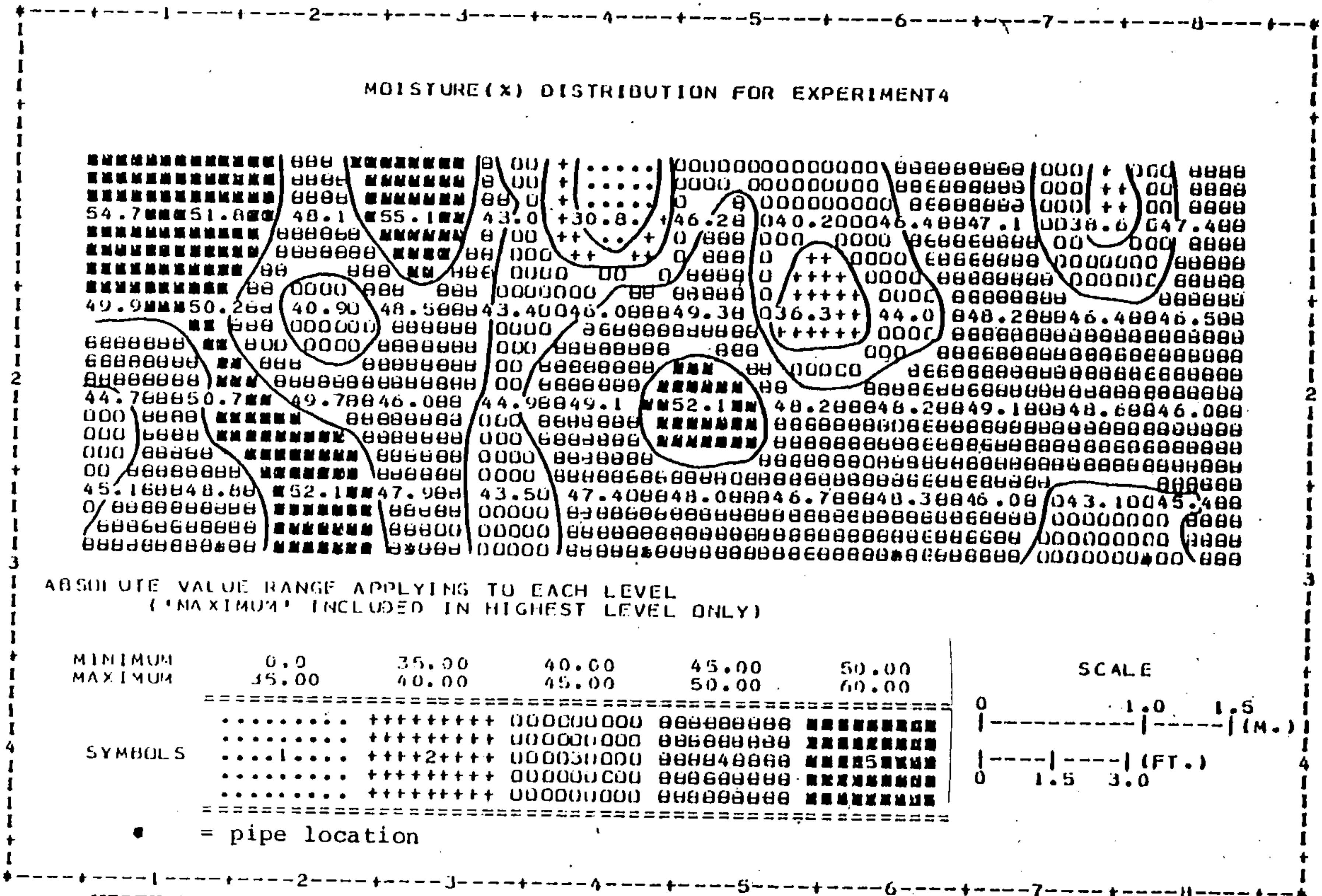
SCALE



* = pipe location

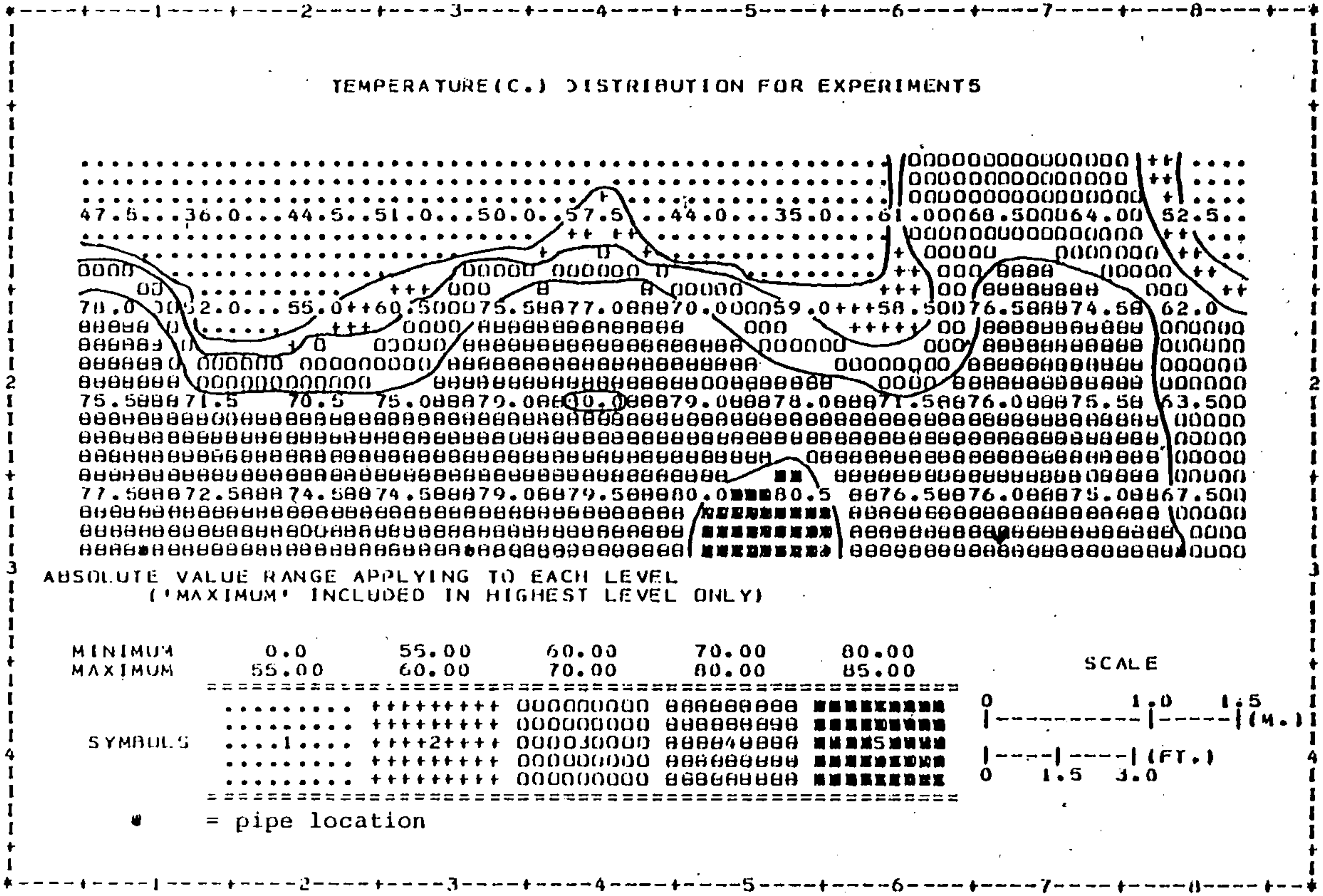
WIDTH WISE CROSS-SECTION THROUGH THE COMPOSTING PILE.
COMPOST PILE #4=10.16 CM. (4 IN.) PIPING AT 1.52 M. (5 FT.) INTERVALS.
AERATION RATE=2 FANS SET AT 2 WKS. CYCLE THEN 2 WKS. CONSTANT SUCTION.

Figure 27



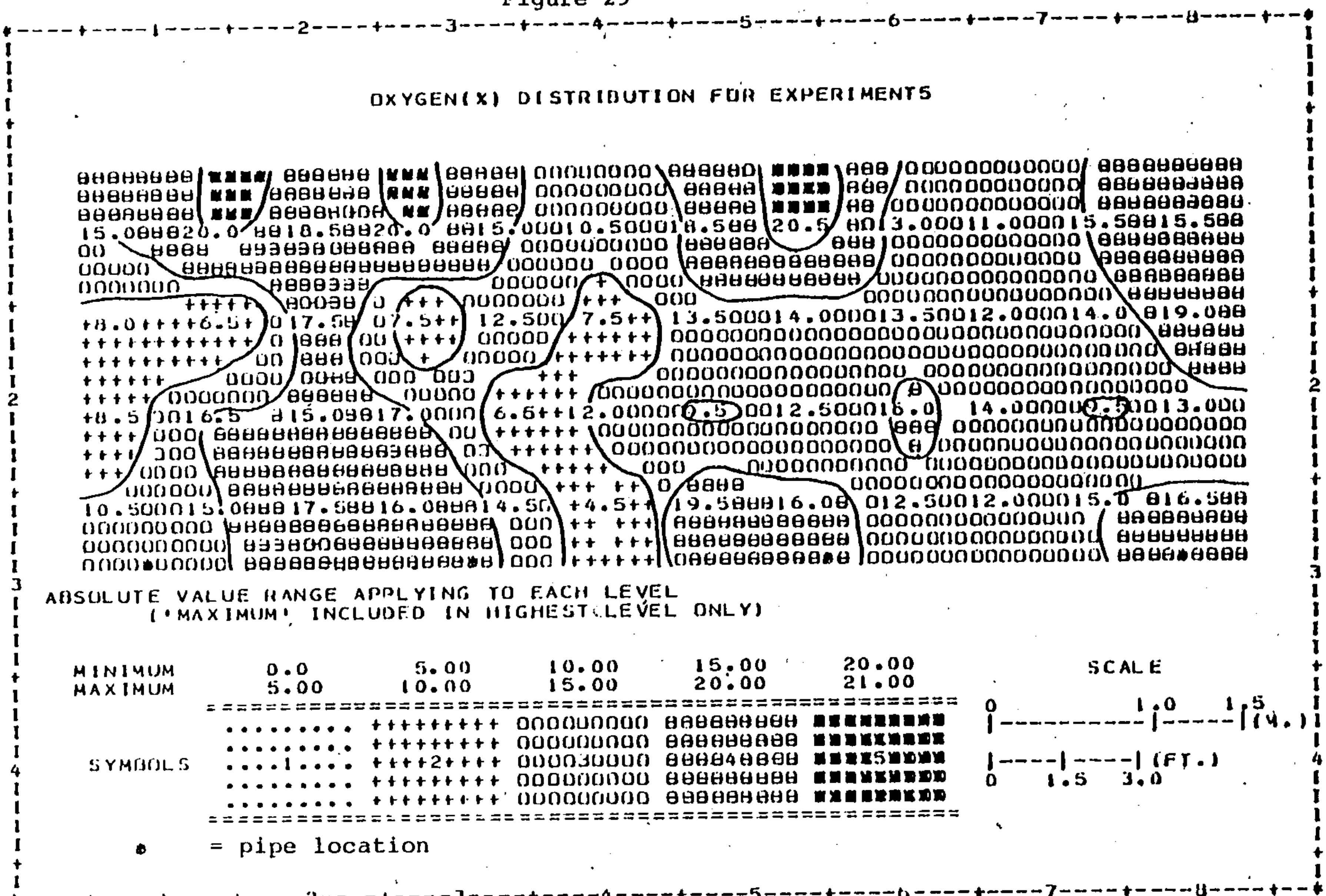
WIDTH WISE CROSS-SECTION THROUGH THE COMPOSTING PILE.
COMPOST PILE #4=10.16 CM. (4 IN.) PIPING AT 1.52 M. (7 FT.) INTERVALS.
AERATION RATE=2 FANS SET AT 2 WKS. CYCLE THEN 2 WKS. CONSTANT SUCTION.

Figure 28



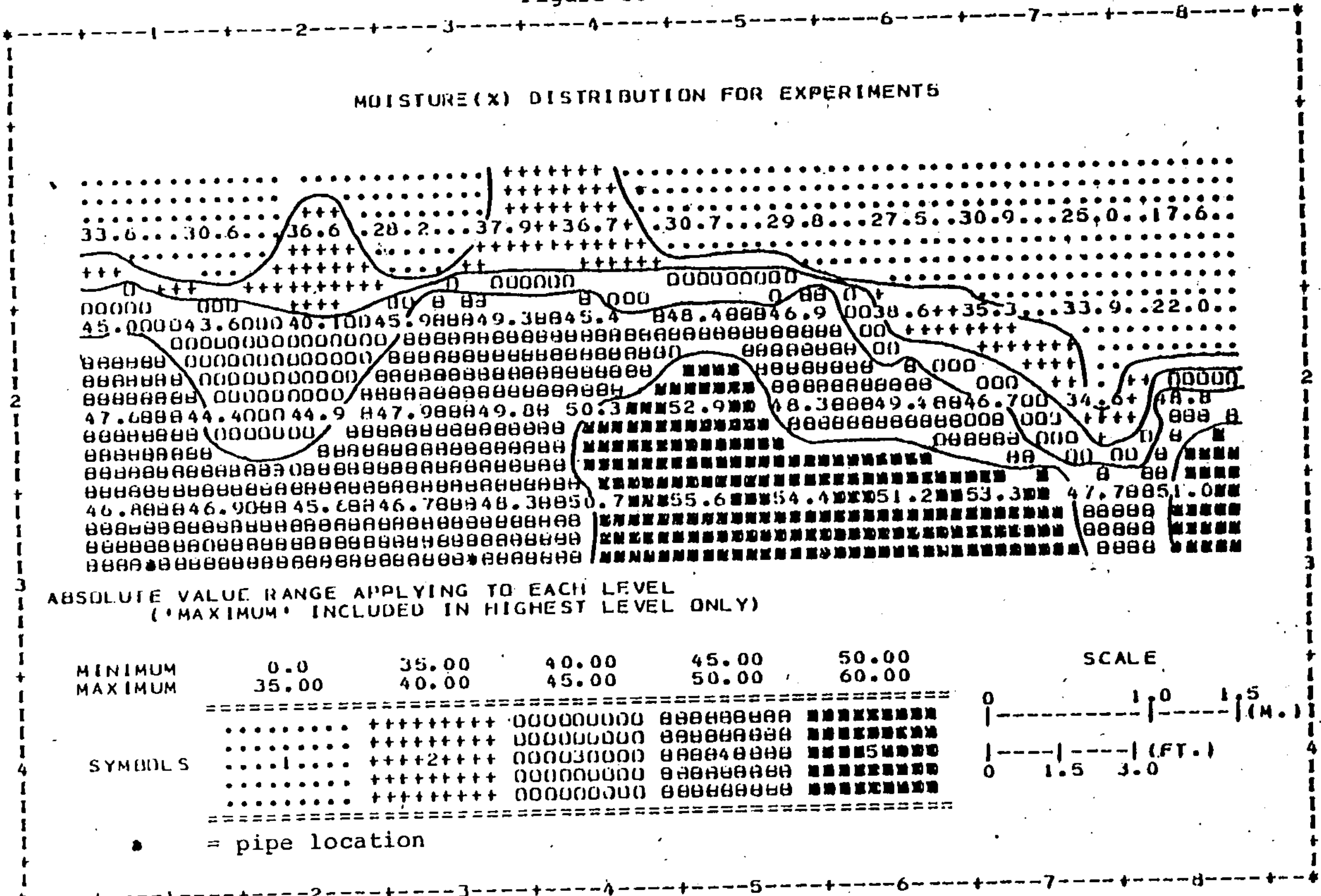
WIDTH WISE CROSS-SECTION THROUGH THE COMPOSTING PILE.
COMPOST PILE #5=10.16 CM. (4 IN.) PIPING AT 2.13 M. (7 FT.) INTERVALS.
AERATION RATE=2 FANS SET AT 2 WKS. CYCLE THEN 2 WKS. CONSTANT SUCTION.

Figure 29



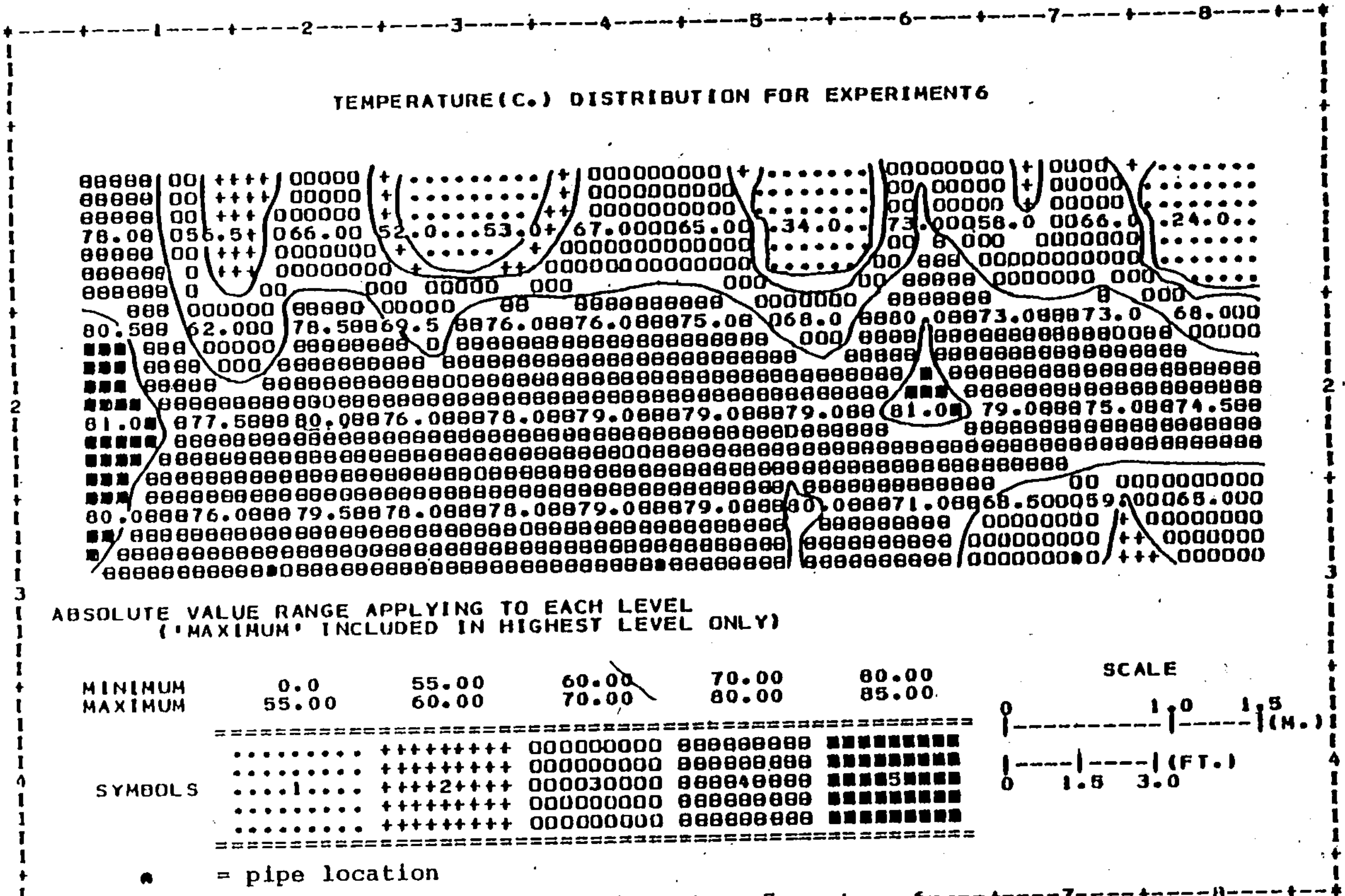
WIDTH WISE CROSS-SECTION THROUGH THE COMPOSTING PILE.
COMPOST PILE #5=10.16 CM. (4 IN.) PIPING AT 2.13 M. (7 FT.) INTERVALS.
AERATION RATE=2 FANS SET AT 2 WKS. CYCLE THEN 2 WKS. CONSTANT SUCTION.

Figure 30



WIDTH WISE CROSS-SECTION THROUGH THE COMPOSTING PILE.
COMPOST PILE #5=10.16 CM. (4 IN.) PIPING AT 2.13 M. (7 FT.) INTERVALS.
AERATION RATE=2 FANS SET AT 2 WKS. CYCLE THEN 2 WKS. CONSTANT SUCTION.

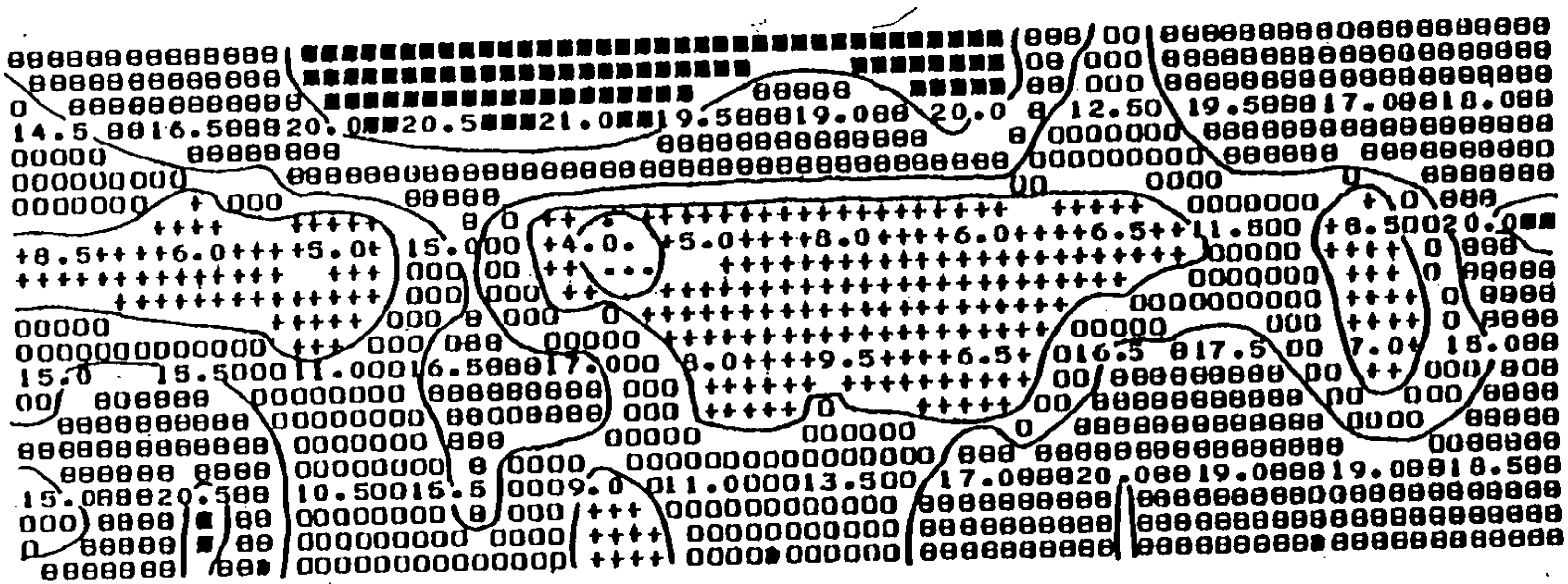
Figure 31



WIDTH WISE CROSS-SECTION THROUGH THE COMPOSTING PILE.
COMPOST PILE #6=10.16 CM. (4 IN.) PIPING AT 2.44 M. (8 FT.) INTERVALS.
AERATION RATE=2 FANS SET AT 2 WKS. CYCLE THEN 2 WKS. CONSTANT SUCTION.

Figure 32

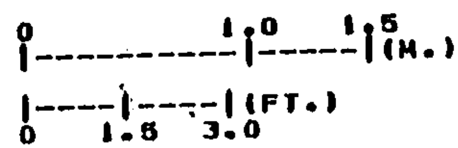
OXYGEN(X) DISTRIBUTION FOR EXPERIMENT6



ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
('MAXIMUM' INCLUDED IN HIGHEST LEVEL ONLY)

MINIMUM	0.0	5.00	10.00	15.00	20.00
MAXIMUM	5.00	10.00	15.00	20.00	21.00
SYMBOLS	....	+++++++++	000000000	888888888	■■■■■■■■■

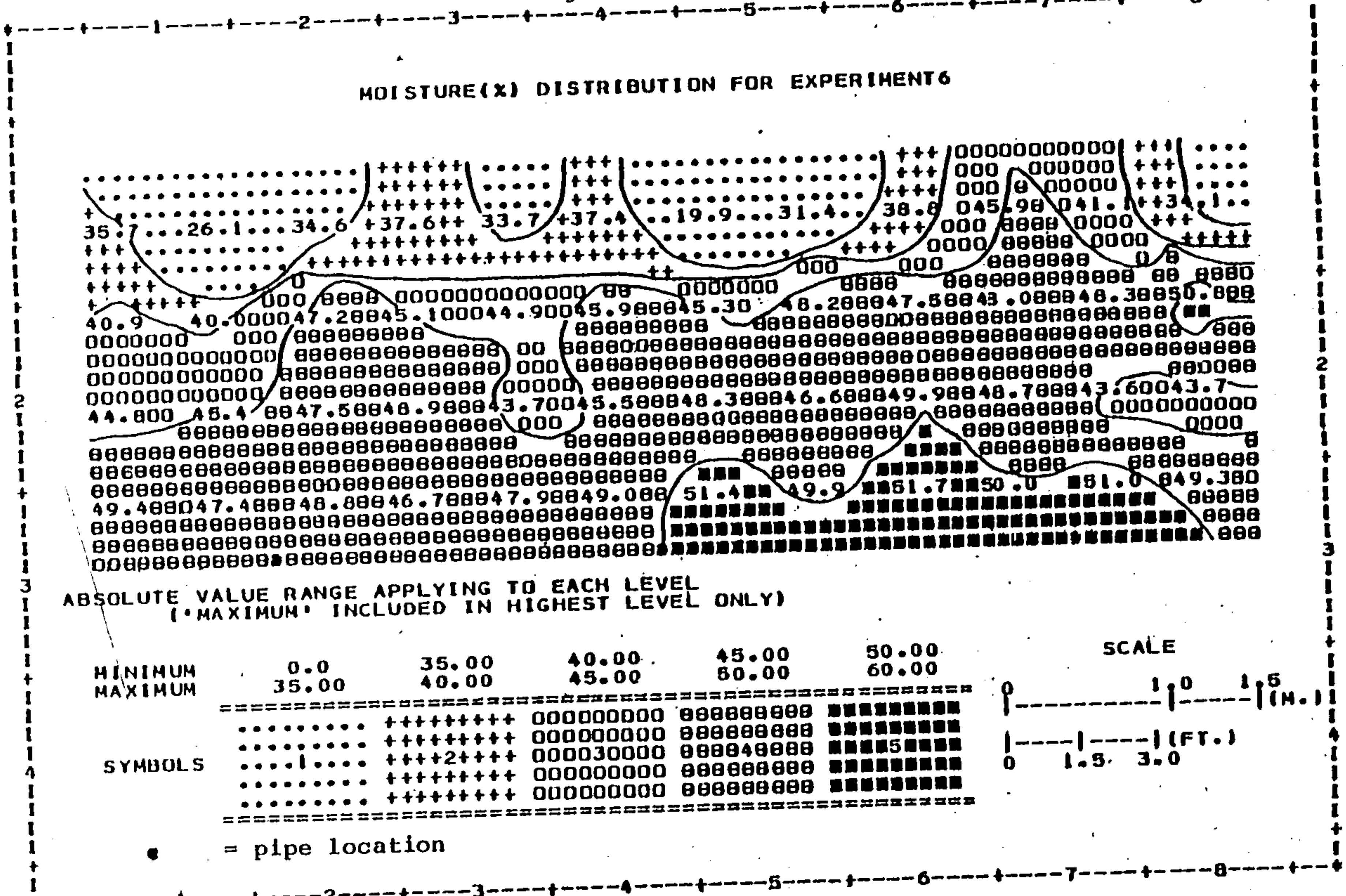
SCALE



● = pipe location

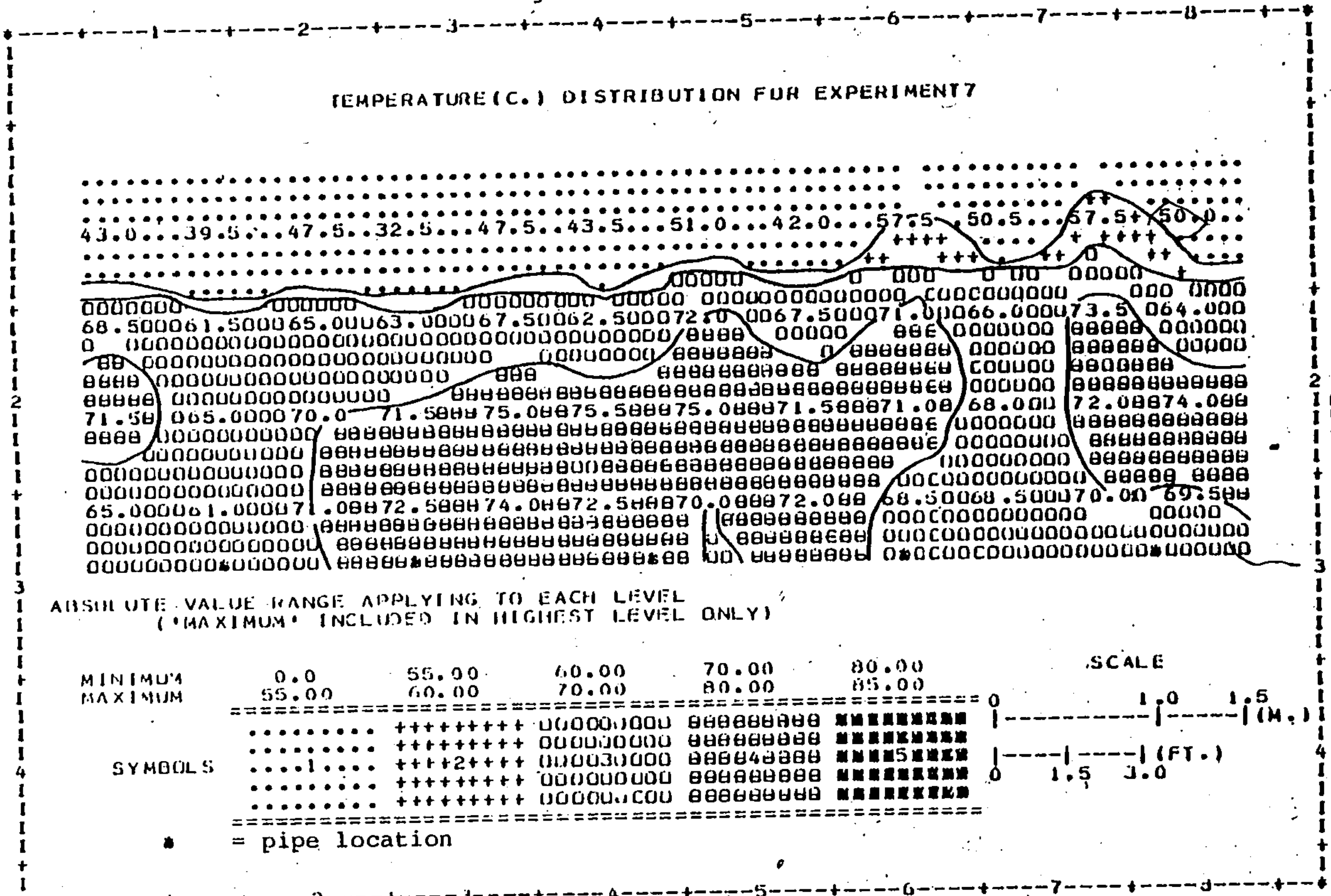
WIDTH WISE CROSS-SECTION THROUGH THE COMPOSTING PILE.
COMPOST PILE #6=10.16 CM. (4 IN.) PIPING AT 2.44 M. (8 FT.) INTERVALS.
AERATION RATE=2 FANS SET AT 2 WKS. CYCLE THEN 2 WKS. CONSTANT SUCTION.

Figure 33



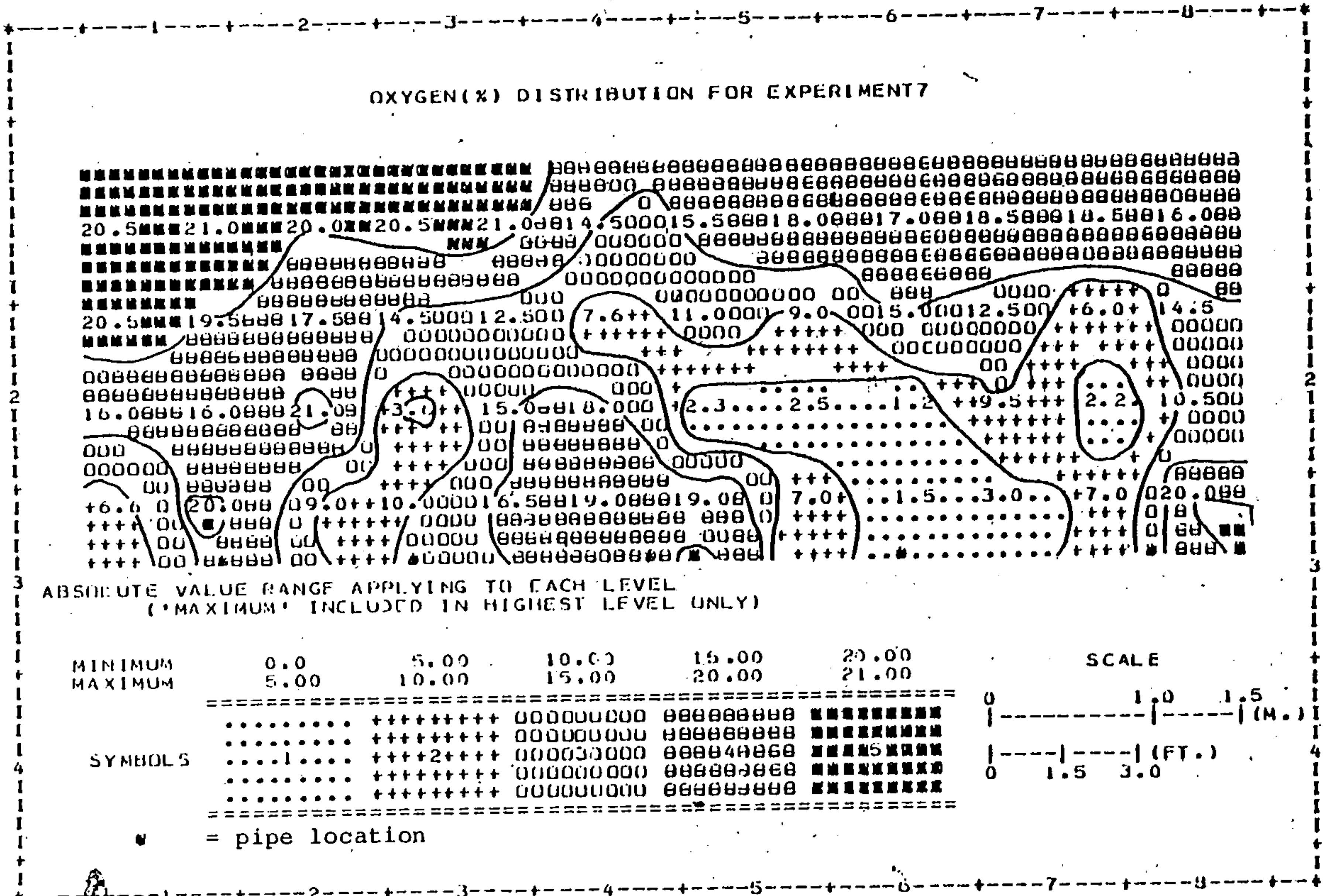
WIDTH WISE CROSS-SECTION THROUGH THE COMPOSTING PILE.
COMPOST PILE #6=10.16 CM. (4 IN.) PIPING AT 2.44 M. (8 FT.) INTERVALS.
AERATION RATE=2 FANS SET AT 2 WKS. CYCLE THEN 2 WKS. CONSTANT SUCTION.

Figure 34



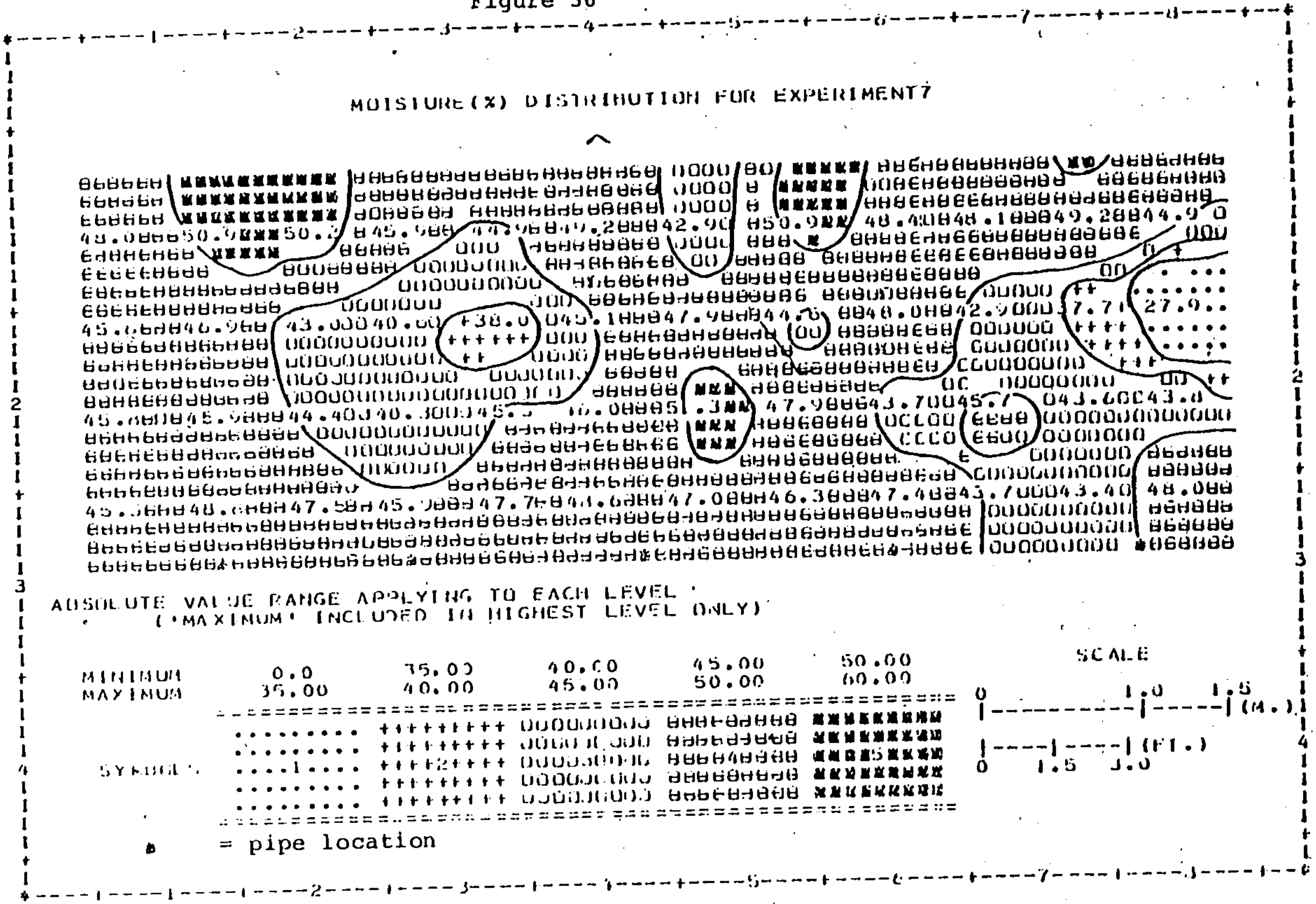
WIDTH WISE CROSS-SECTION THROUGH THE COMPOSTING PILE.
COMPOST PILE #7=15.24 CM. (6 IN.) PIPING AT 1.52 M. (5 FT.) INTERVALS.
AERATION RATE=2 FANS SET AT 2 WKS. CYCLE THEN 2 WKS. CONSTANT SUCTION.

Figure 35



WIDTH WISE CROSS-SECTION THROUGH THE COMPOSTING PILE.
COMPOST PILE #7=15.24 CM. (6 IN.) PIPING AT 1.52 M. (5 FT.) INTERVALS.
AERATION RATE=2 FANS SET AT 2 WKS. CYCLE THEN 2 WKS. CONSTANT SUCTION.

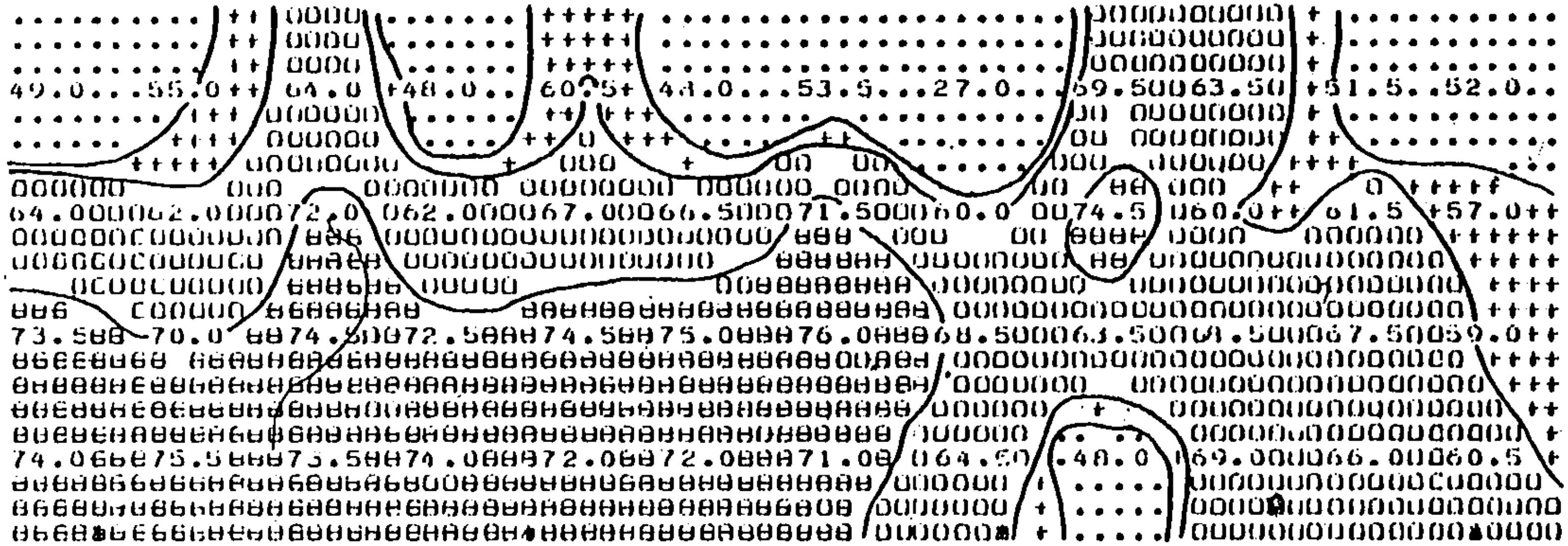
Figure 36



WIDTH WISE CROSS-SECTION THROUGH THE COMPOSTING PILE .
COMPOST PILE #7=15.24 CM. (6 IN.) PIPING AT 1.52 M. (5 FT.) INTERVALS.
AERATION RATE=2 FANS SET AT 2 WKS. CYCLE THEN 2 WKS. CONSTANT SUCTION.

Figure 37

TEMPERATURE(C.) DISTRIBUTION FOR EXPERIMENT8



ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
('MAXIMUM' INCLUDED IN HIGHEST LEVEL ONLY)

MINIMUM	0.0	55.00	60.00	70.00	80.00
MAXIMUM	55.00	60.00	70.00	80.00	85.00
SYMBOLS	....1....	++++2++++	000030000	8888488888	■■■■5■■■■

SCALE

0 1.0 1.5 (M.)

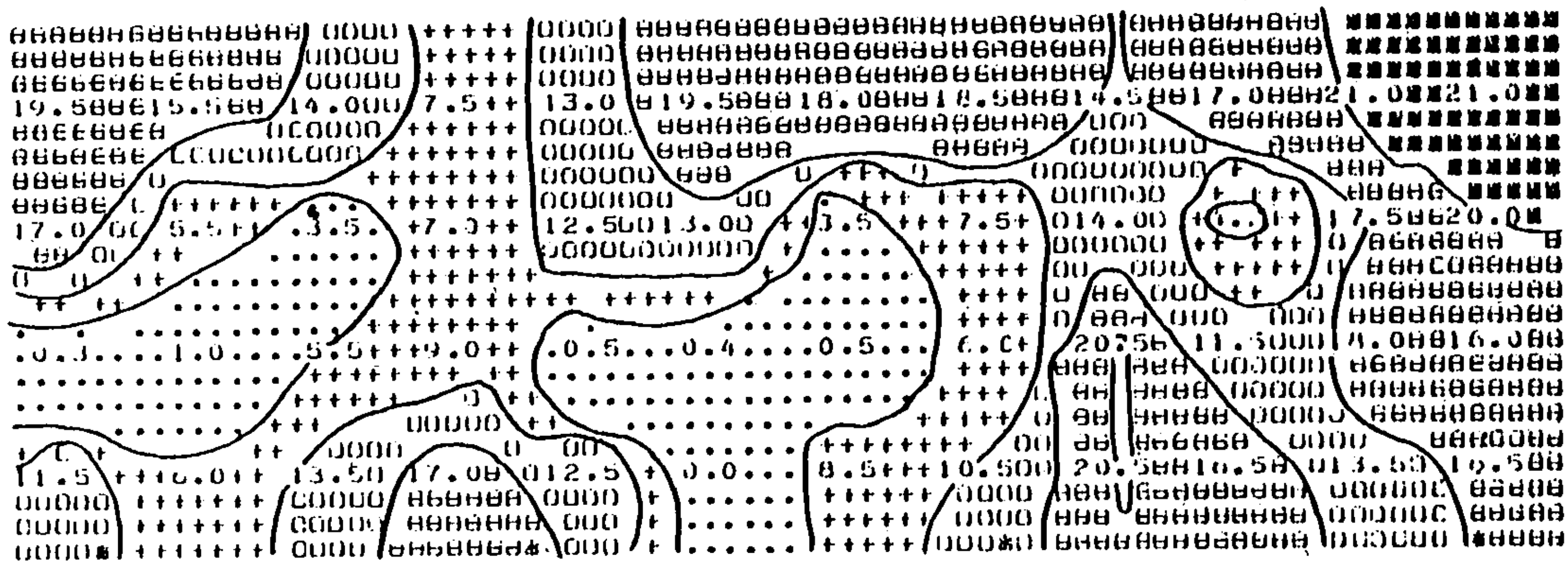
0 1.5 3.0 (FT.)

■ = pipe location

WIDTH WISE CROSS-SECTION THROUGH THE COMPOSTING PILE.
COMPOST PILE #8=15.24 CM. (6 IN.) PIPING AT 2.13 M. (7 FT.) INTERVALS.
AERATION RATE=2 FANS SET AT 2 WKS. CYCLE THEN 2 WKS. CONSTANT SUCTION.

Figure 38

OXYGEN(%) DISTRIBUTION FOR EXPERIMENT8



ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
('MAXIMUM' INCLUDED IN HIGHEST LEVEL ONLY)

MINIMUM	0.0	5.00	10.00	15.00	20.00
MAXIMUM	5.00	10.00	15.00	20.00	21.00
SYMBOLS	....1....	++++2++++	0000З0000	88884888	■■■■5■■■■

SCALE

0 — 1.0 — 1.5 (M.)

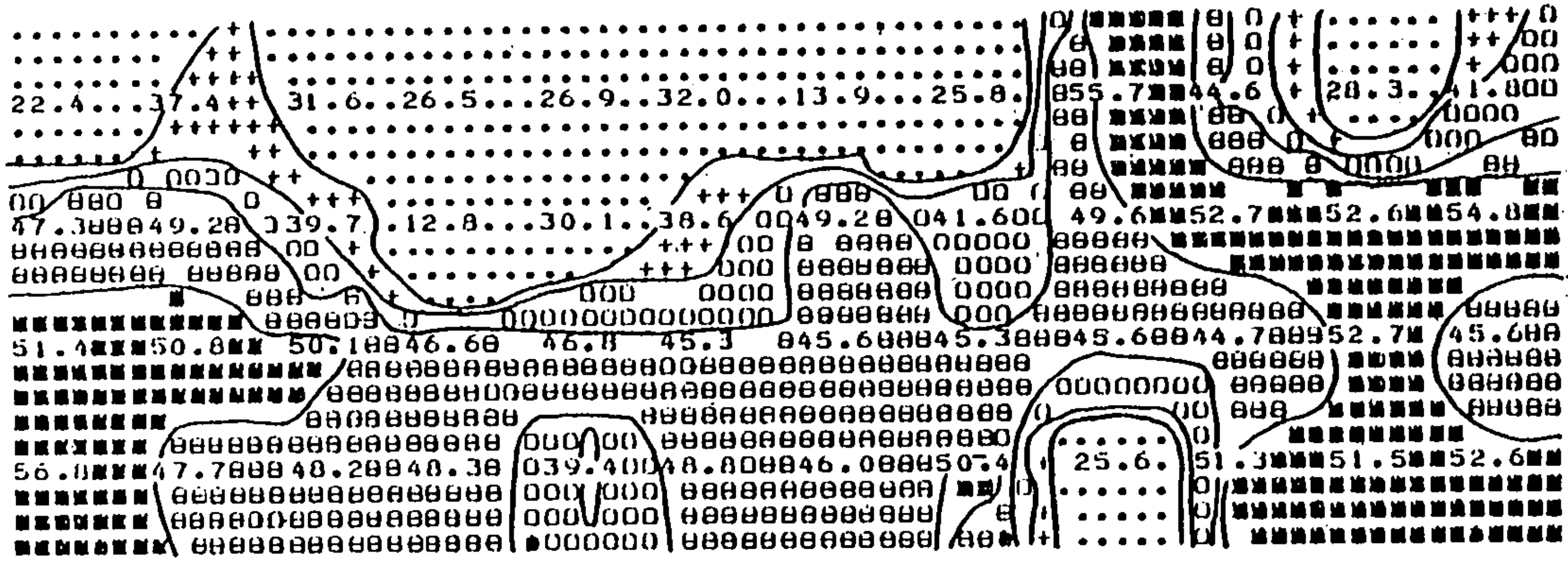
0 — 1.5 — 3.0 (FT.)

* = pipe location

WIDTH WISE CROSS-SECTION THROUGH THE COMPOSTING PILE.
COMPOST PILE #8=15.24 CM. (6 IN.) PIPING AT 2.13 M. (7 FT.) INTERVALS.
AERATION RATE=2 FANS SET AT 2 WKS. CYCLE THEN 2 WKS. CONSTANT SUCTION.

Figure 39

MOISTURE(%) DISTRIBUTION FOR EXPERIMENT8



ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
('MAXIMUM' INCLUDED IN HIGHEST LEVEL ONLY)

MINIMUM	0.0	35.00	40.00	45.00	50.00
MAXIMUM	35.00	40.00	45.00	50.00	60.00
SYMBOLS	....1....	++++2++++	000030000	88884888	■■■■5■■■■

■ = pipe location

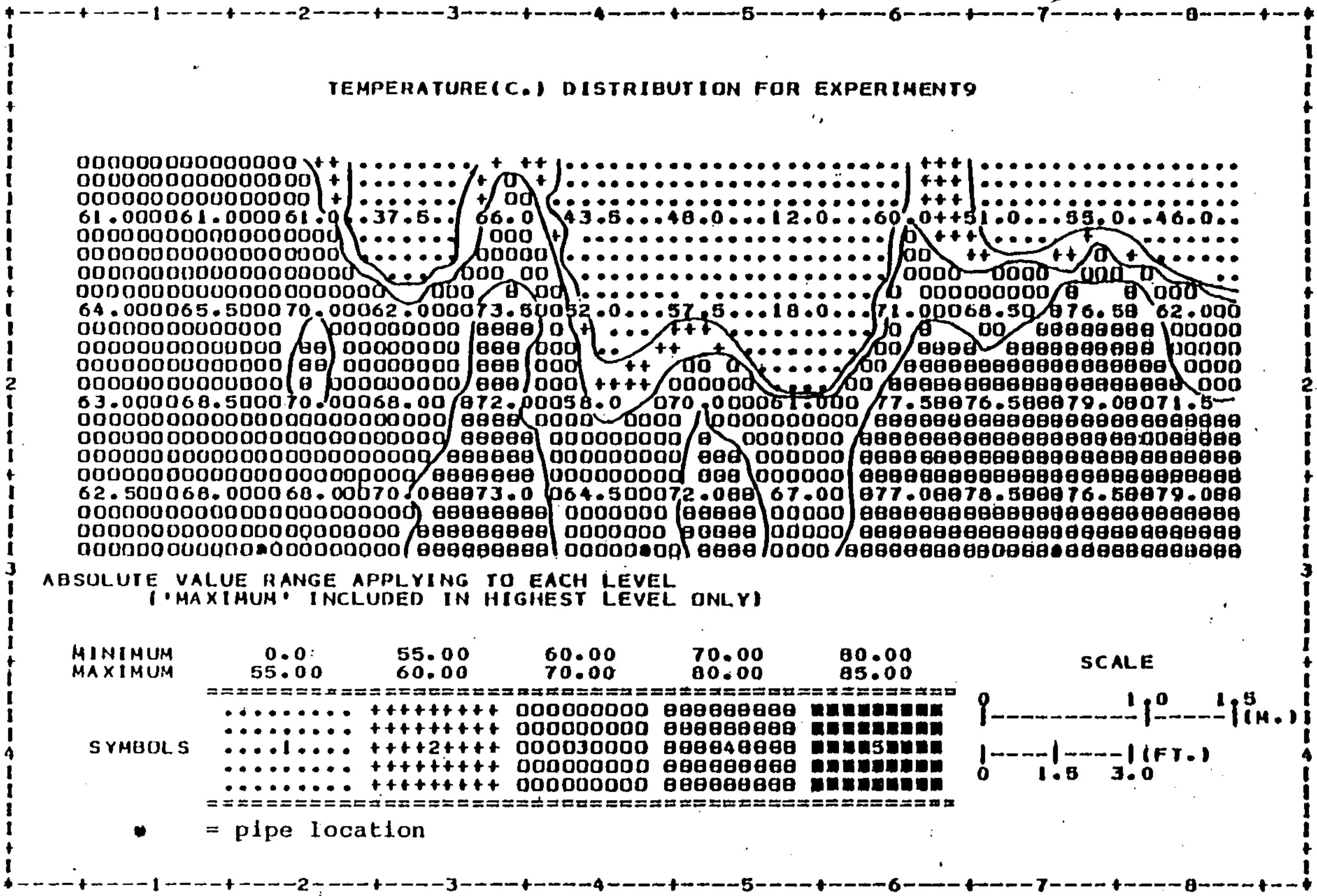
SCALE

0 — 1.0 — 1.5 (M.)

0 — 1.5 — 3.0 (FT.)

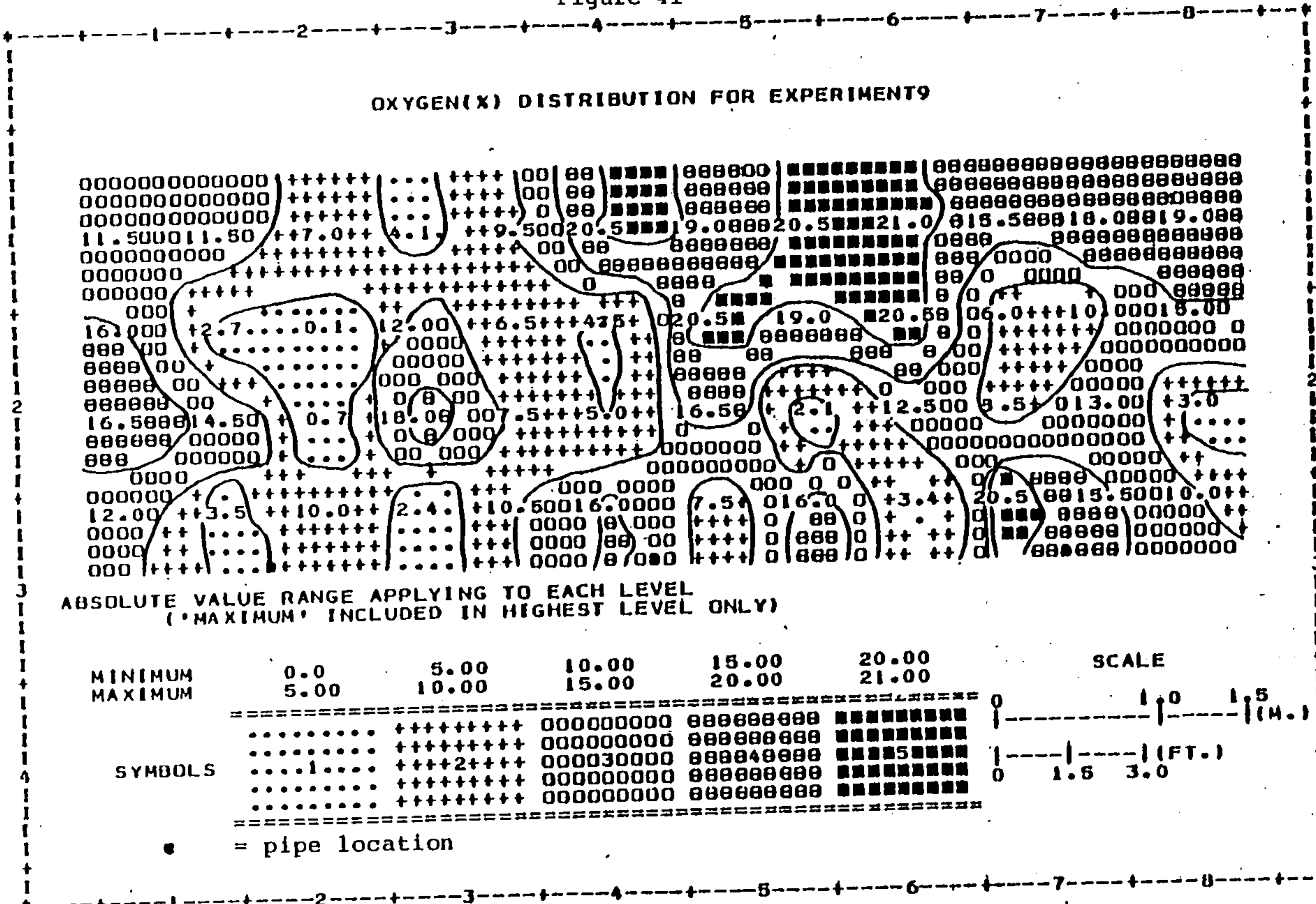
WIDTH WISE CROSS-SECTION THROUGH THE COMPOSTING PILE ..
COMPOST PILE #8=15.24 CM. (6 IN.) PIPING AT 2.13 M. (7 FT.) INTERVALS .
AERATION RATE=2 FANS SET AT 2 WKS. CYCLE THEN 2 WKS. CONSTANT SUCTION.

Figure 40



WIDTH WISE CROSS-SECTION THROUGH THE COMPOSTING PILE.
COMPOST PILE #9 =15.24 CM. (6 IN.) PIPING AT 2.44 M. (8 FT.) INTERVALS.
AERATION RATE=2 FANS SET AT 2 WKS. CYCLE THEN 2 WKS. CONSTANT SUCTION.

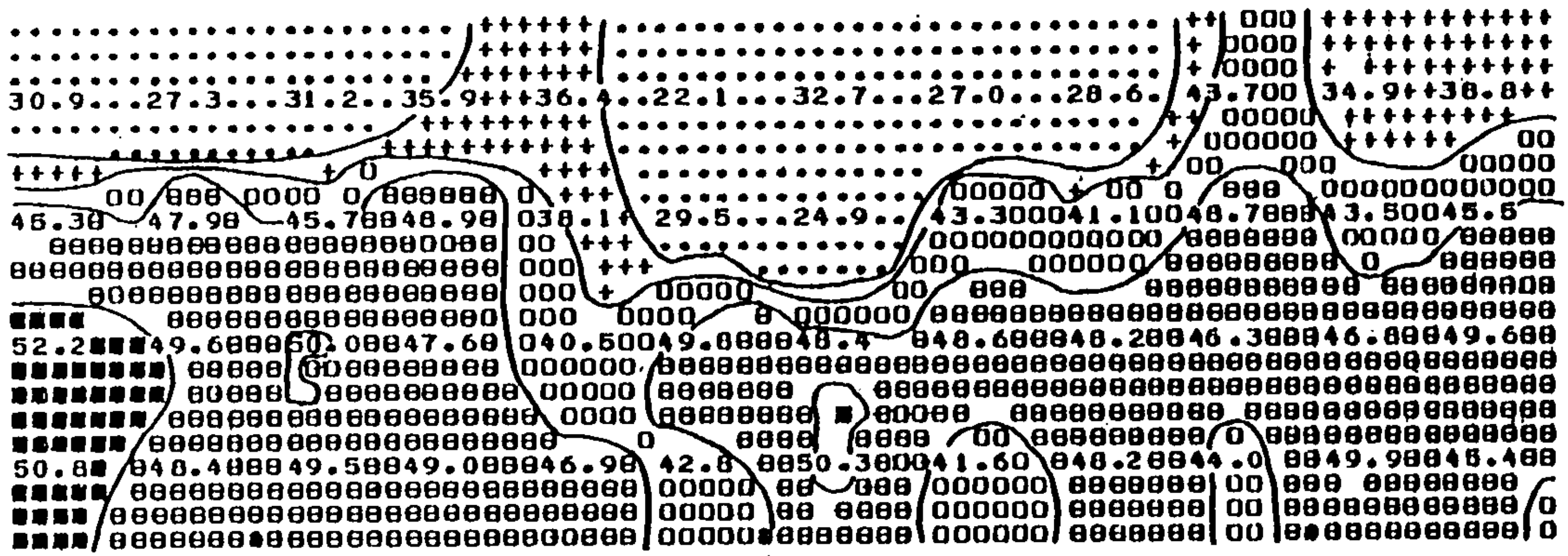
Figure 41



WIDTH WISE CROSS-SECTION THROUGH THE COMPOSTING PILE.
COMPOST PILE #9=15.24 CM. (6 IN.) PIPING AT 2.44 M. (8 FT.) INTERVALS.
AERATION RATE=2 FANS SET AT 2 WKS. CYCLE THEN 2 WKS. CONSTANT SUCTION.

Figure 42

MOISTURE(%) DISTRIBUTION FOR EXPERIMENT9



ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
('MAXIMUM' INCLUDED IN HIGHEST LEVEL ONLY)

MINIMUM	0.0	35.00	40.00	45.00	50.00
MAXIMUM	35.00	40.00	45.00	50.00	60.00
SYMBOLS	....1....	++++2++++	000030000	888848888	■■■■5■■■■

SCALE

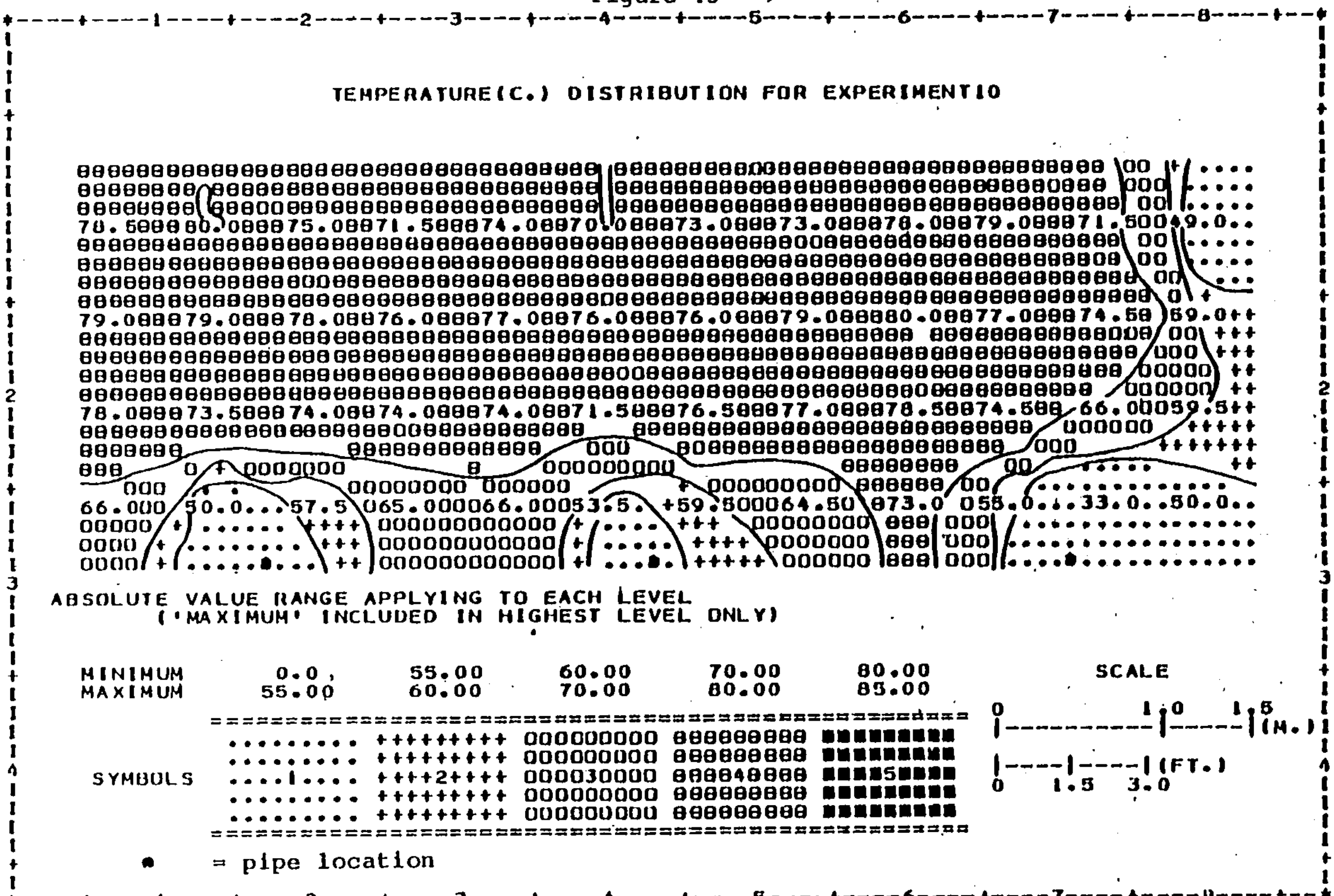
0 — 1.0 — 1.5 (M.)

0 — 1.5 — 3.0 (FT.)

■ = pipe location

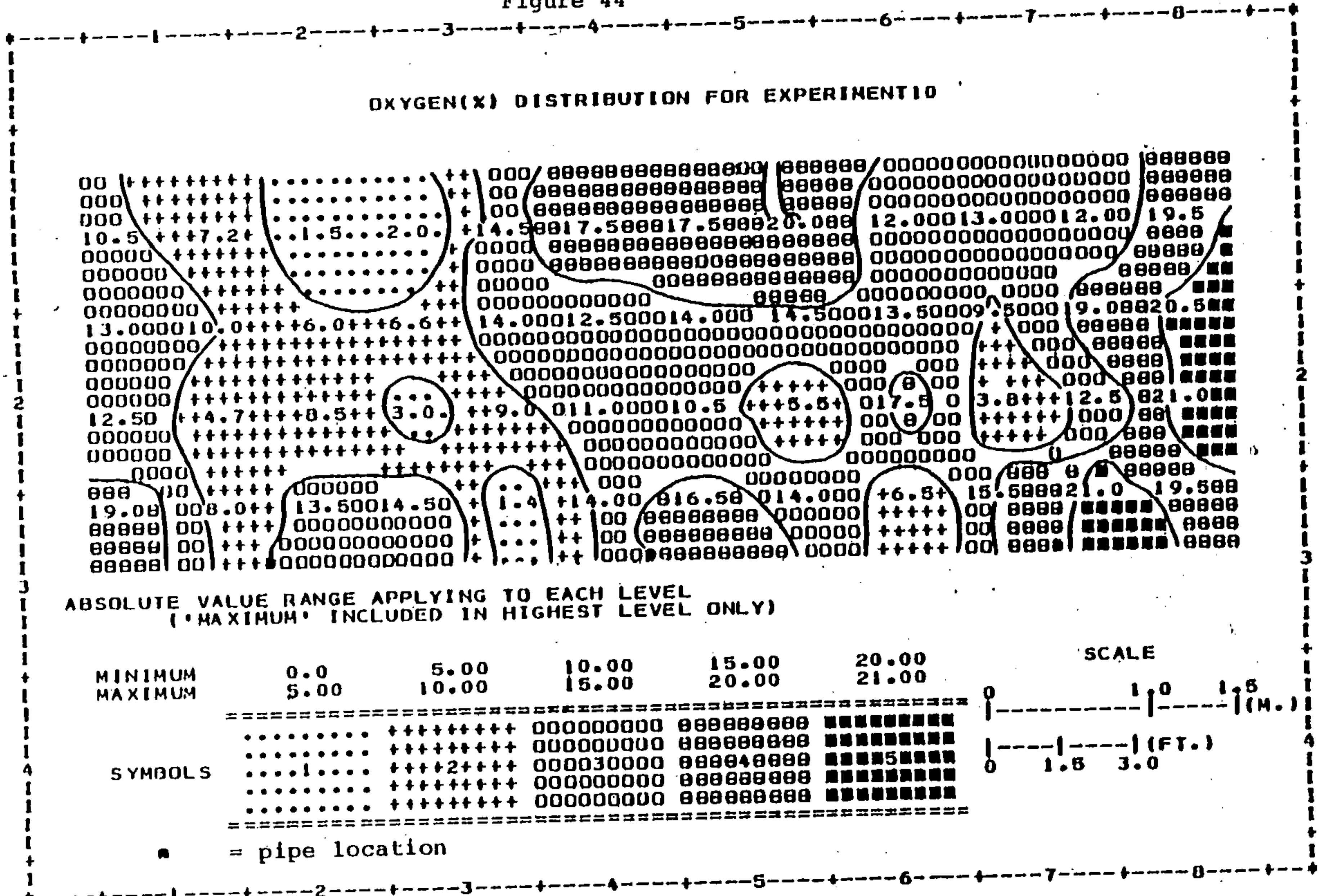
WIDTH WISE CROSS-SECTION THROUGH THE COMPOSTING PILE.
COMPOST PILE #9=15.24 CM. (6 IN.) PIPING AT 2.44 M. (8 FT.) INTERVALS.
AERATION RATE=2 FANS SET AT 2 WKS. CYCLE THEN 2 WKS. CONSTANT SUCTION.

Figure 43



WIDTH WISE CROSS-SECTION THROUGH THE COMPOSTING PILE.
COMPOST PILE #10=10.16 CM. (4 IN.) PIPING AT 2.44 M. (8 FT.) INTERVALS.
AERATION RATE=1 FAN SET AT 2 WKS. CYCLE SUCTION THEN 2 WKS. BLOWING .

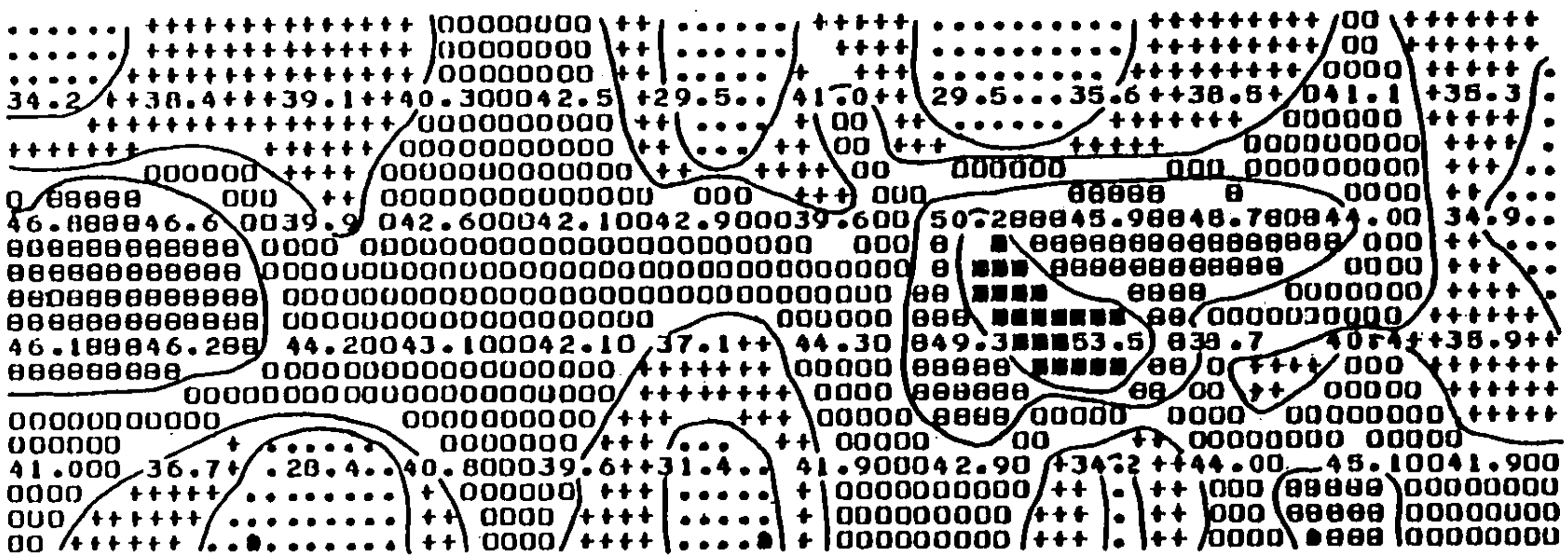
Figure 44



WIDTH WISE CROSS-SECTION THROUGH THE COMPOSTING PILE.
COMPOST PILE #10=10.16 CM. (4 IN.) PIPING AT 2.44 M. (8 FT.) INTERVALS.
AERATION RATE=1 FAN SET AT 2 WKS. CYCLE SUCTION THEN 2 WKS. BLOWING.

Figure 45

MOISTURE(X) DISTRIBUTION FOR EXPERIMENT10



ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
('MAXIMUM' INCLUDED IN HIGHEST LEVEL ONLY)

MINIMUM	0.0	35.00	40.00	45.00	50.00
MAXIMUM	35.00	40.00	45.00	50.00	60.00
SYMBOLS	....1....	++++2++++	000030000	888848888	■■■■5■■■■

SCALE

0 — 1.0 — 1.5 (M.)

0 — 1.5 — 3.0 (FT.)

● = pipe location

WIDTH WISE CROSS-SECTION THROUGH THE COMPOSTING PILE.
COMPOST PILE #10=10.16 CM. (4 IN.) PIPING AT 2.44 M. (8 FT.) INTERVALS.
AERATION RATE=1 FAN SET AT 2 WKS. CYCLE SUCTION THEN 2 WKS. BLOWING.

BIBLIOGRAPHY

Bertoldi, M. De, Citernesi, U. and Griselli, M. 1980: Bulking Agents in Sludge Composting. Compost Science/Land Utilization, 21(1), 32-25.

Bolan, Michael P., Nieswand, George H. and Singley, Mark E. 1979: How Research Helps the Operation of a Compost Plant. Compost Science/Land Utilization, 20(5), 17-21.

Computer Mapping - Symap Version 5.17 & 5.19. 1975: Department of Geography, University of Windsor.

Council for Agricultural Science and Technology. 1978: Evaluating Heavy Metal Hazards. Compost Science/Land Utilization, 19(2), 8-9.

Coulson, Michael Roland. 1978: Composting Municipal Wastes Using the Forced Aeration Technique. M.Sc. Thesis, University of Windsor Geography Department.

Crombie, George. 1979: A Public Works Strategy for Composting. Compost Sicence/Land Utilization, 20(4), 21-24.

Dallaire, Gene. 1978: Aerated-Pile Composting: A Promising New Alternative for Disposing of Sewage Sludge. Civil Engineering - ASCE, 48(9), 110-117.

Dean, Robert B. 1978: European Manufacturers Display Systems at Kompost'77. Compost Science, 19(2), 18-21.

Dyer, Jon C. 1979: Pretreatment Regulations and Recycling Sludge. Compost Science/Land Utilization, 20(4), 27-29.

Epstein, Eliot. 1977: Sludge Composting Projects in U.S. Cities. Compost Science, 18(5), 5-7.

Epstein, Eliot. 1978: Updating Biological Aspects of Composting Technology. Design of Municipal Sludge Composting Facilities, Rockville, Maryland, Information Transfer Inc. 23-26.

Epstein, E., et al. 1976: A Forced Aeration System for Composting Wastewater Sludge. Journal of Water Pollution Control Federation, 48(4), 688-694.

Erlich, Paul R. and Erlich, Anne H. 1972: Population, Resources, and Environment. San Francisco, W.H. Freeman and Company.

Foin, Theodore C. Jr. 1976: Ecological Systems and the Environment. Boston, Houghton Mifflin Company.

Golueke, Clarence G. 1978: Compost Installations and Modern Systems. Compost Science/Land Utilization, 19(3), 10-14.

Gouin, F.R., Link, C.B. and Kundt, J.F. 1978: Forest Seedlings Thrive on Composted Sludge. Compost Science/Land Utilization, 19(4), 28-30.

Hagerty, D. Joseph, Pavoni, Joseph L. and Heer, John E. Jr. 1973: Solid Waste Management. New York, Van Nostrand Reinhold Company.

Harshbarger, Thad R. 1977: Introductory Statistics: A Decision Map. New York, MacMillan Publishing Co.

Haug, Roger T. 1978: Composting Wet Organic Sludges - A Problem of Moisture Control. 1977 National Conference on Design of Municipal Sludge Compost Facilities, Rockville, Maryland, Information Transfer Inc., 27-38.

Haug, Roger T. and Haug, Lester A. 1977: Sludge Composting: A Discussion of Engineering Principles - Part I. Compost Science, 18(6), 6-11.

Haug, Rogert T. and Haug, Lester A. 1978: Sludge Composting: A Discussion of Engineering Principles - Part II. Compost Science/Land Utilization, 19(1), 10-14.

Morse, Norman and Roth, Edwin W. 1970: System Analysis of Regional Solid Waste Handling. Washington, U.S. Department of Health, Education and Welfare.

Municipal Refuse Disposal. 1970: Chicago, Illinois. Prepared by the Institute for Solid Wastes of America, Public Works Association, U.S. Department of Health, Education and Welfare.

Nie, Norman, et al. 1975: SPSS-2nd Ed. New York, McGraw-Hill Book Company.

Norcliffe, G.B. 1977: Inferential Statistics for Geographers. London, Hutchinson Co. Ltd.

Patterson, J. 1975: Enrichment of Urban Soil with Composted Sludge and Leaf Mold. Compost Science, 16(3), 18-21.

Pollard, J.H. 1977: A Handbook of Numerical and Statistical Techniques. Cambridge, Cambridge University Press.

Romano, Louis S. and Faust, John. 1978: Composting Sewage Sludge By Means of Forced Aeration At Windsor, Ontario. Design of Municipal Sludge Compost Facilities, Rockville, Maryland, Information Transfer Inc., 105-112.

Shea, T.G., Braswell, J. and Coker, C.S. 1979: Bulking Agent Selection in Sludge Compost Facility Design. Compost Science/Land Utilization, 20(6), 20-21.

Stanier, Roger Y., Adelberg, Edward A. and Ingraham, John. 1976: The Microbial World. New Jersey, Prentice Hall Inc.

Steffen, Robert. 1979: The Value of Composted Organic Matter in Building Soil Fertility. Compost Science/Land Utilization, 20(5), 34-37.

Taffel, William. 1978: Evaluating Sludge Demand in Boston. Compost Science/Land Utilization, 19(3), 16-18.

Taylor, Peter J. 1977: Quantitative Methods in Geography. Boston, Houghton Mifflin Company.

Unwin, David J. 1975: An Introduction to Trend Surface Analysis. Cat Mog 5-Concepts and Techniques in Modern Geography.

Walker, John M. and Willson, George B. 1973: Composting Sewage Sludge: Why? Compost Science, 14(5), 10-12.

Willson, George B. 1978: Equipment for Composting Sewage Sludge in Windrows and in Piles. 1977 National Conference on Composting of Municipal Residues and Sludges, Rockville, Maryland, Information Transfer Inc., 56-60.

Willson, George B. May 9, 1979: Personal Communication.

Willson, G.B., Parr, J.F. and Casey, D.H. 1978: Critera for Effective Composting of Sewage Sludge in Aerated Piles and for Maximum Efficiency of Site Utilization. Design of Municipal Sludge Compost Facilities, Rockville, Maryland, Information Transfer Inc., 79-87.

Willson, G.B., Epstein, E. et al. 1978: A Manual for Composting Sewage Sludge by the Beltsville Aerated Pile Method. Beltsville, Maryland, USDA Biological Waste Management and Soil Nitrogen Laboratory.

Willson, George B. and Walker, John M. 1973: Composting Sewage Sludge: How? Compost Science, 14(5), 30-32.

Wolf, Ray. 1977: Mechanized Sludge Composting at Durham, New Hampshire. Compost Science, 18(6), 25-26.

Yeates, Maurice. 1974: An Introduction to Quantitative Analysis in Human Geography. New York, McGraw-Hill Book Company.

VITAS AUCTORIS

Full Name:	Robert John Ceschan
Date and Place of Birth:	September 23, 1955, Windsor, Ontario
Education:	
1969-1974	Attended Assumption College, Windsor, Ontario
1974	Degree: Honours Secondary Graduate Diploma
1974-1978	Attended University of Windsor, Windsor, Ontario
1978	Degree: Honours Bachelor of Science in Biology and Geography
1978-1980	Attended University of Windsor, Windsor, Ontario
1981	Degree: Master of Arts in Geography with Specialization in Environmental Studies.