SUITABILITY OF BENCH SCALE COMPOSTING AS AN INDICATOR OF FULL SCALE BIOREMEDIATION OF OILY SLUDGES

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NOMENCLATURE

BA	bulking agent
BA/S	bulking agent to sludge ratio (volume/volume unless indicated otherwise)
BOD	biochemical oxygen demand
CC	container capacity of bulking agent (mass water/dry mass material)
DE	diatomaceous earth
dwt	dry weight (mass)
GC	gas chromatography
HC	hydrocarbon
KOH	potassium hydroxide
M	molar concentration (moles/liter)
ppm	parts per million, equivalent to mg/kg or mg/liter at low concentrations
VOC	volatile organic carbon
VS	volatile solids

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CHAPTER I

INTRODUCTION

The Problem: Remediation of Hydrocarbon Contaminated Soils

Within the oil industry, one of the waste byproducts of concern has been separator and waste pit sludges consisting mainly of crude oils. In the field, these waste streams have been conveniently disposed of in unlined earthen pits. With time these oils have seeped into the pit bottoms and the surrounding soils where they reach a high degree of saturation. The light ends have long since been removed through volatilization leaving heavier, longer chained hydrocarbons in the soil which are resistant to further reduction by volatilization. This is what is known as a "weathered sludge." Because of the remoteness of many of the locations, removal and transportation of the hydrocarbon saturated soils to reclamation or incineration centers is very expensive and is considered impracticable.

A Potential Solution: Bioremediation Through Composting

Composting is defined as the enhanced natural degradation by microorganisms of an undesirable substance by means of material amendments. Water and nutrients are added to enhance microbial growth rates, and bulking agents are added to increase porosity so that more oxygen is available to the microorganisms for energy conversion.

Composting is an attractive treatment alternative for several reasons: (1) it requires a relatively low level of technology, (2) it uses easily attainable common materials, (3) it costs less than other remediation methods, (4) it is an enhanced naturally occurring process, and (5) it permanently destroys the contaminating substance by converting it to water, carbon dioxide and other nonhazardous substances. Pilot scale composting projects to remediate hydrocarbons have been run by major oil companies with reported results as high as 97% reduction of hydrocarbons (Fyock *et al.*, 1991; McMillen *et al.*, 1993).

Implementation: Bench Scale Composting in Closed Reactors

Because of the complexity of the materials used in composting, the optimum conditions for full remediation of a contaminated soil have been difficult to define. A repeatable method of evaluating the various effects of environmental parameters on the composting process is needed. Microorganisms generate energy by enzyme-mediated electron transport from an electron donor (hydrocarbons and other organic compounds in the case of heterotrophs) to an external electron acceptor (oxygen in the case of aerobes). Oxygen uptake, as measured by respirometry, is proportional to the microbial population and activity and therefore to the utilization rate of the substrate. Likewise, the production of carbon dioxide through microbial respiration within closed compost reactors, as measured in the exiting air, is related to the activity of the microbial population and to the substrate utilization rate.

Investigation of the individual parameters, alone and in combination, through respirometry points out possible optimum compost conditions. The parameters of hydrocarbon concentration, bulking agent to sludge ratio, moisture content, and nutrient concentration were investigated in a previous study (Kriegh, 1993) with respect to the Farmington sludge as Phase I of this project. Phase I was a short term (10 days), micro-scale study of the Farmington sludge that was used in the first composting series. It was comprised of a series of compost formulations designed to test the effects of individually varying parameters on microbial activities as measured by oxygen uptake rates. Oxygen uptake was analyzed on the basis of specific growth rates equated to uptake and on the basis of "steady state" or constant rate BOD respiration. The compost hydrocarbon concentration was 18.7% on a wet weight basis. The Phase I study proposed optimal parameters for composting the Farmington oily sludge which were used in the current study of the weathered Farmington sludge.

Phase II, the present study, is an investigation of the projected optimum parameters by composting two series of formulations of two separate weathered sludges in closed compost reactors for a period in excess of 100 days. The first series of Phase II is a closed reactor compost study of the Farmington sludge varying selected parameters in conjunction with the optimal formulation proposed by the Phase I study. The purpose of this first series is to test the accuracy of the Phase I short term (10 days) respirometry prediction when carried out in closed reactors for a longer period of time (120 days).

The second series starts with a respirometry study of the Pit 82093 sludge parameters. Once the optimal parameters are chosen, the closed reactor study begins. In this study the compost parameters do not vary. Only the time that the compost remains in the reactor varies. This is done to study the changing composition over time.

The results of this study are expected to reflect the respirometer findings found in Phase I. The information gleaned from the closed compost reactor experiments can help determine maintenance requirements for biodegradation and the time required to complete the process. Phase III is a companion study wherein one set of parameters is being investigated on a pilot plant scale (Denham, 1994).

Thesis Topic: Suitability of Bench Scale Composting as an Indicator of Full Scale Bioremediation of Oily Sludges

The motivation behind this study was to determine if a micro scale study (respirometry) could be used to accurately predict optimum parameter ranges for optimal full scale field results. If a bench scale composting study confirmed the results of a respirometry study of parameters and matched the results of a pilot scale study using the same parameters, this information could be projected to full scale field remediation. The consequences of this would be a savings of time and money over the life of a bioremediation project. The three main concerns were: (1) whether oxygen uptake results as measured through respirometry can be projected to determine optimum composting conditions, (2) whether CO_2 production is a true indicator of hydrocarbon reduction, and (3) whether bench scale composting results predict the results of field scale composting.

Respirometry is a short-term process but is useful in examining the initial microbial activity. It does not measure the conversion of hydrocarbon to biomass. CO_2 is produced by the complete reduction of hydrocarbons to CO_2 and water. The partial reduction of hydrocarbons does not produce CO_2 and may alter the hydrocarbon to a nonextractable form. Scaling up the results of bench scale experiments to a working field scale process has always been a concern of research programs.

CHAPTER II

BACKGROUND AND LITERATURE REVIEW

A literature search was performed to provide insight into the composting process and give a general idea of accepted values for environmental parameters. A literature review of respirometry provided information on how oxygen uptake data have been interpreted. This knowledge made it possible to formulate an experimental composting design based on optimal environmental conditions.

Composting

Composting of municipal wastewater treatment plant sludge has been practiced for many years as an alternative to landfarming and landfill disposal. The objectives of sewage sludge composting are: (1) reduction of sludge volume, (2) pathogen eradication, and (3) formation of an odor free, stabilized end product suitable for land application and soil amendment. In 1978 the U.S. EPA developed a forced aeration process employing static compost piles known as the Beltsville process. This process succeeded in achieving the objectives of sewage sludge composting (Nell and Ross, 1987). Since then, various types of composting processes have been used throughout the U.S. for treatment of sewage sludge and other types of municipal refuse and organic industrial wastes.

Documentation of composting as a means of biologically degrading hydrocarbons has existed for only the last few years. Taddeo *et al.* (1989) demonstrated an in-vessel composting process which degraded 94% of the total hydrocarbons present in coal tar, including 84% of the polyaromatic hydrocarbons (PAH) which was the pollutant category of primary concern. As a result of recent feasibility testing in laboratory experiments and pilot projects, documentation on the composting of oily soils and sludges is beginning to be available. Among the major oil companies, Exxon and Chevron have conducted research into the composting of oily sludges and have experienced encouraging results. Exxon researchers reported a laboratory scale composting experiment that reduced a 10.8% total petroleum hydrocarbon (TPH) sludge by 92% over four weeks (McMillen *et al.*, 1992). Nordrum *et al.* (1992) documented the field scale composting of a high petroleum content (8%) oil tank bottom sludge, reporting a 97% reduction in 27 major petroleum hydrocarbons (TPH) over 41 days. Kamnikar (1992) reported the successful composting of a mixture of wood chips and manure with a low level concentration (up to 1,300 ppm) gasoline, fuel oil, and diesel contaminated soil.

Indigenous microbial populations that are capable of using hydrocarbons as their sole source of carbon and energy are found in soils throughout the world (Rosenberg and Gutnik, 1981). They are represented in many genera, including *Pseudomonas*, *Actinetobacter*, *Flavobacterium*, *Arthrobacter*, and others. A lack of nutrients, water and/or carbon will limit the growth activity of the microbes in the soil. Soils contaminated with oil can be physically limited as to the availability of oxygen, water and nutrients due to an excessive carbon content which can bind up the pore spaces. This is especially true in soils of low permeability such as clays.

Individual environmental parameters affecting composting have been investigated by researchers to determine what values or ranges most favor microbial activity. Commonly investigated parameters have been: (1) bulking agent requirements, as to type of material and ratios used in relation to sludge or soil, (2) moisture content of compost, (3) temperature, (4) nutrient requirement, based on nitrogen and phosphorus, and (5) porosity and permeability as related to bulking agent and degree of compaction.

Bulking Agent

Bulking agent to sludge or soil ratio (BA/S) has been the most commonly considered parameter of compost design. Most of the studies mentioned previously employed wood chips as the bulking agent of choice (Nell and Ross, 1987; Fyock *et al.*, 1991; Kamnikar, 1992; Nordrum *et al.*, 1992; Martinson *et al.*, 1993). Stegmann *et al.* (1991) investigated BA/S ratios ranging from 1:2 to 1:16 (dwt) using bioreactors and respirometers. Aged biowaste (sewage sludge) compost was used as the bulking agent for diesel contaminated soil. They reported the 1:2 ratio as most favorable for microbial activity and TPH reduction.

Taddeo *et al.* (1989) investigated several materials which might be suitable as bulking agents including wood chips, wood shavings, peat moss, sand, vermiculite, sawdust, and coconut shells. Biodegradability tests showed that, regardless of material, all showed 90% reduction of coal tar over an 80 day period. Based upon permeability measurements of compacted compost samples, Taddeo and co-workers selected wood chips as the bulking agent. Kriegh (1993) also selected wood chips as a bulking agent for their ability to resist compaction and their capacity for holding water.

Moisture Content

Most studies of the composting process have indicated an optimal value or range of moisture content considered most favorable for microbial activity as a wet weight percentage (wt%). Nell and Ross (1987) suggest a minimum moisture content of 40% for sewage sludge compost and report a range of 50% to 60% as optimal. MacGregor *et al.* (1981) used an initial moisture content of 76% of field capacity in their sludge composting investigation. Both these groups indicated that 90% of microbially generated heat is lost through the vaporization of water and suggested the importance of maintaining a water content sufficient to meet that need. Chevron employed a minimum 40% moisture content (MC) in the

Red Wash pilot project whereas a minimum of 25% was used in the follow-up field scale operation (Fyock *et al.*, 1991; Nordrum *et al.*, 1992). Stegmann, *et al.* (1992) conducted a series of respirometry tests with diesel contaminated soil compost and identified 60% of "total water capacity" (gm H_2O/gm dry weight compost) as optimal with 50% to 80% as an acceptable range. For an Exxon project, McMillen *et al.* (1992) used 39% moisture content, described as being 87% of compost "saturation". Kriegh (1993) concurs that the optimal moisture content range is from 30% to 83% of wood chip container capacity. The concepts of "saturation" and "total water capacity" are similar to "container capacity" (CC) as it is used in a later chapter. The overall moisture contents utilized in these studies range from 25 wt% to 76 wt%. Only Stegmann *et al.* (1992) demonstrated a method for determining an optimal water content. That method is described in the discussions on respirometry.

Temperature

It is well known that temperature affects microbial activity. Microbial heat production and concurrent air circulation are the primary causes of compost dehydration. However, forced air ventilation may be necessary to maintain compost temperatures below an incapacitating limit (<60°C) (Hogan *et al.*, 1989). Temperatures in excess of 60°C are required to eradicate pathogens in sewage sludge compost but are liable to destroy hydrocarbon degrading microbes in an oily sludge compost.

Chevron limited temperatures in their pilot scale compost piles by mixing when 135°F (57°C) was reached (Fyock *et al.*, 1991). The pile with a BA/S of 4:1 exceeded 110°F (43°C), while the two piles with lower ratios exceeded 130°F (54°C). TPH reduction was reported for the 4:1 pile at approximately 90%. The follow-up field scale compost project also intended to limit temperatures to 135°F by mixing (Nordrum *et al.*, 1992).

Even though pile temperatures reached 140°F (60°C), 97% reduction in TPH was still reported in the field study.

In an in-vessel composting system for coal tar, Taddeo *et al.* (1989) maintained a temperature of 65 to 85°F (18 to 29°C) and achieved a 94% reduction in TPH over 80 days. Respirometry and bioreactor tests on oily compost conducted by Stegmann *et al.* (1992) at temperatures no greater than 30°C showed significant microbial activity and reduction in hydrocarbons. Bench scale composting experiments conducted at 35°C and 50°C by Hogan *et al.* (1989) used six specific hydrocarbon compounds including phenanthrene, fluoranthene, and pyrene, which were amended into a sewage sludge cake and composted for 35 days. Greater reduction of hydrocarbons was experienced at 35°C than at 50°C, ranging from 75.1% to 99.7% reduction. Kriegh (1993) stated that substantial and rapid degradation of hydrocarbons occurred at temperatures within the mesophilic range, specifically 25°C to 40°C. This was attributed to the greater diversity of microbes at mesophilic temperatures compared to the thermophilic range.

Nutrient Addition

Traditional composting of sewage sludges requires the presence of nutrients based on the stoichiometric determination for the conversion of substrate carbon to biomass and CO_2. Some researchers recommend a carbon to nitrogen ratio (C:N) of 30 to 40:1 (Nell and Ross *et al.*, 1987) while others recommend a C:N of 30 or less (Haug, 1980). Chevron's pilot scale composting of hydrocarbon contaminated soil used an initial nitrogen concentration of 500 ppm (0.089 M nitrogen) at 40% moisture content. Additions of nutrients were made to maintain minimum nitrogen and phosphorus concentrations of 50 ppm and 20 ppm respectively (Fyock *et al.*, 1991). When manure was used for 15% of the bulking agent in the field scale project that followed, it was difficult to maintain the minimum nitrogen and phosphorus levels. Additions of up to 230 ppm nitrogen and 160 ppm phosphorus, twice a week, were required to maintain the level of 50 ppm nitrogen and 20 ppm phosphorus. Manure, added as part of the bulking agent, would also serve as an additional source of nitrogen, phosphorus, and other nutrients, as well as serving as an inoculum.

Hydrocarbon Concentration

The hydrocarbon concentration is a factor which influences what BA/S ratio will be used in a compost formulation. A high TPH sludge or soil has a room temperature consistency of mud or paste and a very limited permeability to air. To effectively increase the permeability, the addition of a bulking agent is required. A low TPH contaminated soil has a texture similar to uncontaminated soil, allows some permeability to air, and requires less bulking agent. The amount of bulking agent used determines the hydrocarbon concentration in the resulting compost mixture. In the previously cited cases, original TPH concentrations have ranged from a low of 50 ppm to a high of 300,000 ppm (30%) (Kamnikar, 1992; Martenson *et al.*, 1993). The 30% TPH sludge used the highest compost BA/S ratio among the cited studies (4:1). In most of the studies, the hydrocarbon concentration of the compost did not exceed 10% by weight. However, Kriegh (1993) employed a compost TPH of 18.7% and found it capable of being biodegraded.

Respirometry

Respirometry is the measurement of oxygen consumption by living organisms. Oxygen consumption can be taken as a measure of the microbial population's growth or level of metabolic activity through time and provides an indication of its viability under varying environmental conditions. The most common application of respirometry has been in measuring the five-day biological oxygen demand (BOD) of wastewaters. The purpose of measuring BOD was to provide a measure of the concentration of biodegradable organic material and the microbial population's ability to consume it. More recently respirometry has been used to measure the biodegradability of specific substances, often to rank them in relation to other compounds (Brown *et al.,* 1990; Desai *et al.,* 1990). Recently, respirometry has been applied to solid phase materials such as soils and composts to determine conditions which favorably influence the rate of microbial activity on organic contaminants (Stegmann *et al.,* 1991). An in-depth discussion of respirometry can be found in the report of the Phase I study (Kriegh, 1993).

CHAPTER III

MATERIALS, METHODS, AND EXPERIMENTAL DESIGN

Before the composting study was designed, the materials that would be combined to form the compost were investigated. Several parameters were defined quantitatively. The bulk density, moisture content, moisture holding capacity, hydrocarbon content, and biological activity (microbial oxygen uptake) of the components gave information upon which bulking agent to sludge ratios were based. Two types of compost were investigated in this study. This chapter presents the materials used to build the investigated composts and the methods used to characterize the parameters of those materials, and the experimental apparatus used to carry out the bench scale composting trials.

Characterization of Farmington Compost

The compost used in the first batch of tests was composed of a high hydrocarbon concentration (24% by wt) weathered waste pit sludge from Farmington, New Mexico, which was combined with extracted pine wood chips and a nutrient supplement which was a combination of a mineral salts medium and a trace element solution. The soil to be remediated, the bulking agent of choice, and the type of nutrient system to be used were investigated using the methods described below. Results of these characterization tests attributed to Kriegh (1993) were performed in Phase I of the overall study and are reported again here.

Sludge or Contaminated Soil

The sludge had a dark, pasty appearance and an oily odor. The sludge contained no fresh oil or light ends because it had been exposed to the atmosphere for many years.

Moisture Content

Moisture content of the sludge was measured in a Denver Instruments Company, Inc. moisture balance. The temperature was set to 105°C and the minimum rate of mass loss cut off was set at 0.05%. Five samples were measured to find a mean moisture mass content of 19.8% + or - 0.5%. This value was rounded to 20% for design calculations.

Hydrocarbon Content

Hydrocarbon content of the sludge was determined using two methods. In one method, hydrocarbons were extracted from the sludge with methylene chloride using the Tecator Soxtec HT2 1045 extraction unit and analyzed by gas chromatography (GC) for a "type analysis" which returns results in terms of carbon number and percentage of extract sample. The carbon number indicated the number of carbons in the hydrocarbon chain. As the carbon number increases, the volatility decreases. The carbon at the ends of the chain must be consumed in the microbial respiration before the next carbon in the chain is available. Within this process, the sludge from the field was first well mixed to distribute the hydrocarbon as evenly as possible throughout the sludge. Then a portion of the mixed sludge was weighed out, combined with diatomaceous earth (DE) at a 4:1 ratio to bind available water, ground to a very fine texture, apportioned into extraction thimbles and solvent-extracted. A description of this procedure can be found in Appendix A. The extract was then transferred to a sealable container, liquefied with methylene chloride and sent for GC analysis. Carbon-23 represented the median hydrocarbon size in terms of carbon number with approximately 47.3% of the molecules having a lower carbon number. No hydrocarbons less than carbon-9 were detected (Kriegh, 1993).

The second method involved incineration of the sludge in ceramic crucibles at 550°C for three hours. This was accomplished in two ways. In one the dried sludge remaining from the moisture content analysis was incinerated. The average mass loss with respect to the original wet weight of the samples for the Farmington sludge was 24.2% + or - 0.5%. In a like manner, samples of the fresh, wet sludge were incinerated to find the total volatile solids to be 43.2% + or - 1.3%. Subtracting the average moisture content obtained from the Denver moisture balance analysis resulted in an average volatile solids content of 23.6%. The results for the raw sludge and the dried sludge are close and give a combined average volatile solids of 23.9% which was rounded to 24% for design calculations (Kriegh, 1993).

Inert Materials

Inert materials making up the remaining portion of the sludges, as determined by X-ray defraction performed by Mineralogy, Inc., consisted of very fine grained quartz sand and clay (Kriegh, 1993).

Microbial Populations

The microbial populations in the sludge were found to be very low, in the range of 100 to 1,000 bacterial cells per gram of sludge (Kriegh, 1993). However, preliminary tests of microbial activity performed in the N-Con respirometers indicated that there was sufficient activity present to rely completely on the indigenous population for hydrocarbon degradation. Assuming all other conditions are favorable, the low initial bacterial count should ensure a period of exponential growth. Based upon the reports of these research groups (Dang, *et al.*, 1989; Brown *et al.*, 1990; Desai, *et al.*, 1990), four requirements are necessary for exponential growth to occur and for the resulting oxygen uptake data to be valid for making kinetic parameter estimations. These requirements are: (1) biomass growth and associated substrate consumption must be the only activities contributing to oxygen uptake, i.e., the biomass must be free of nitrifying bacteria and have a low population of protozoa, (2) all of the biomass must be capable of metabolizing the substrate of interest, thereby eliminating oxygen demand due to endogenous metabolism (Grady *et al.*, 1989), (3) starting microbial populations should be relatively small so that exponential growth can occur, and (4) all factors necessary for growth must initially be present in abundance. It is believed that microbes indigenous to waste pit sludges meet the first three of the above requirements by virtue of natural selection and acclimatization during their long exposure to sludge, and by their low population counts as measured for this study (100 to 1000 microorganisms per gram).

Bulking Agent

The bulking agent investigated was pine wood chips. From the Phase I study (Kriegh, 1993), it was determined that the wood chips would be obtained from 1" x 2" x 8' long white pine wood strips which had been processed through a chipper as a means of controlling material consistency. Initial respirometry testing of biological activity of the raw wood chips showed a high degree of activity. Consequently, it was decided that the chips' oils and resins, which could serve as substrate for microbial activity, should be removed through solvent extraction in 1.75 liter Soxtec vessels. The wood chips were extracted with two different solvents in series and are therefore termed "double extracted". The average moisture content determined by the Denver moisture balance for the extracted wood chips was measured to be 12% and varied from 6% to 18%. The bulk density of the wood chips was determined to be 0.17 gm/cm^3 by weighing a one liter container of loosely packed chips. The extracted chips were used in this study despite the fact that a full scale composting project conducted under field conditions would not go to the expense of extracting the amount of chips that such an operation would require. Extraction was performed here because of the need to quantify the enhanced bioremediation activity of the indigenous microbial population alone.

Container Capacity

Container capacity is defined as the ratio of the mass of water retained by a material against gravity drainage to the dried mass of the material present (Cassel and Nielsen, 1986). The container capacity for the wood chips was determined to be 2.96 gm H_2O/gm dry weight (dwt). A detailed procedure for the calculation of container capacity is included in Appendix B. Upon calculation of the container capacity for the sludge it was observed that the raw sludge was already at its saturation point. Therefore the container capacity of the bulking agent was used as the basis for decisions regarding amounts of added moisture in the compost.

Mineral Nutrients

Mineral nutrient supplements are useful for increasing the bacterial growth rates within the composting materials. A combination of a mineral salts media (Evans, *et al.*, 1965) and a trace element solution (Drews, 1974) was added in liquid form. The Evans mineral salts media had originally been concocted for culturing *Pseudomonas* strains of hydrocarbon-degrading soil bacteria on anthracene and phenanthrene. It consisted of salts containing the most important growth requirements: nitrogen, phosphorus, sulfur, magnesium, and iron. Drews trace element solution contained many trace elements and nutrients necessary for growth. The formulations for both Evans and Drews can be found in Appendix C.

Since nitrogen is the element required in greatest amounts, its concentration in the form of ammonium will be used for the basis of the entire nutrient addition calculated from stoichiometric requirements. Generally, phosphorus is required to be present at about 20% of the mass of nitrogen (Metcalf and Eddy, 1979; Grady and Lim, 1980). The Evans solution has phosphorous present at 84% of the nitrogen mass. A standard solution of Evans media contains nitrogen as ammonium at a concentration of 0.01515 moles/liter (Kreigh, 1993). At this concentration, the amount of liquid required to meet stoichiometric nitrogen requirements would turn the compost into a slurry that would not be confined above the support grating of the closed compost reactors. To meet stoichiometric requirements without adding inordinant amounts of water, a more concentrated Evans solution was used for these tests (50X standard). Proportionality of all constituents was preserved.

Oxygen

Oxygen is required for aerobic microbial respiration. During respirometry, the oxygen was provided in the form of commercially available bottled oxygen which was 99.6% pure. During the bench scale composting study conducted in the forced air closed reactors, the oxygen was supplied by Amoco Research Center "plant air" at a rate of 15 cm^3/min to each reactor, which is roughly equivalent to one reactor pore volume per hour for uncompacted mixtures. This rate ensures that enough excess oxygen is supplied to compost material to guarantee that the compost cannot become oxygen starved. The air flow was adjusted daily to maintain the target flow rate.

Characterization of Pit 82093 Compost

The compost used in the second batch of tests was composed of a low hydrocarbon concentration production pit sludge (designated Pit 82093) from Oklahoma which was combined with raw straw and commercially available fertilizers containing nitrogen and phosphorus. The soil to be remediated, the bulking agent of choice, and the type of nutrient system to be used were investigated using the methods described below.

Sludge or Contaminated Soil

The sludge had a dark, pasty appearance and an oily odor. The sludge contained no fresh oil or light ends because it had been exposed to the atmosphere for many years.

Moisture Content

Moisture content of the sludge was measured in a Denver Instruments Company, Inc. moisture balance. The temperature was set to 105°C and the minimum rate of mass loss cut off was set at 0.05%. Three samples were measured to find a mean moisture mass content of 16.58% + or - 0.6%. This value was rounded to 17% for design calculations.

Hydrocarbon Content

Hydrocarbon content of the sludge was determined using the same two methods previously described for the Farmington sludge, and summarized in Appendix A.

For the Pit 82093 sludge, carbon-27 represented the median hydrocarbon size in terms of carbon number with approximately 51% of the molecules having a lower carbon number. No hydrocarbons less than carbon-11 were detected. The gravimetrically determined extract mass was 13.07% + or - 0.45% of the original sample's mass. Repeating the second characterization process for the Pit 82093 sludge, incineration of the raw sludge gave a total volatility of 31.48%. Subtracting the average moisture content determined from the Denver moisture balance analysis resulted in an average volatile solids content of 14.9%. The volatile solids content from incineration of the dried sludge was 18.8%. Averaging these two numbers gives an average hydrocarbon content of 17%. Comparing the 13.07% volatile solids obtained from the extraction of hydrocarbons to the 14.9% obtained by incineration of raw sludge shows a difference of <2%.

The incineration method is considered to be more exacting than the extraction method which does not always exhibit a 100% extraction efficiency. Therefore, the raw pit sludge was determined to contain approximately 15-19% volatile solids.

Inert Materials

Inert materials making up the remaining portion of the sludges, as determined by X-ray defraction performed by Mineralogy, Inc., consisted of very fine grained quartz sand and clay. The precise composition of the pit sludge can be found in Appendix D.

Bulking Agent

The bulking agent investigated was straw. Raw straw showed high levels of activity during respirometry studies. However, it was felt that extracted straw would not be able to retain the porous structure required of a bulking agent and that a true representation of a practical field study required that it be used in its raw state. Its bulk density and moisture content were obtained in the same manner as for the wood chips and were 0.123 gm/cm^3 and 10.25% respectively.

Container Capacity

The container capacity for the straw was determined to be 3.827 gm H_2O/gm dwt. A detailed procedure for the calculation of container capacity is included in Appendix C. Upon calculation of the container capacity for the sludge it was observed that the raw sludge was already at its saturation point. Therefore the container capacity of the straw will be used as the basis for decisions regarding amounts of added moisture in the compost.

Mineral Nutrients

Mineral nutrient supplements are useful for increasing the bacterial growth rates within the composting materials. Commercially available fertilizers provided nitrogen in the form of urea granules and phosphorus as powdered phosphoric acid (P_2O_5). The nutrients were dissolved in the water which was added to the straw and then mixed with the sludge. Urea was added to reach a solution normality of 0.25 with respect to total moisture content of the compost. This value was arrived at through respirometric testing of this parameter as addressed in a later section of this thesis. Phosphorus was added in a 4:1 N:P ratio. Commercial fertilizers were used instead of the Evans and Drews solution of the Farmington compost, because they are more readily available and less complicated to use in addition to being more cost effective.

Test Preparation for Respirometry

Sterilization measures were taken to ensure that the only microbes involved in the testing were those indigenous to the sludges. All reactor bottles, nutrient solution, mixing containers and implements were sterilized in a Harvard/LTE Benchtop 90 autoclave at 120°C for 15 minutes. Sterilized deionized water was used for added moisture. A particular order was followed in the make up and mixing of compost batches for respirometer tests because it was found that the order of the moisture addition step was important. First the nutrient and supplemental water were mixed together to ensure that the nutrients were well dispersed. Then the bulking agent was added to the liquid to ensure thorough wetting. Lastly, the sludge was added to the mixture.

N-Con Respirometry - Biological Activity as a Measure of Oxygen Uptake

All of the parameter optimization tests were performed in N-Con Systems, Inc. piezometric respirometers. The respirometer senses gas pressure drops in the reactors and responds with oxygen deliveries. The companion computer maintains a cumulative record of oxygen deliveries over a selected time increment. Oxygen deliveries for all tests in this experiment were recorded on an hourly basis.

The pressure drop is generated during respiration in the presence of potassium hydroxide (KOH). Oxygen becomes depleted in a sealed atmosphere as respiration takes place. Carbon dioxide is released to the atmosphere through microbial respiration. The carbon dioxide is removed from the atmosphere by the carbon dioxide trap (the KOH pellets) as potassium carbonate. The resulting pressure drop in the reactor is detected by a pressure sensor. Upon pressure sensor activation, a pulse of oxygen is released into the reactor. The computer monitors this event and the time of its occurrence and maintains a simple cumulative record of oxygen consumption.

Facilities and Reactors for Bench Scale Composting

After the parameters have been investigated through respirometry and analyzed to determine the most probable optimum conditions for the compost media, the physical design of the experimental equipment was the next item of concern. The bench test facility centered around a Despatch temperature controlling heater box (Figure 1) which housed the compost filled reactors at a constant temperature. Tubing was placed into the box to deliver saturated air to the reactors and out of the box to various monitoring equipment. Air was supplied from a filtered plant air source. The upstream pressure was kept constant by a Tescom Pressure Regulator. Prior to entering the distribution manifold, the air was humidified at the test temperature (35°C). Air flow rates to the individual reactors were

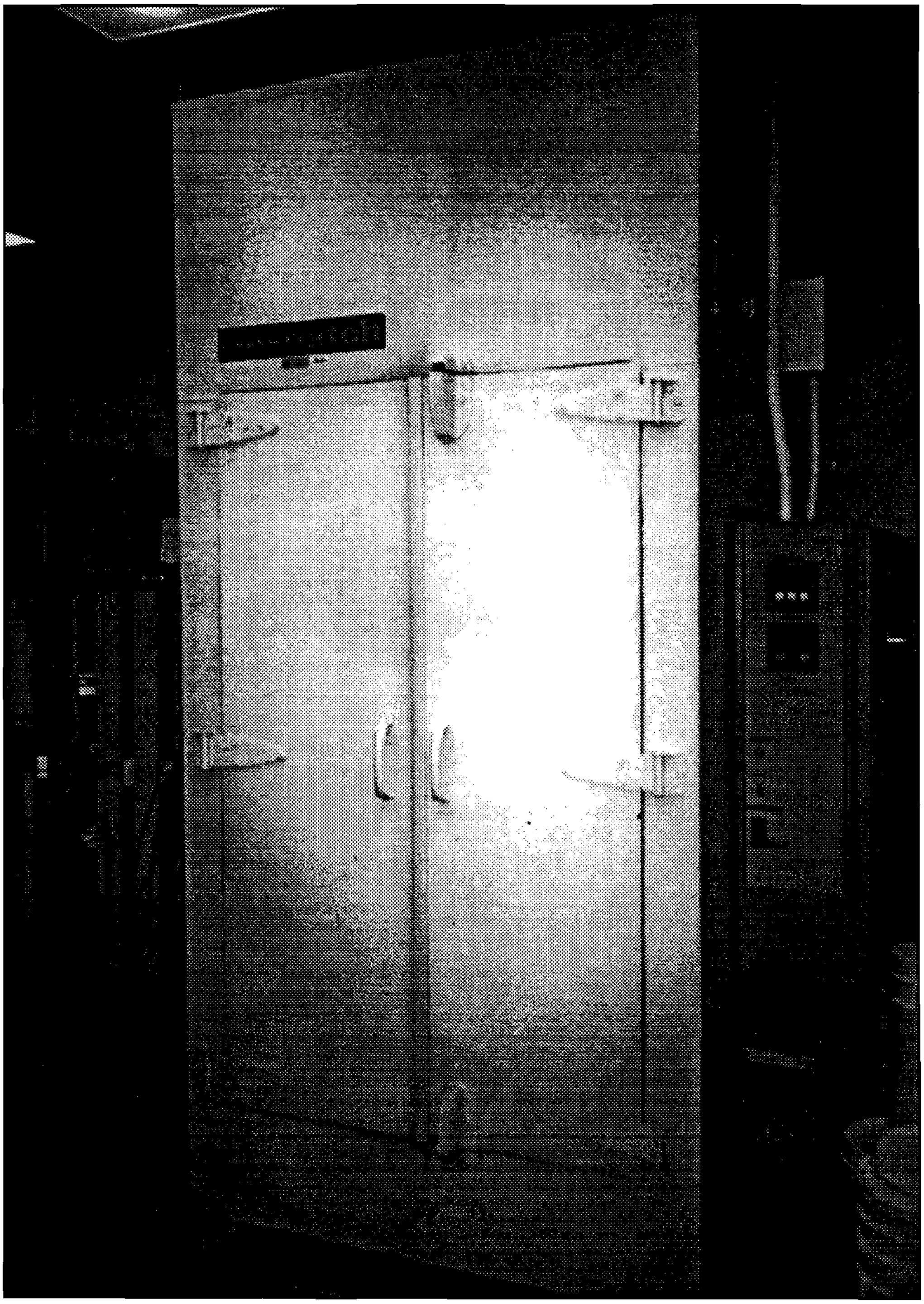


Figure 1. Despatch Heater Box.

controlled with Omega Model FL-3861G-HRV rotometers with metering valves. The reactors themselves were constructed of 20" sections of 5" diameter jet stream schedule 40 PVC piping with threaded caps on the ends. Each reactor had 5 ports: one in the side for the temperature probe, one in the top for the moisture probe, one in the bottom for drainage of accumulated liquid, and one each top and bottom for passage of saturated forced air. Figure 2 is a generalized drawing showing the location of these ports. The candy-cane shaped tubing shown as part of the air outlet was a modification used in the second test series to prevent leachate from reaching the condensers. The condensers were located outside of the heater box to remove moisture from the exiting air as it cooled. Figure 3 shows the reactors as they were installed in the heater box. The stainless steel high pressure cannisters at the back wall are the hydrators that were used to saturate the air before it was sent through the distribution manifold to the individual compost reactors. Figure 4 shows the external rack that supported the flow meters, condensers and sample ports for the system.

Experimental Design of the First Test Series

The test series utilizing the Farmington sludge was designed to employ ten reactors. Eight were housed in the Despatch heater box (35°C) and two were installed outside the box at ambient temperature (25°C). Each reactor contained approximately 3 liters of compost material. All formulations were run in duplicate for 106 days. Table 1 gives the parameters for each set of compost formulations. The respirometry for the Farmington sludge parameters was performed in the previous Phase I study (Kriegh, 1993). The Phase I study suggested that a ratio of 3:1 would be the optimal BA/S parameter. After the 1:1 BA/S compost was mixed, it was determined that there was not enough sludge available for the proposed 3:1 BA/S compost formulations and that another BA/S ratio would have to be employed. The BA/S ratio was determined by calculating the amount of bulking agent that would be required to extend the limited amount of available sludge to attain the total amount of compost material required to fill the reactors and include all of the projected

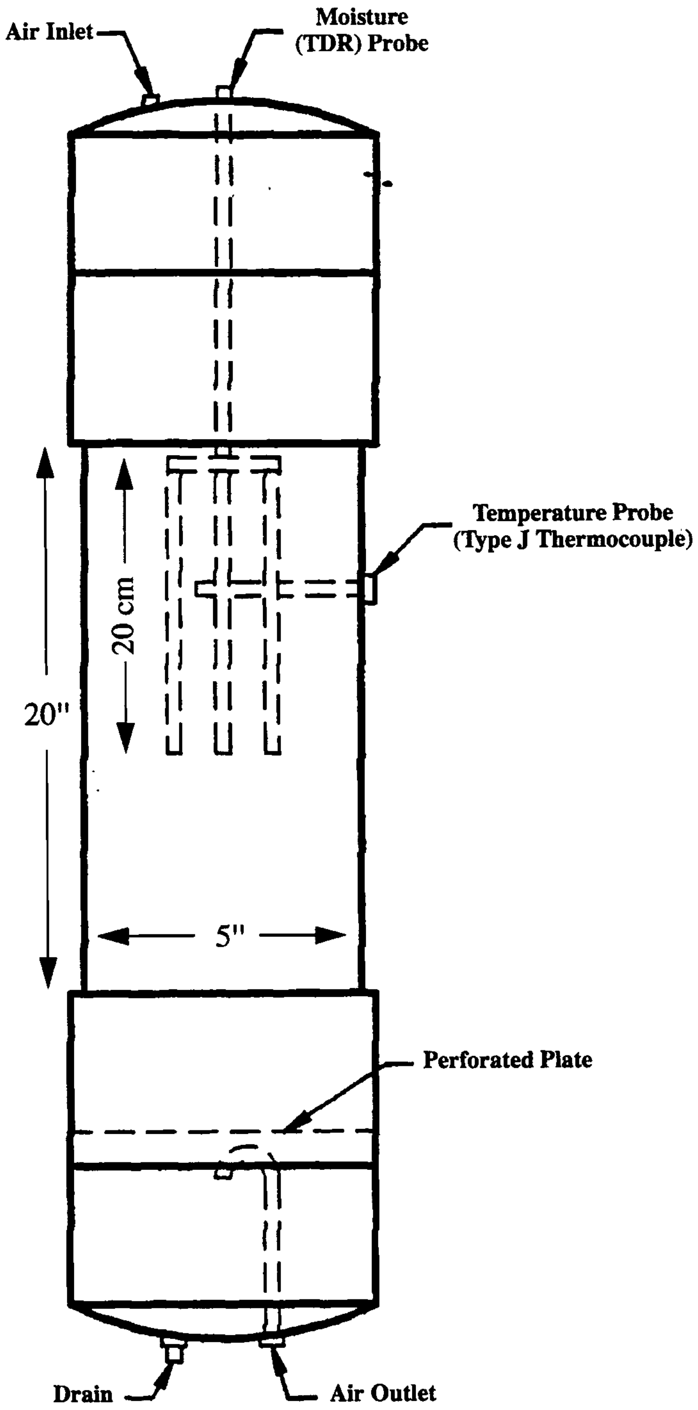


Figure 2. Compost Reactor.

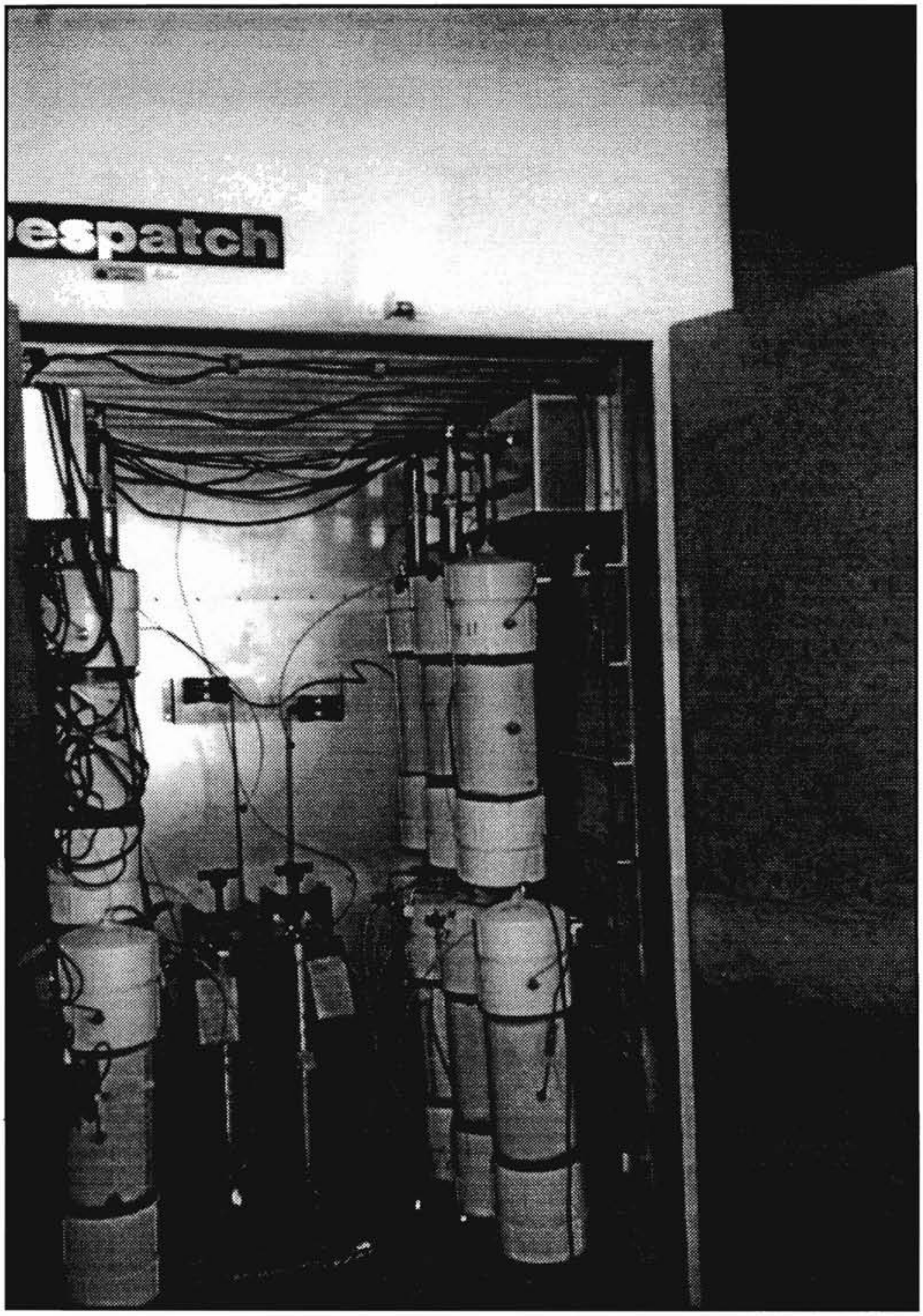


Figure 3. Compost Reactors Installed in Despatch Heater Box.

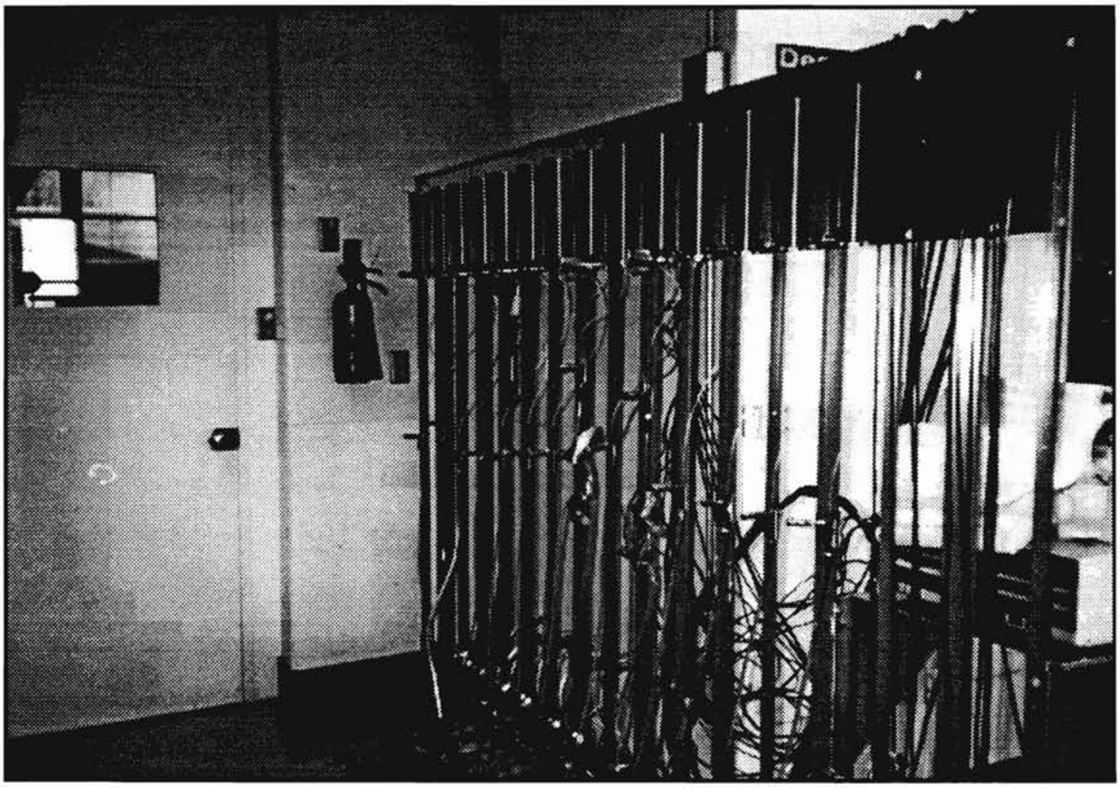


Figure 4. External Support Rack for Flow Meters, Condensers, and Sample Ports.

test cases. Therefore, the BA/S ratio became 5.85:1. Because this ratio is almost twice the proposed ratio, the sludge will be spread over twice the surface area. This makes is more available for oxygen electron transfer. However, the Phase I study (Kriegh, 1993) indicates that as the BA/S ratio moves away from 1:1, the oxygen uptake rate decreases. Therefore, a decreased bioremediation is expected with the increased BA/S ratio.

TABLE 1

COMPOST FORMULATIONS FOR FARMINGTON SLUDGE

Batch Parameter	BA/S	Nutrient Conc.	Temperature	H_2O Conc.	Reactor
Base Optimal	5.85:1	0.7M	35°C	33%CC_{chip}	7&8
Control (**$HgCl_2$**)	5.85:1	0.7M	35°C	33%CC_{chip}	9&10
BA/S	**1:1**	0.7M	35°C	33%CC_{chip}	1&2
Temperature	5.85:1	0.7M	**25°C**	33%CC_{chip}	5&6
Nutrient	5.85:1	**0.07M**	35°C	33%CC_{chip}	3&4

Pine wood chips were used as a bulking agent. The chips were sequentially extracted with methanol and chloroform to remove biodegradable resins and oils before use.

Moisture Content Monitoring

Moisture content of the compost was measured with a Trase System I moisture meter. The model 6050x1 Trase System uses time domain reflectometry (TDR) to measure instantaneously the volumetric water content of soils and other moist media. For these experiments the model 6005 Buriable Wave Guides (3 pronged, 20 cm in length) were permanently installed in the reactors for the duration of the tests. The Trase software then determines the correct volumetric water percentage and displays it in the meter's data window. In an effort to maintain the moisture content of the compost, the leachate was collected separately from each of the reactors. The pH was adjusted to approximately 7 and the leachate was returned to its respective reactor. If the TDR reading indicated low moisture and there was little or no leachate, the reactor was amended with distilled water.

CO_2 Monitoring

Two separate meters were utilized in the measurement of CO_2. One was the Anarad (Model AR450S) Dual Gas Portable Analyzer and the other was the Gastechtor Model 3252OX.

The Anarad Gas Analyzer is a non-dispersive infrared (NDIR) gas analyzer. The Anarad system consists of an optical unit, signal processors, and meters with a detection limit of 0.001%. The Model 3252OX Gastechtor is a portable gas detection instrument calibrated with 2.5% CO_2 in nitrogen and designed to determine carbon dioxide content of the air around various industrial processes. It reads carbon dioxide over the range of 0 - 5% CO_2, actuating a characteristic alarm whenever a reading exceeds a preset level, and oxygen over the range of 0 - 25% O_2, actuating an alarm when the O_2 reading falls below a preset level.

VOC Measurements

Total volatile organic compounds (VOCs) were measured with the Trace-Techtor Portable Hydrocarbon Vapor Tester. It is designed for the detection of hydrocarbon vapors over a broad range (0 - 10,000 parts per million). Hydrocarbon concentrations (ppm) are displayed on a meter. The meter was calibrated with 4,400 ppm hexane in air standard.

pH Measurements

pH measurements for the condensate and leachate of the reactors were performed on a Beckman 45 pH meter using undiluted condensate and leachate. pH measurements on the compost material were performed on the liquid that was recovered from mixing equal masses of compost material and deionized water, allowing it to rest for one hour, draining the liquid into another container, inserting the pH probe and temperature correction probe into the liquid and reading the pH.

Hydrocarbon Content Testing

Hydrocarbon content testing was conducted on the compost material using solvent extraction and GC analysis as described in Appendix A.

Experimental Design of the Second Test Series

The test series utilizing Pit 82093 sludge was designed to employ 16 reactors. This required extensive modification of the air manifold. All of the reactors contained the same basic compost formulation. The only difference was that half of the reactors had mercuric chloride ($HgCl_2$) or sodium azide (NaN_3) added to sterilize the microbial population so that they could be used as controls. The purpose of this test case was to track the changes in the compost material over time by sacrificing and testing an active reactor and a control reactor according to a timed schedule in an effort to document the rate of decomposition and remediation. The reactors were dismantled on a schedule of 7, 14, 21, 35, 49, 70, 98, and 120 days. During the run time of the experiment several parameters were monitored. On a daily basis, the flow rate of the air through the reactors, the moisture content of the compost, the temperature of the compost, and the oxygen, carbon dioxide and volatile organic concentrations of the exiting air were monitored. On a weekly basis the reactors were checked for leachate and the condensers for condensate. These liquids were tested for pH, nitrogen and phosphorus levels. As each set of reactors was sacrificed, it was refrigerated at 4°C until completely cooled before the compost material was removed from the reactor and tested. Then the pH, nitrogen, and phosphorus levels of the compost material were tested and aliquots of the compost material were solvent extracted to determine the amount of hydrocarbon remaining in the compost. The methods and materials used to accomplish these tests were the same as those used with the Farmington sludge with the exception of the NH_3-N and phosphorus tests which are described in the following paragraph.

NH_3-N and Phosphorus Tests

The NH_3-N and the phosphorus tests can be conducted using the same liquid used for the pH test. The liquid is filtered to remove particulates which can affect the accuracy of the results. Nitrogen as ammonia is found using the EPA approved Nessler Method in the HACH DR/2000 direct reading spectrophotometer. A detailed procedure is included in Appendix C. Phosphorus concentration is found using the EPA approved PhosVer 4 Method in the HACH DR/2000 direct reading spectrophotometer. A detailed procedure for this method is also found in Appendix C.

Pit 82093 Compost Formulation

The materials used to make up this compost, in addition to the pit sludge, were raw straw, nutrients in the form of urea (nitrogen) and Rapifeed (phosphorus), and water. Respirometry tests were run to investigate the effects of nutrient concentrations in compost, the sludge, and the straw, BA/S ratios, and microbial activity in the raw sludge and the raw straw. Respirometry tests were run for approximately two weeks (300 hours) and are described in the following paragraphs.

Moisture Content of Straw was the first parameter investigated through respirometry. The moisture content was measured as a percentage of the container capacity (CC) of straw as determined during the characterization study. The moisture added to the straw was deionized water that had been previously sterilized. Six series were run in triplicate: 0%, 25%, 50%, 75%, 100% CC, along with a control set to which 2% mercuric chloride had been added to sterilize the microbes. The mass of straw in each series was held constant while the amount of added water varied.

Nutrient Addition to Sludge was the second parameter to be investigated by respirometry. Four series were run in triplicate using 100% raw sludge with varying concentrations of nutrients added based on nitrogen content. Three of the series employed nitrogen as urea in concentrations of 0.0 N, 0.27 N, and 0.54 N urea. The fourth series employed an Evans nutrient solution having 0.5 N nitrogen. The mass of raw sludge was held constant and the mass of nutrient, which in the case of urea was added dry, was allowed to vary.

Bulking Agent to Sludge Ratio was the third parameter to be investigated by respirometry. Four series were run in triplicate. Each had a moisture content equal to eighty percent (80%) of the container capacity of the straw. The bulking agent to sludge ratios (BA/S) that were employed were 0.5:1, 1:1, 2:1, and 3:1. In this series the volume of the mixtures was held constant while the masses of straw and sludge were varied to match the required BA/S.

Compost Nutrient Concentration was the fourth parameter to be investigated by respirometry. Again the moisture was based on 80% of CC. The same four nutrient concentrations that were used in the raw sludge and raw straw were used with a 2:1 BA/S compost mixture. The volume of compost was held constant while only the nutrient concentrations varied. Results of this study are discussed in Chapter IV.

Respirometry results led to the determination of the parameters that were employed in the bench scale composting study as follows:

BA/S	2:1
Moisture content	60% on a dry weight basis
Nitrogen (Urea)	0.25 N/H_2O content
Phosphorus (P_2O_5)	4:1 as N:P ratio
Temperature	35°C
Vol. per reactor	4 liters
Air flow rate	15 cm^3/hr

CHAPTER IV

RESULTS AND DISCUSSION

This chapter summarizes results from the three tests conducted during this study. In chronological order, the Farmington composting trial, the respirometry of the Pit 82093 sludge, and then the compost study of the Pit 82093 sludge are reviewed.

Farmington Compost

After the compost formulations were made up and apportioned to their respective reactors, the reactors were closed, placed in the heater box or hung on the sampling rack, connected to the air supply and to the exit/sampling lines. The heater box was then closed and the air supply was turned on and the air flow pressure was brought to 15 cc/hr. It then became apparent that the air flow pressure did not register on the rotometers in the exit lines, indicating leaks between the air inlet and the rotometers. Upon investigation of the problem it was found that the reactors themselves were leaking around the threaded top and bottom caps. For the next 12 days, while the leaks were being repaired, there was no forced aeration to the reactors. The consequences of this can only be speculated. During this time all reactors were kept at 20°C (room temperature). "Snoop" surfactant solution was used to locate and mark each leak location. Then sealant (RTV) was applied to the leaking areas, and a hand held vacuum pump was used to draw the sealant into the leaking areas. This process was repeated until each reactor held a 10 psi vacuum for at least five minutes. They were then allowed to cure for twenty-four (24) hours before restarting the system. No moisture was added to the reactors prior to startup. During this time, it was decided that a more reliable air flow source than the original O_2 bottles was needed. Plant air was routed to the reactors, and filters were added upstream of the reactors.

On day 12 the forced air flow to all reactors was begun. The temperature of the reactors in the Despatch heat box was raised simultaneously to 35°C. Except for individual moisture and pH adjustment, the operation of the system remained unchanged until day 82. Because of the very low rates of CO_2 production, the temperature of the reactors in the Despatch heat box was raised to 48°C. On day 106 this test series was terminated.

Discussion of Individual Tests and Their Results

Moisture and pH Control were difficult throughout the operating period. Moisture content of the compost was measured on a daily basis with the time domain reflectometry (TDR) moisture probes. The reading given by this method was based on the percentage of the metal probe that was wet which in turn depended on the percentage of the probe that was in physical contact with the compost material. Another factor affecting the TDR readings was the path of the air flow through the compost material and the drying effect it might have on the compost material. These readings were used to gauge when the reactors were in need of additional moisture. Four of the reactors consistently gave TDR failure readings, indicating an inability to obtain a moisture reading. This was caused by TDR probe contact with the metal support grid at the base of the compost. These contained the 1:1 BA/S ratio compost and the low nutrient 5.85:1 BA/S ratio compost. In an effort to determine the moisture content, a RapiTest moisture probe, generally used for house plants, was inserted through a port in the reactors to obtain a relative moisture reading unrelated to the TDR. Figure 5 illustrates the daily variance of moisture as measured by the buried probe. When the reactors were emptied at the end of the test period it was observed that the compost at the top of the reactors was dry to the touch while that at the bottom was frequently saturated. Condensate from each reactor's air flow was collected in condensers that had been installed outside the heater box in the air line prior to the monitoring valve connection. The condensers were emptied periodically and the condensate was discarded.

Leachate (water formed during the biodegradation of hydrocarbons) collected in the bottom of the reactor, where it was drained off periodically and returned to the top of the compost in each reactor. Where it was felt that the compost needed more moisture than the leachate could provide it was amended with deionized water. pH testing was conducted on the fluid that leached from the compost over the period of the experiment. The leachate's pH was either adjusted up with 1 M sodium hydroxide (NaOH) or down with 1 N hydrochloric acid (HCl) to a pH near 7.0 and returned to the respective reactor through one of the ports at the top of the column of compost. Table 2 gives a representation of the pH readings of the leachate before it was adjusted. As can be seen in the table, pH in all reactors started between 9 and 10, well above the desirable range of 6.5 to 7.5. As pH adjustments were made to the liquid and it was injected back into the proper reactor, the pH of the leachate leaving the reactors slowly came down into the range considered most desirable for biodegradation. However, at no time did the pHs stabilize in the desired operating range.

TABLE 2

pH OF LEACHATE AS IT LEAVES THE COMPOST REACTORS

Formulation (BA/S, Nutrient, Temperature)	Number of Weeks					
	4	6	7	8	10	14
1:1, 0.7N, 35°C	9.60	8.45	7.23	7.42	6.49	6.39
1:1, 0.7N, 35°C	9.11	8.02	7.76	9.27	6.52	5.90
5.81:1, 0.07 N, 35°C	9.53	8.75	8.56	8.14	8.26	6.02
5.81:1, 0.07 N, 35°C	9.55	9.43	8.29	7.44	6.56	5.78
5.81:1, 0.7 N, 25°C	9.71	7.58	6.83	6.21	6.25	6.15
5.81:1, 0.7 N, 25°C	9.92	9.42	9.04	8.88	6.25	5.94
5.81:1, 0.7 N, 35°C	9.12	8.13	8.25	7.38	7.17	6.97
5.81:1, 0.7 N, 35°C	9.31	9.48	8.77	7.81	7.00	6.73
5.81:1, 0.7 N, 35°C, (2% $HgCl_2$)	10.19	9.53	8.20	6.71	7.28	7.14
5.81:1, 0.7 N, 35°C, (2% $HgCl_2$)	9.86	9.93	9.35	8.36	8.84	5.17

At the end of the test time, the compost was removed from the individual reactors, mixed well so that the moisture in the compost would be distributed throughout the compost, sealed in paint cans, labeled and refrigerated for several days before they were opened and tested for moisture content with the Denver Moisture Balance. Table 3 contains the moisture percentages of the compost on day one of the test and at the end of the test by reactor. The headings "Reactor A" and "Reactor B" are used to indicate the duplicate reactors for each compost formulation. Among the reactors housed within the heater box, four (4) of them displayed significant decreases in moisture content while the other four (4) were relatively unchanged. Conversely, the two reactors that were operated at ambient temperature (25°C) displayed a significant increase in water content. This increase is attributed to the condensation of the saturated forced air stream at the lower operating temperature of these reactors.

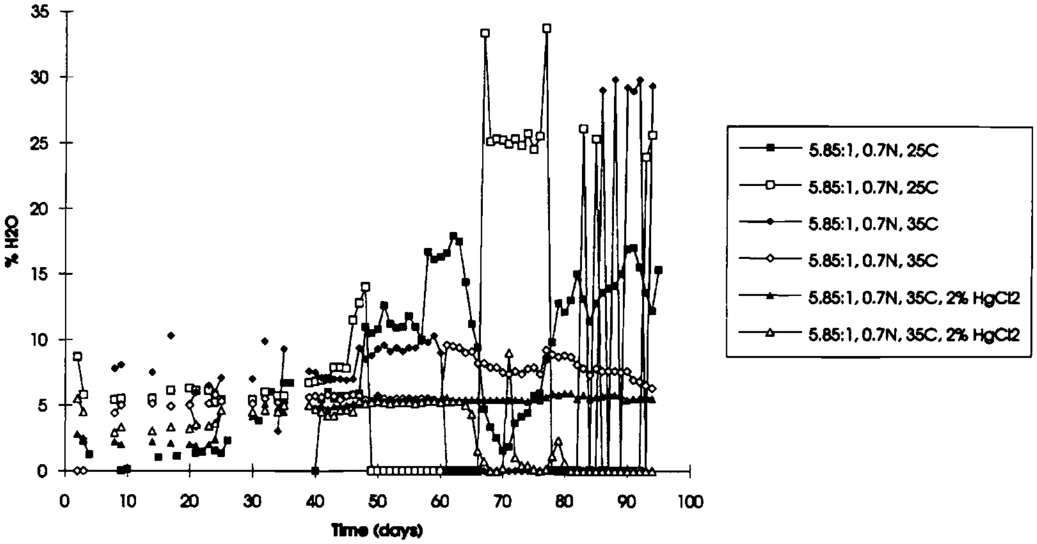


Figure 5. TDR Moisture Content Readings for Farmington Compost.

On day 53, 20cc of 0.5M Evans nutrient was added to the reactors containing the 1:1 BA/S ratio and the 25°C reactors to see if there would be an increase in microbial activity, and in turn the production of CO_2. At the same time 20cc of 0.05M Evans was added to the reactors containing low nutrient formulation. As can be seen in Figure 6, there was no increase in CO_2 production that would indicate an increase in microbial activity.

TABLE 3

DENVER BALANCE MOISTURE CONTENT OF COMPOST

Formulation of Compost	Day Zero % H_2O	Final % H_2O Reactor A	Reactor B
1:1, 0.7N, 35°C	28.66	20.16	19.03
5.85:1, 0.07N, 35°C	32.94	6.65	32.17
5.85:1, 0.7N, 25°C	33.00	49.55	47.19
5.85:1, 0.7N, 35°C	33.00	35.04	29.68
5.85:1, 0.7N, 35°C (2% $HgCl_2$)	33.16	28.11	7.40

On day 82, with steadily decreasing CO_2 production, the set temperature for the heater box was increased to 50°C to see what effect it might have on microbial activity. The effect observed was a virtual shutdown of activity. The temperature was lethal to mesophilic microbes, and any thermophilic population that was present either was too small or needed more time to develop significant activity.

Between days 40 and 45 there were three (3) incidents where there was no air flow through reactors 4 and 10 due to a clogged air exit valve. The clogs were caused by small particles of compost material in the leachate. The curvature of the bottom reactor cap was shallow and the air exit and liquid exit valves were very close to each other. It was felt that leachate was of a large enough volume that it probably covered the air exit valve and some of it was lost as part of the condensate. The clogged valves were cleared and air flow resumed.

<u>CO_2 Content</u> of the composting material was monitored on a daily basis as a percentage of the exiting air from the reactors. These readings, in combination with the air flow rate and the VOC readings, are used to calculate the percent of hydrocarbon that was removed from the composted material on a cumulative basis. The formulas used in performing these calculations are included in Appendix F. Since CO_2 is a product of complete

hydrocarbon biooxidation (Equation 1), the appearance of CO_2 in the reactor exit air can be a good indicator of hydrocarbon biodegradation.

$$\text{Hydrocarbon} + O_2 = CO_2 + H_2O + \text{biomass} \tag{1}$$

Figure 6 depicts the daily CO_2 production measured as percent of exiting air streams for each of the reactors. The legend gives the parameters of each formulation in the order of BA/S, nitrogen content and temperature. All reactors attained their maximum CO_2 output within 5 to 10 days of the initiation of forced aeration. The largest daily CO_2 production was associated with the 1:1 BA/S ratio (13%). The next highest was the predicted optimum (high nutrient) set (9%) followed by the low nutrient set (2%), the low temperature set (0.5%) and lastly by the sterile control set (<0.1%). Except for the sterile control set which maintained a constant low rate of CO_2 production for the entire test period, the peak CO_2 output of all other reactors was sustained for only a few days. They then tapered off to almost no CO_2 production around 85 days. At that time the temperature of the reactors in the heater box was raised to 48°C (near thermophilic). CO_2 production effectively stopped. This may be due more to bacterial mortality than a kinetic dependence on temperature. Figure 7 illustrates the calculated cumulative CO_2 production in cubic centimeters (cm^3) over the life of the composting experiment. It is reported in standard cc's from exit gas CO_2 concentrations and flow rate data. Comparative performance follows the same order as described for the daily CO_2 outputs. By the end of the operating period, the 1:1 ratio set cumulative average CO_2 output had exceeded 70,000 standard cc's while the sterile control set had produced less than 1,000 cc's of CO_2. A noticeable decline in CO_2 production is observed for all but the low temperature and sterile control reactors which coincide with the temperature change at day 82. Figure 8 shows the cumulative volatile organic carbon (VOC) of the exiting air flow in cubic centimeters over the same period of time as measured with the portable hydrocarbon vapor meter. These carbon molecules have not been degraded to CO_2 and H_2O but have been removed from the compost material by mass transfer to the air flow.

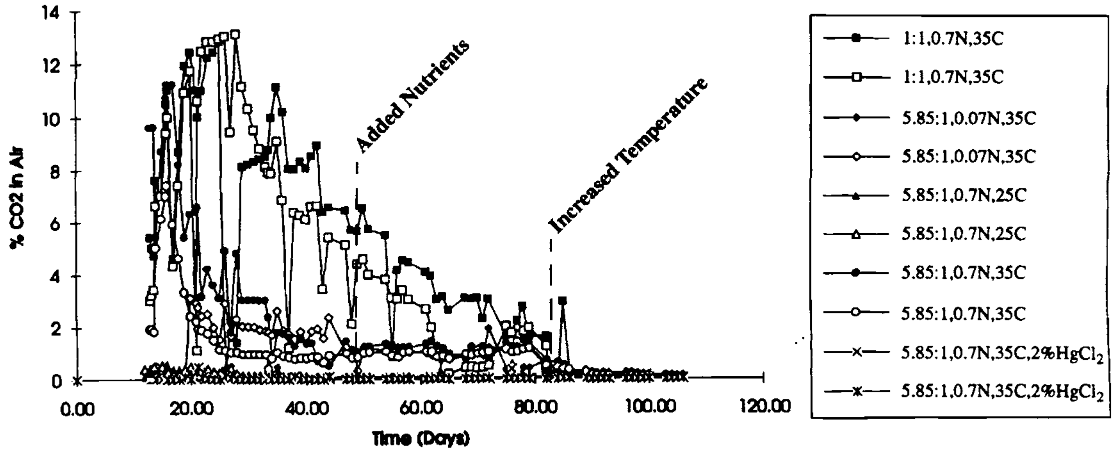


Figure 6. Daily CO_2 Production - Farmington.

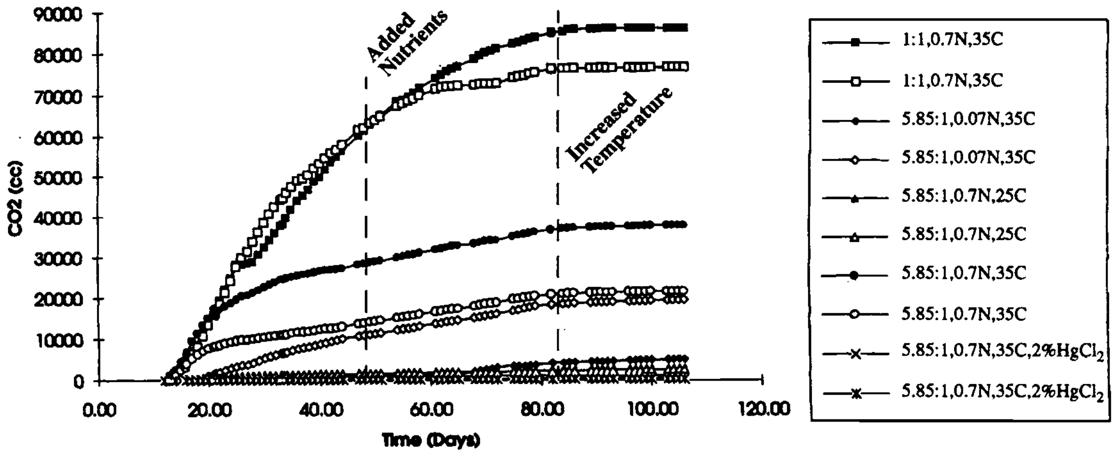


Figure 7. Cumulative CO_2 Production - Farmington.

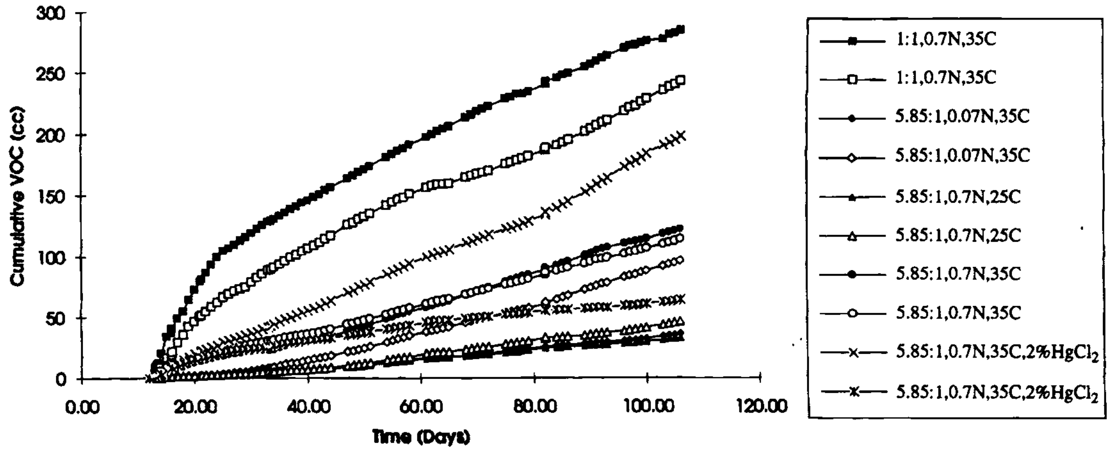


Figure 8. Cumulative VOC Production - Farmington.

Hydrocarbon Content of the various formulations of compost was determined at Day zero and day 120 by methylene chloride extraction using the Soxtec HT2 1045 extraction unit. This method is described in Chapter III. The formulations of the composts are displayed in Table 1 of Chapter III. Three aliquots from each reactor were dried with anhydrous magnesium sulfate and extracted for 6 hours with methylene chloride. Day zero figures signify the percentage of compost mixture that consisted of carbon on a dry weight basis. The total sample mass used per reactor in the performance of the extraction was very small (approximately 25 grams of wet material) and is representative of only one to two percent of the compost material. The extraction data computations for day zero and day 120 are included in Appendix E.

Final extraction percentages are calculated on the same basis with similar sample masses. Percent carbon removed signifies the percentage of the beginning hydrocarbon concentration that has been removed. For instance, where the day zero concentration of carbon is 32.23% and the final day concentration of carbon is 21.44%, the percent of the starting carbon concentration that has been removed by biodegradation is 33.48%. This is calculated using the following formula:

$$\frac{\text{Day Zero \%} - \text{Final \%}}{\text{Day Zero \%}} \times 100 = \text{\% Carbon Reduced}$$

Table 4 summarizes average initial and final gravimetric carbon removal values for each reactor. Ranking the formulations in order of decreasing carbon removed, the 1:1 BA/S ratio had the greatest percent carbon reduction followed by the low temperature set, the low nutrient set, the predicted optimum set, and finally the sterile control set. This sequence suggests that the respirometry predicted optimum was surpassed in carbon reduction by all but the sterile control set.

Portions of each extract were reconstituted with methylene chloride for type analysis by gas chromatography. Figure 9a through 9f presents the gas chromatographs (hydrocarbon fingerprints) representative of the initial and final compost samples. They are

TABLE 4

COMPOST HYDROCARBON REDUCTION DETERMINATION BY EXTRACTION

Formulation of Compost (BA/S, Nutrient, Temperature)	% Carbon Day Zero	% Carbon Final	% Carbon Removed
1:1, 0.7N, 35°C	32.23	21.44	33.48
1:1, 0.7N, 35°C	32.23	22.72	29.51
5.81:1, 0.07N, 35°C	15.19	12.44	18.10
5.81:1, 0.07N, 35°C	15.19	12.28	19.16
5.81:1, 0.7N, 25°C	15.53	12.12	21.96
5.81:1, 0.7N, 25°C	15.53	10.44	32.78
5.81:1, 0.7N, 35°C	15.53	12.90	16.88
5.81:1, 0.7N, 35°C	15.53	12.97	16.48
5.81:1, 0.7N, 35°C, (2%$HgCl_2$)	19.29	16.94	12.18
5.81:1, 0.7N, 35°C, (2%$HgCl_2$)	19.29	17.16	11.04

normalized with respect to concentration but not for changes in response factor. Therefore they cannot be compared on an absolute basis.

Figure 9a is representative of the initial unprocessed compost while 9b through 9e represent the four different formulations and 9f represents the sterile control. Figures 9b through 9e appear equally biodegraded in that the large hydrocarbon peaks have been removed from the undiscriminated hydrocarbon hump while the sterile control, Figure 9f, appears undegraded. Figure 9c, the predicted optimum set, appears to have an increase in higher boiling point material where the others do not. This may be a result of condensation reactions between lower boiling point material to form higher boiling point products and may be unique to the parameters imposed on that compost set.

Hydrocarbon concentration was also computed based on CO_2 production as it was monitored in the air exiting the compost reactors on a daily basis. Figure 10 depicts the calculated percent of carbon removed from the compost material based on the production of CO_2 and VOC concentrations in the exiting air flow. VOC emissions accounted for less than 2% of the total carbon removed except in the case of the sterile control set where it accounted for 9.8%. Table 5 is included here to compare extraction values to values based

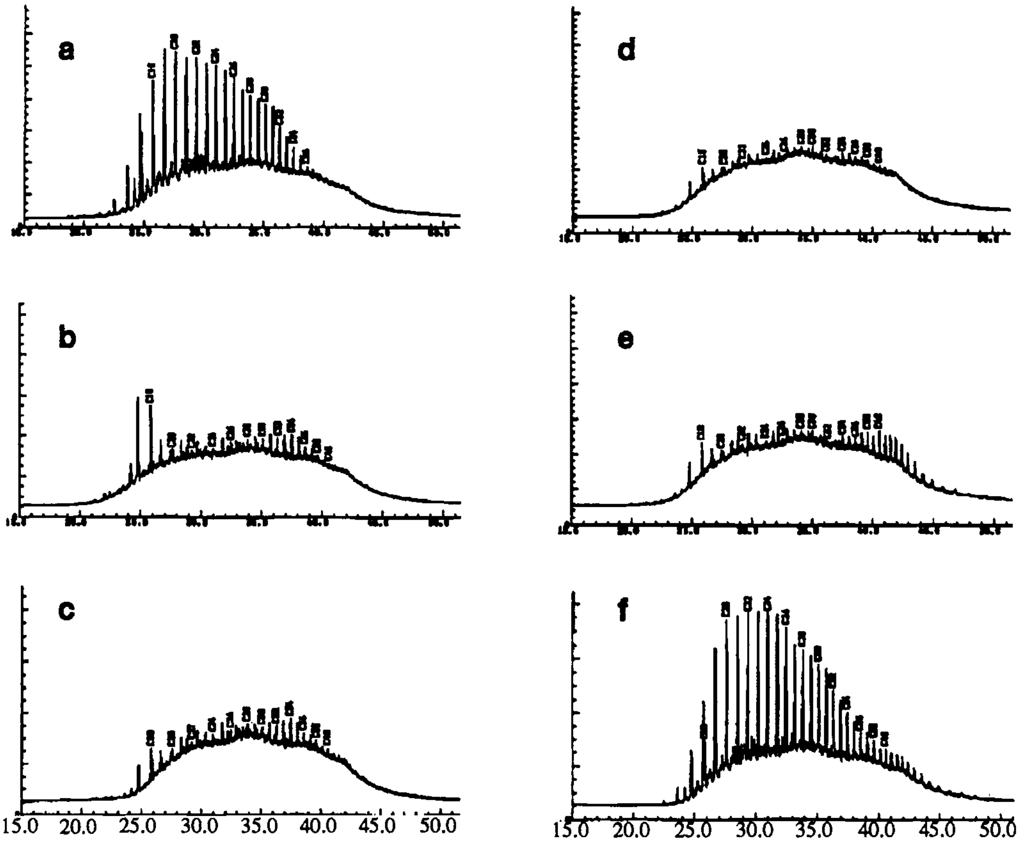


Figure 9. Compost Extract Chromatogram - Farmington: (a) Initial, (b) 1:1, 0.7N, 35°C, (c) 5.81:1, 0.07N, 35°C, (d) 5.81:1, 0.7N, 25°C, (e) 5.81:1, 0.7N, 35°C, (f) Sterile Control.

on monitoring data. Extraction data are based on a heterogeneous mixture from which a minute (1%) sample is taken. In spite of this fact the results seem to be within a small range with respect to each formulation of compost.

The results based on CO_2 production follow a more expected pattern. All the reactors, except for the two noted in Table 5, had final compost moisture contents ranging from 20 to 50%. The reactor that is noted as having low moisture content had Denver Moisture Balance value less than 7%. Since adequate moisture is considered critical for biodegradation, it is not surprising that this reactor did not perform as well as the others. From these data, the best performing formulation was the 5.81 BA/S, 0.7 N nitrogen, 35°C temperature, with 35% moisture content (18.4% removal). The next best overall performer was the

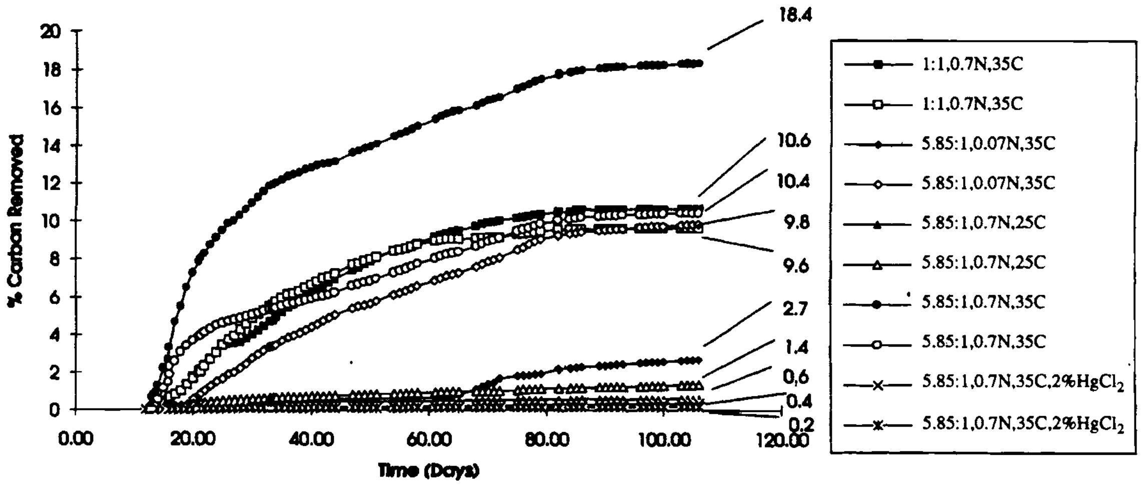


Figure 10. % Carbon Removed - Farmington (Based on CO_2 Production).

1:1 BA/S (10.1% removal) which also exhibited the largest instantaneous CO_2 production., followed closely by the low nutrient set (9.8%). The low temperature (1.4%) set and the sterile control set (0.4%) were close in value and significantly lower than the others.

TABLE 5

COMPARISON OF EXTRACTION VALUES TO MONITORING DATA VALUES AS RELATED TO HYDROCARBON REDUCTION IN COMPOSTING

Formulation of Compost (BA/S, Nutrient, Temperature)	% Carbon Removed by Extraction	% Carbon Removed Based on CO_2 Production
1:1, 0.7N, 35°C	33.48	10.6
1:1, 0.7N, 35°C	29.51	9.6
5.81:1, 0.07 N, 35°C	18.10	2.7 (low moisture)
5.81:1, 0.07 N, 35°C	19.16	9.8
5.81:1, 0.7 N, 25°C	21.96	0.6
5.81:1, 0.7 N, 25°C	32.78	1.4
5.81:1, 0.7 N, 35°C	16.88	18.4
5.81:1, 0.7 N, 35°C	16.48	10.4
5.81:1, 0.7 N, 35°C,(2% $HgCl_2$)	12.18	0.4
5.81:1, 0.7 N, 35°C,(2% $HgCl_2$)	11.04	0.2

When looking at the gross CO_2 production over time (Figure 7), the predicted optimum set produced less than half the CO_2 produced by the 1:1 BA/S set. Since gross CO_2 production is partially linked to the total amount of hydrocarbon available to be degraded, the gross CO_2 values are also related to the BA/S ratios. When expressed as a percentage of the initial hydrocarbon present (Figure 10), the predicted optimal set outperformed all others. From this perspective the respirometric optimization appears to be successful.

From the perspective of field operations, Figure 10 suggests that the 1:1 BA/S set of conditions would be best for minimizing the total amount of hydrocarbon degraded, whereas the predicted optimum set of conditions (5.81:1, 0.7N, 35°C) would be best for achieving a desired endpoint in the minimum amount of time.

Referring again to Table 5, which compares the carbon removal by extraction to that based on CO_2 production, it can be seen that the two methods do not agree. Since regulatory agencies commonly use the extraction method to establish remediation endpoints, it is reasonable to give more weight to data gathered by this method. The most probable reason for the difference between the two methods is the partial oxidation of hydrocarbons at some composting conditions. On the other hand, partial oxidation of hydrocarbons does not result in CO_2 production and carbon removal rates based on CO_2 production alone will appear low. Parameter optimization through respirometry is a good method if the goal is complete mineralization of hydrocarbons.

Theoretically the mineralization of hydrocarbons with oxygen requires 3.48 grams of O_2/gram hydrocarbon. The respirometry work performed by Karl Kriegh in the Phase I study reported an oxygen utilization rate of 0.75 to 0.79 grams of O_2/gram HC. This converted to a hydrocarbon reduction rate of 0.17 to 0.27 grams HC/day. Kriegh felt that the low O_2 consumption rate was due to a large proportion of the carbon being incorporated into biomass instead of being oxidized by oxygen to form CO_2. The carbon in biomass escapes extraction and contributes to the observed loss in hydrocarbon without being reflected as oxygen consumption. Kriegh's extraction data for his "Best Combination" which corresponds to the "predicted optimum" for this study reported a 19.7% HC reduction over a 14 day period. If that high rate of activity could be sustained, the desired end point of 1% HC contamination could be achieved in approximately 67 days. However, as this study has shown, the period of high activity, under optimum conditions, lasts about 14 days and is followed by a long period of gradual decline. The cumulative CO_2 plot (Fig. 7) was used to estimate the reaction order for the hydrocarbon degradation that occurred in this study. It was determined that the low nutrient set, the low temperature set and the sterile control set are zero order, the 1:1 BA/S set is first order and the predicted optimum set was initially first order but switched to zero order kinetics around 700 hours.

Table 6 summarizes zero order rate constants estimated from CO_2 and hydrocarbon extraction data for the active sets. It is assumed that biodegradation is the only hydrocarbon loss mechanism. The rates are expressed as grams of carbon per gram dry compost per day. The number of days required to reach 1 wt% closure standards are calculated from these rates.

TABLE 6

ZEROTH ORDER RATE CONSTANTS

	CO_2		Extract	
set	Rate g/g · D x 10^4	Closure Days	Rate g/g · D x 10^4	Closure Days
1:1 BA/S	2.14	1093	6.35	368
low nutrient	1.08	1360	3.92	375
low temp	0.19	7911	4.54	324
predicted optimum	2.42	609	2.08	708

Inspection of the rate constants based on extraction discloses that the formulations which promote partial mineralization of hydrocarbons are expected to reach closure at a minimum of approximately one year. The 1:1 BA/S ratio would process a larger volume of sludge, but the process would be no less effective at the higher BA/S ratios with low nutrient or low temperatures. Inspection of the optimum conditions for complete mineralization predicted by the Phase I study conducted by Kriegh, however, discloses a two year closure period which is ten times longer than that estimated from his studies.

Because it is unlikely that laboratory conditions can be maintained in a field setting for periods close to or beyond a year, further refinements to the composting conditions need to be made to reduce the required operating times. The most practical approach would be to dilute the original hydrocarbon contaminant concentrations from 15 wt% to a concentration below 8 wt%.

Pit Sludge Respirometry Results

The materials to be used in the pit sludge compost were investigated through respirometry in three groups: (1) pit sludge, (2) straw, and (3) combined straw and sludge.

Pit Sludge

Pit sludge was investigated to determine the biological oxygen demand (BOD) of the raw straw and of raw sludge with varying degrees of nutrient amendment. The nutrient addition was based on nitrogen in the form of urea. Urea is an agricultural fertilizer that is readily available. The urea and phosphorus (a commercial fertilizer known as Rapifeed) were added to the raw sludge as dry granules by stirring vigorously. One of the series was run utilizing the Evans mineral salts nutrient solution that was used with the Farmington compost formulations as a comparison. Figure 11 shows the results of this series of tests. Any addition of nutrients exhibited a significantly higher oxygen demand than that of raw sludge. Although the addition of 0.5 N Evans solution showed earlier increased activity patterns, the 0.54 N urea addition surpassed the final BOD of the Evans addition, and the 0.27 N urea closely approximated the final Evans addition BOD. Overall there was not a great difference in the final BOD with respect to the degree of nutrient addition, but the increased activity pattern indicated that there were microorganisms native to the sludge that were available for biodegradation of the hydrocarbons in the soil.

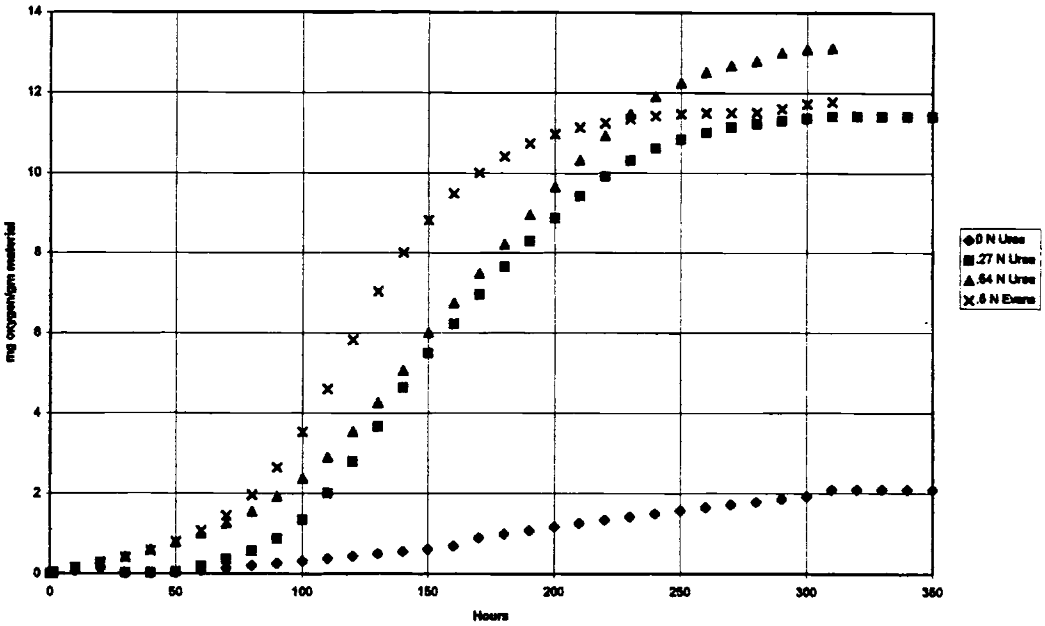


Figure 11. Average Cumulative BOD of Sludge by Nutrient Addition (Dry).

Straw

Straw was investigated to determine the BOD with respect to moisture content and nutrient content. The moisture content was expressed as a percentage of the container capacity (CC) of the straw. Container capacity of straw was reported earlier (Materials, Methods, and Experimental Design, Chapter III) to be 3.827 times the mass of dry straw. Six series of tests were run ranging from zero to 100 percent of CC including a sterilized control set at 75% of CC. Figure 12 demonstrates the results of this series of tests. The moisture content series that exhibited the highest BOD was 75% of CC. Nutrients (nitrogen and phosphorus) were added to the straw after being dissolved in distilled water at a concentration of 0.5 N nitrogen and a moisture content of 0.5 CC. Respirometry was run on this mixture and raw straw also with a moisture content of 0.5 CC. As can be seen in Figure 13, the addition of nutrients to the straw significantly depressed BOD of the straw from 56 mg/gm of material to 6 mg/gm of material. Because of this occurrence, a sample of the raw straw was sent to Soil Analytical Services, Inc. to determine the amount of naturally occurring nitrogen in the straw. The lab report can be found in Appendix G. The reported concentration of naturally occurring nitrogen in raw straw was 4,592 ppm, which converts to only 0.46% by weight and is only 8% of the total nitrogen in the samples that were run in the respirometers. Therefore the amount of naturally occurring nitrogen in the straw was considered insignificant. Respirometry tests for nutrient addition to straw were run at only 0.0 N and 0.5 N nitrogen. If tests had been run at several intermediate concentrations, a nutrient dosage might have been found that was not apparently toxic. Nutrient concentrations are investigated further in the section on combined straw and sludge. Figure 14 shows the BOD of the straw in comparison to the BOD of the sludge. It is curious to note that the BOD of the 0.5 N sludge matches the BOD of the 0.5 N straw. This carries no significance other than that of coincidence.

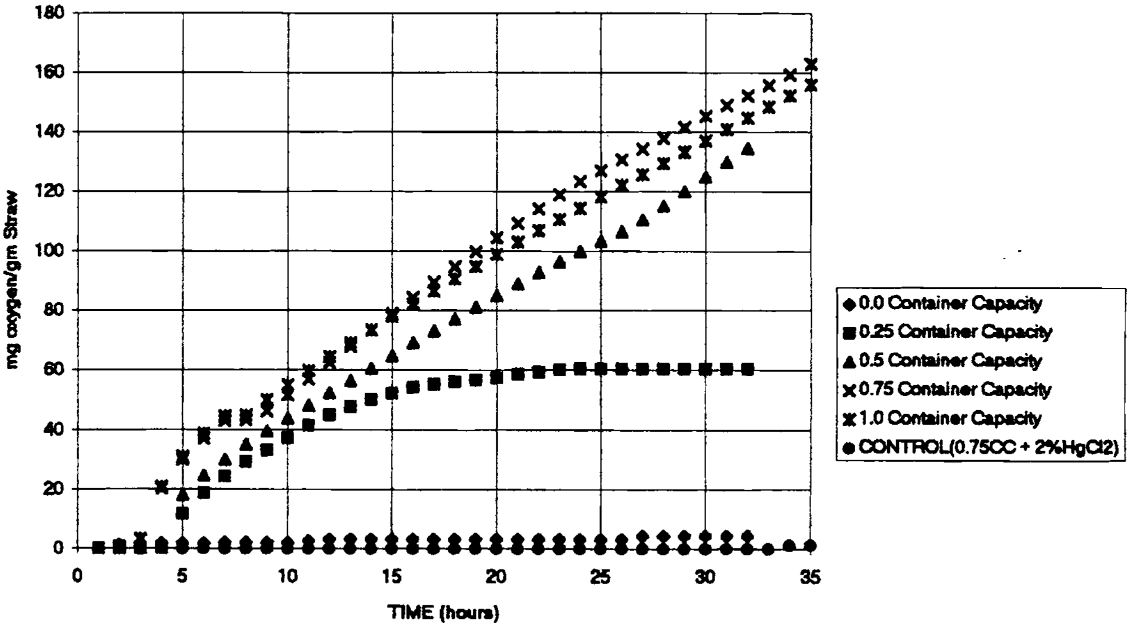


Figure 12. Average Cumulative BOD with Respect to Moisture Content of Straw.

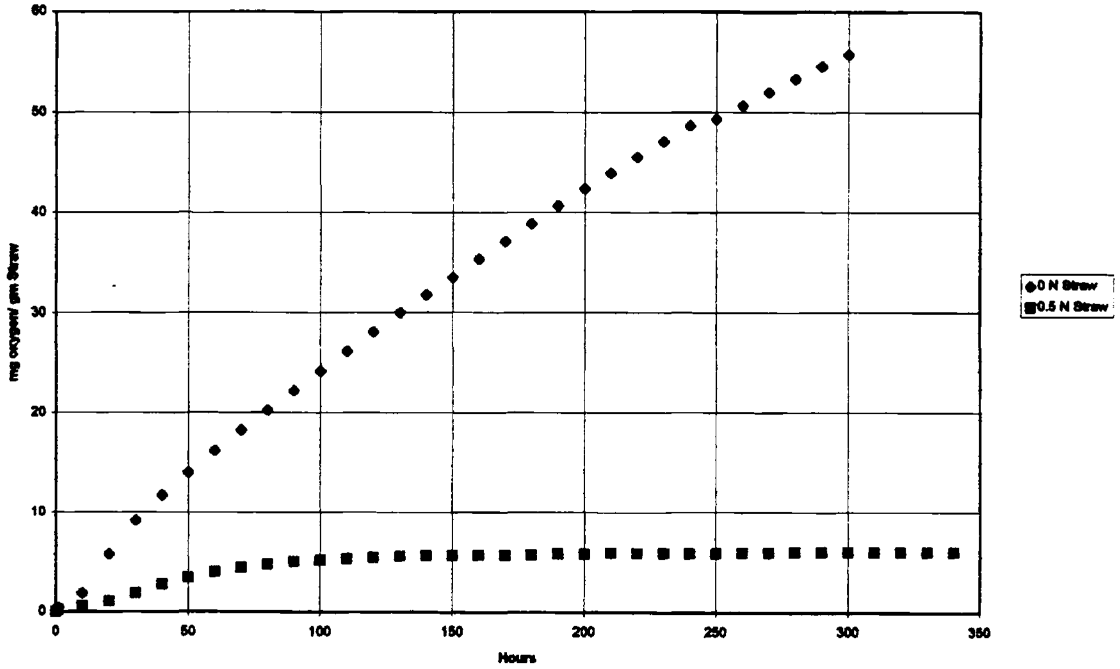


Figure 13. Average Cumulative BOD of Straw with and without Nutrients.
(Straw is 50% Saturated)

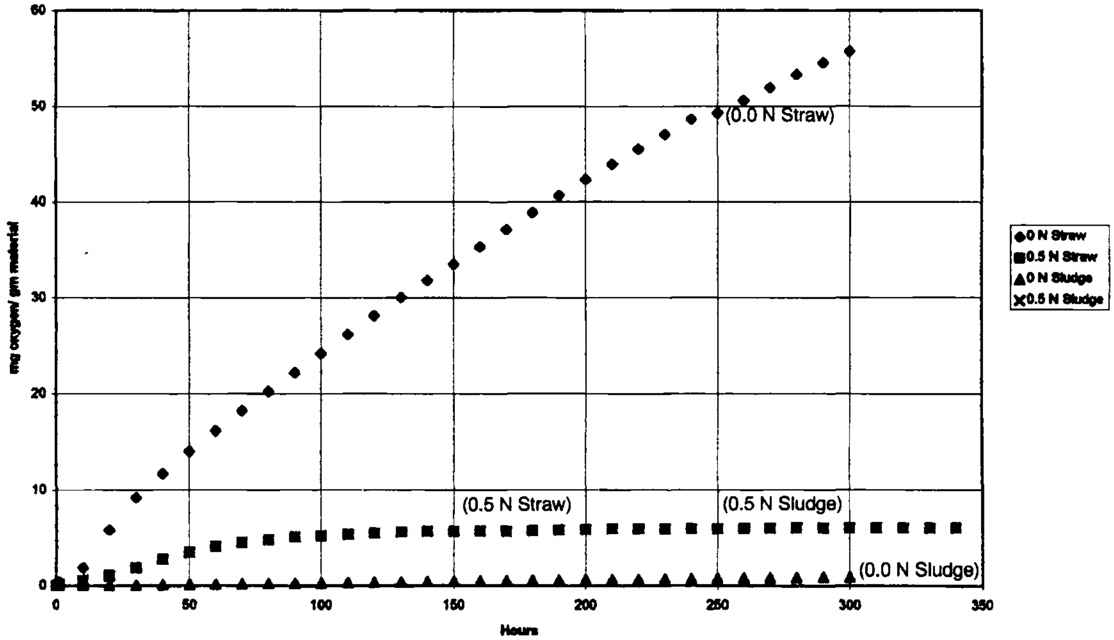


Figure 14. Cumulative BOD of Straw and Sludge with and without Added Nutrients.
(Sludge has 14% Added H_2O)
(Straw is 50% Saturated)

Combined Straw and Sludge

Combined straw and sludge were investigated to determine the most appropriate BA/S ratio and then the desired level of nutrient addition. The BA/S ratios tested were 0.5:1, 1:1, 2:1, and 3:1. The moisture content and the nutrient level were held constant at 80% CC and 0.5 N nitrogen respectively. The results of this investigation are presented in Figure 15. The BA/S that performed best was the 3:1 BA/S with the others ranking in descending order. The 2:1 BA/S was 80% of the 3:1 BA/S, 1:1 was 50% and 0.5:1 was 30%. The forced air closed reactor study was to be performed in conjunction with a pilot scale study conducted by Dan Denham. Based upon container capacity measurements made by Denham on composts with 3:1 and 2:1 BA/S ratios, a decision was made to use the 2:1 BA/S ratio. Thus, the nutrient level investigation was conducted on the 2:1 BA/S. The nutrient levels tested were 0 N, 0.27 N, and 0.54 N as urea and 0.5 N as Evans nutrient solution. Moisture content was again held constant at 80% CC. Figure 16 illustrates the results of this series of tests. Again the range is very narrow between the best and worst performers. The formulation utilizing 0.27 N urea has two periods of increased activity, a small one very early on and another larger one starting around 100 hours and leveling out around 175 hours at approximately 11 mg oxygen/gm of material. The formulation with no added nutrients has a small period of increased activity within the first 12 hours, which then changed to a linear-like pattern of activity that showed no signs of leveling out until the very end of the allotted test time. The 0.54 N Urea formulation showed the same early increased activity and later linear activity as the 0 N urea but at a lower BOD and was the poorest performer. The best performer was the 0.5 N Evans formulation which was tested strictly for comparison to the Farmington compost and was not being considered for the Pit Sludge compost experiments. It had one period of increased activity with a later onset than the other three, and though starting to recede around 170 hours into the test still showed some signs of activity to the very end. Once again, the BOD spread among the various formulations was very small (4 mg oxygen/gm material). Since the reasoning behind this experiment was to evaluate the feasibility of using commercial fertilizers as the nutrient source in field scale composting, the decision was made to use 0.25 N nitrogen as urea with the nitrogen to phosphorus ratio (N:P) as 4:1. It exhibited a biodegradation rate of 5.86×10^{-4} gm HC/gm dry compost. For an average respirometer reactor volume of 200 ml (150 gm mass) the minimum operating time required to bring this compost mixture to regulatory limits of 1% would be 150 days.

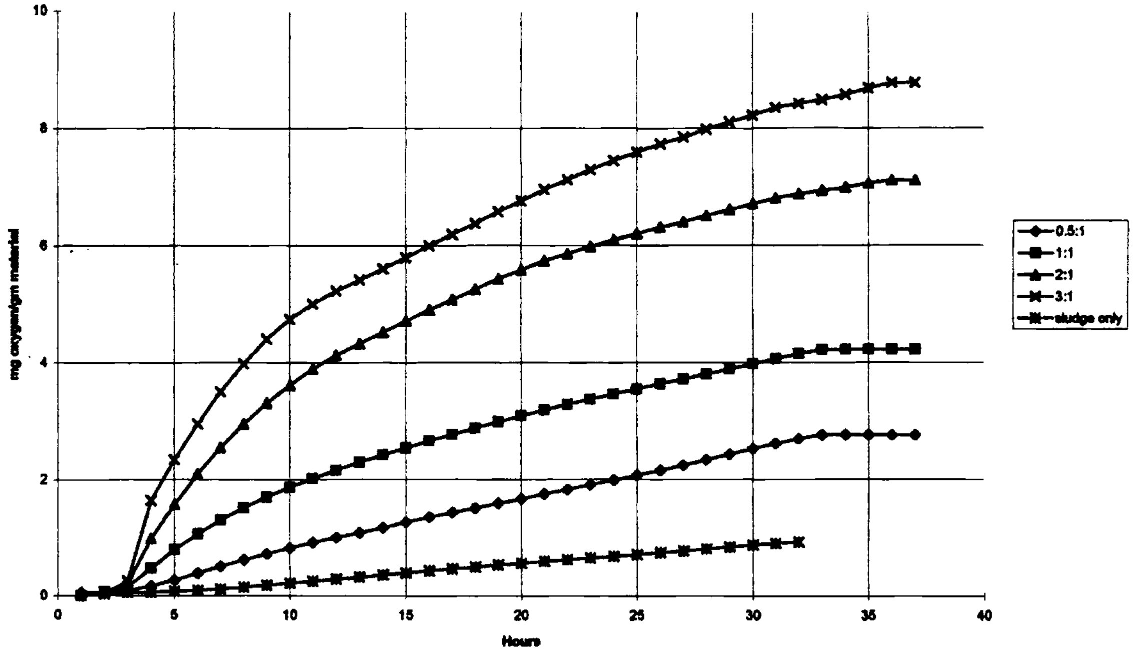


Figure 15. Average Cumulative BOD of Straw and Sludge by Bulking Ratio. (Moisture = 80% of Container Capacity of Straw)

Pit Sludge Composting Results

Final Composting Formulation Parameters

The final composting formulation parameters were formed from the results of the testing that was performed in the previous section and are listed below in Table 7. The physical dimensions of the compost reactors were given in Chapter III. Each reactor is capable of holding a total volume of five (5) liters. The sludge was very dense (like clay),

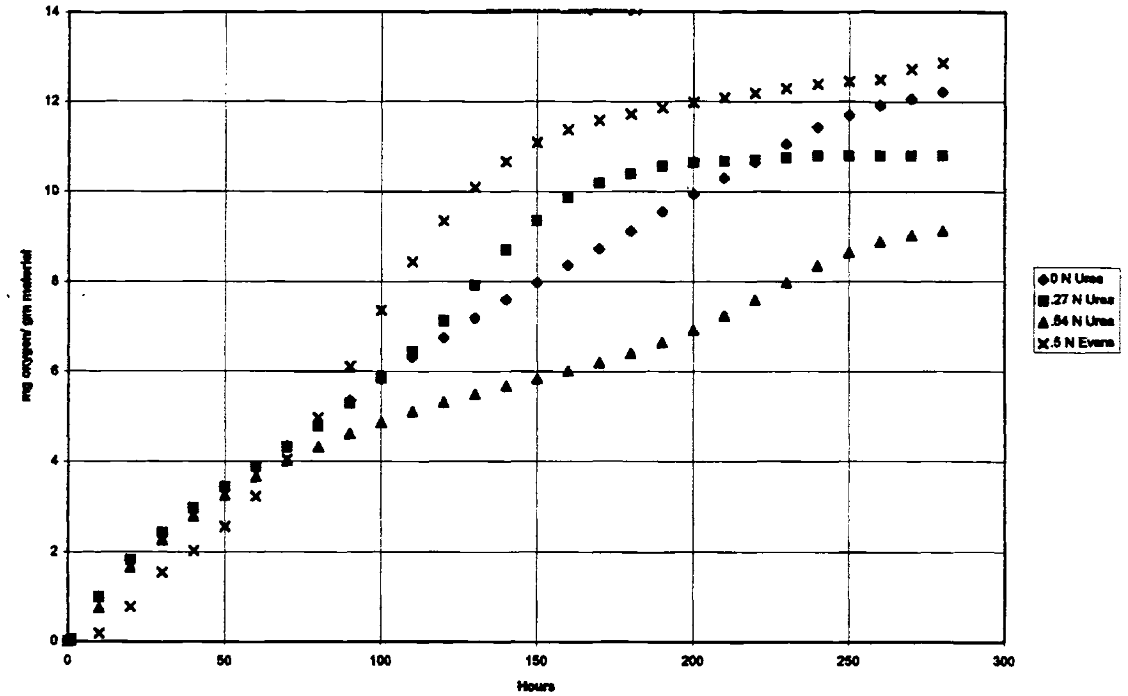


Figure 16. Average Cumulative BOD of 2:1 Straw and Sludge by Nutrient Addition. (Moisture = 80% of Container Capacity of Straw)

and the straw was very porous. When mixing the sludge with the nutrients dissolved in water and then with the straw, the mixture had a tendency to form clumps or sticky clods. To promote permeability, an attempt was made to keep the clumps as small as possible and only lightly tamp them into the reactors so as not to restrict air flow. Therefore the volume of compost placed in each reactor was approximately 4 liters. The compost for the biologically active series was mixed in three batches which were then mixed together in one larger batch prior to placement in the reactors. The compost for the sterile control series was handled in the same manner except for the addition of 2% mercuric chloride ($HgCl_2$). The reactors were weighed before and after the compost was placed inside so that an accurate accounting could be made of the compost mass and to ensure that all reactors had the same mass of compost + or - 1 gram. Every effort was made to ensure that all reactors experienced the same environment.

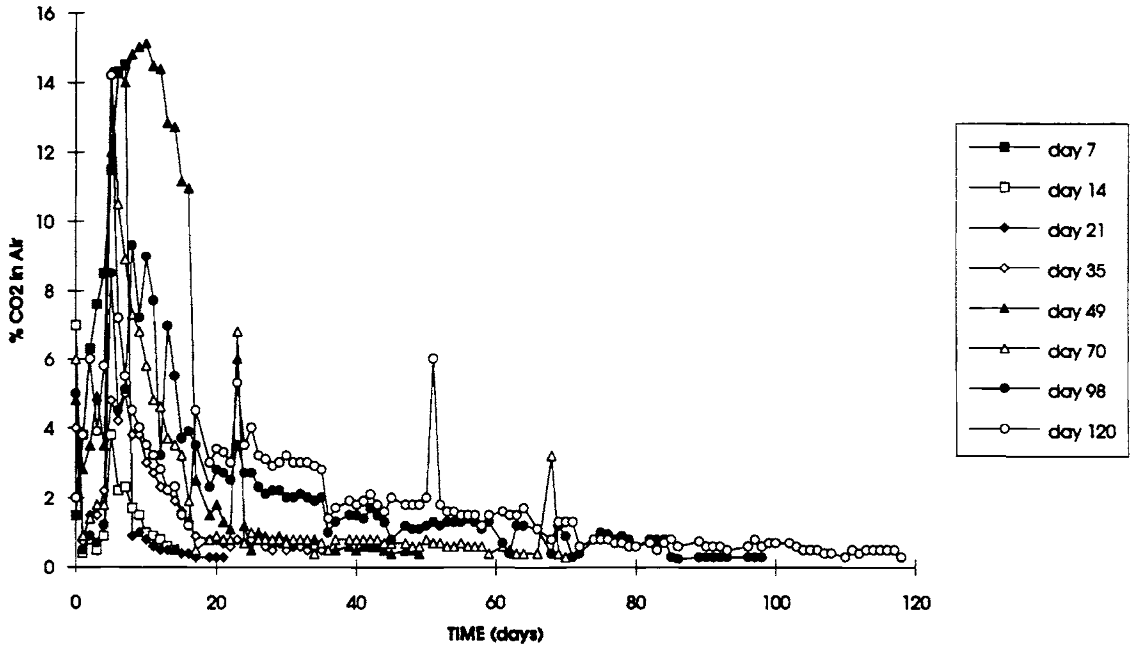
TABLE 7

COMPOSTING PARAMETERS OF PIT SLUDGE

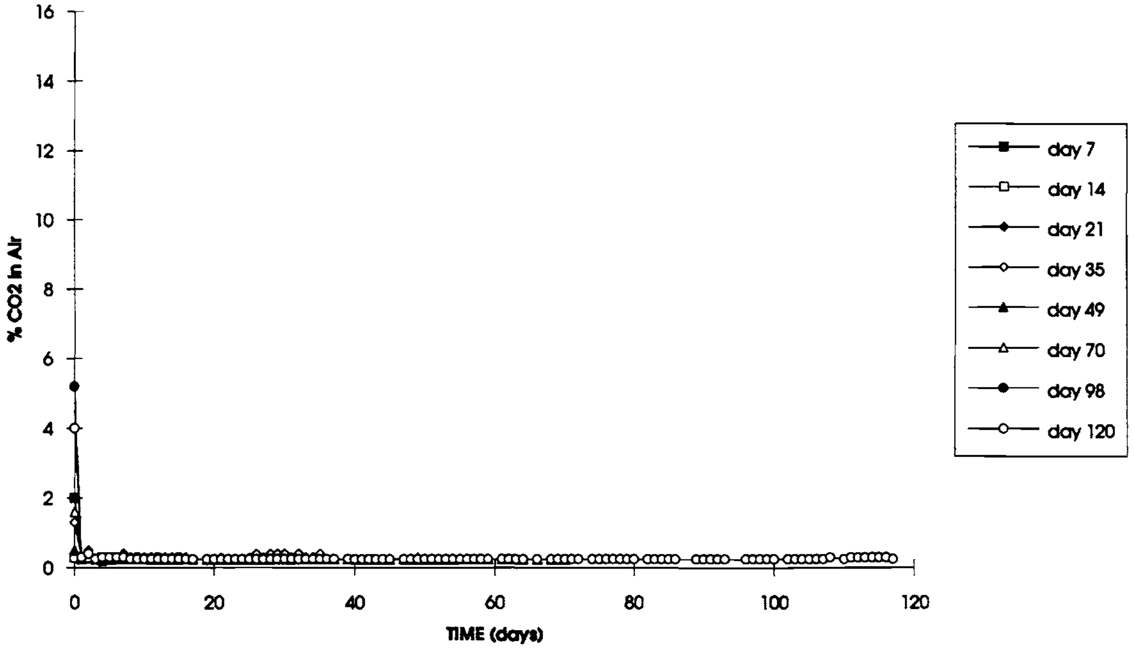
Volume	4 Liters
BA/S	2:1 by volume
Moisture content	38% by weight or 73% CC
Nutrient addition	
nitrogen (Urea)	0.25 Normality/H_2O content
phosphorus (P_2O_5)	4:1 as N:P ratio
Temperature	35°C (95°F)
Air Flow Rate	15 cm^3/hr (3/4 Pore Vol./hr.)

Production of CO_2 and VOCs

The production of CO_2 and VOCs was monitored on a daily basis with the readings being entered into a spreadsheet for tracking and computation purposes. Figure 17 is a set of graphs of these data. Reactors are identified according to the day they were taken off line for final sampling. The data are separated as to biologically active compost or sterilized control compost. Figure 17 (a) and (b) show the daily production of CO_2. Figure 17 (c) and (d) show the cumulative CO_2 produced over the testing time. In each of these sets it can be seen that the sterilized control compost produced virtually no CO_2 above the amount occurring naturally in air while the biologically active compost produces CO_2 in amounts up to 16% of air volume within the first 10 days before rapidly tapering off to almost nothing around 70 days after the start of the experiment. The CO_2 production of the reactors during the first 10 days ranged from 300 cm^3 of CO_2 to 2000 cm^3 of CO_2 per day with an average of 1170 cm^3 CO_2 per day. Between day 20 and day 40, the CO_2 production of the active reactors still in service ranged from 80 cm^3 CO_2 to 570 cm^3 CO_2 per day for an average rate of 265 cm^3 CO_2 per day. Figure 17 (e) and (f) show the cumulative VOCs produced by the composts and portray a pattern similar to that of the CO_2, except the control set indicates that the air is picking up a very small amount of volatile organics as it passes through the compost. VOCs accounted for less than 1% of the carbon removed from the compost.

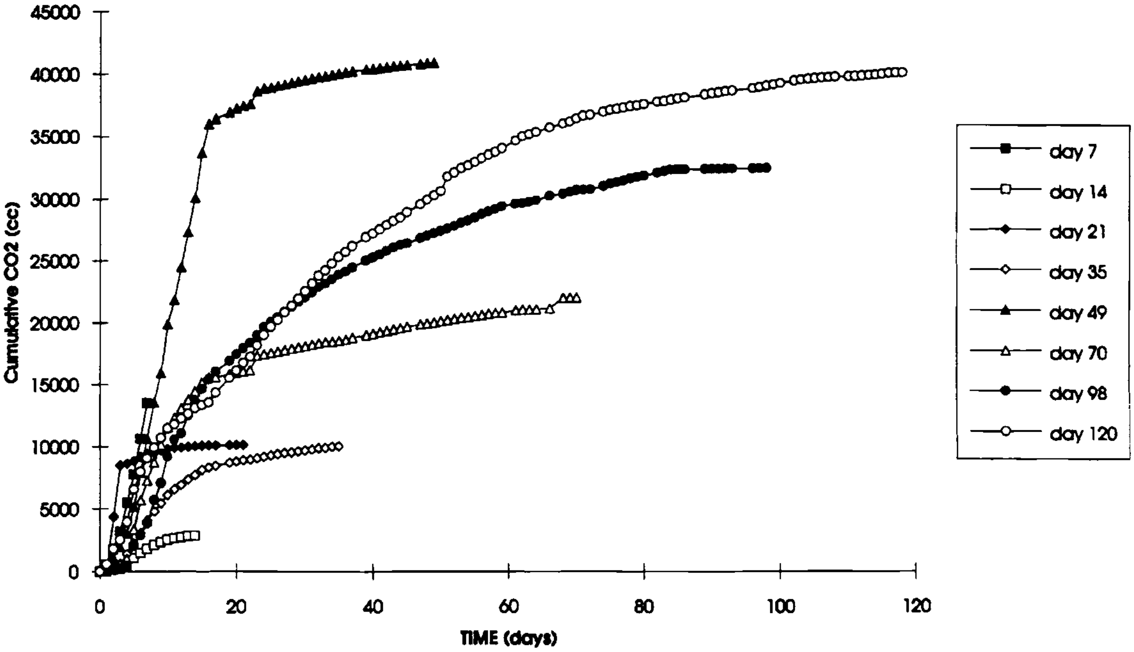


(a) Daily CO_2 Produced by Pit 82093 Compost (Active)

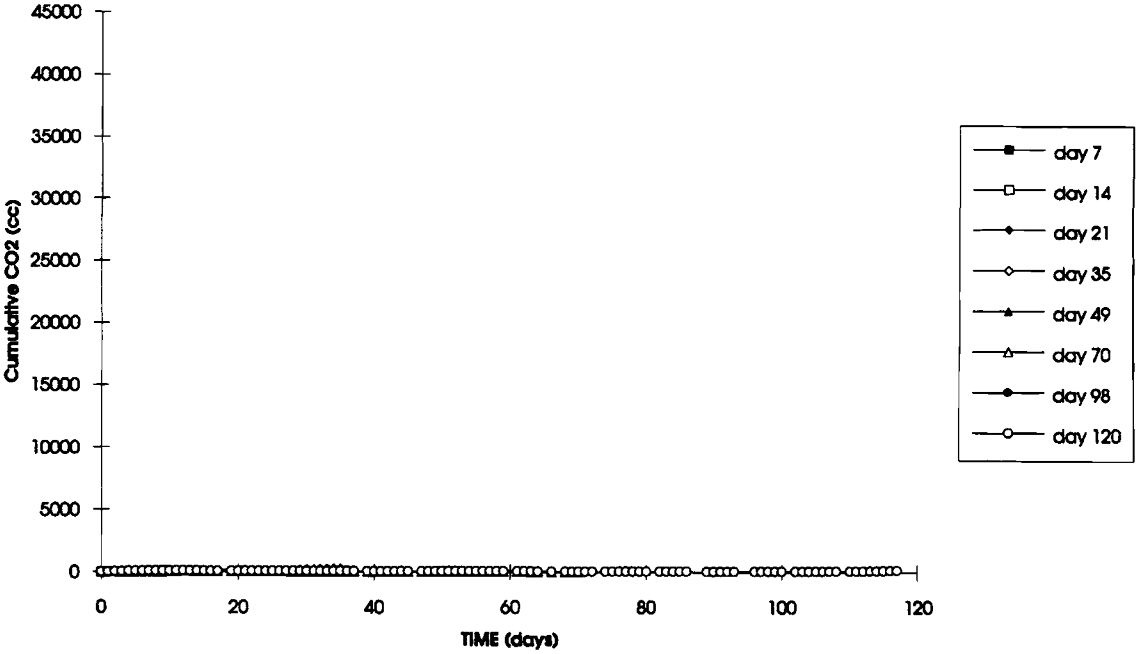


(b) Daily CO_2 Produced by Pit 82093 Compost (Control)

Figure 17. Daily and Cumulative CO_2 Production and Cumulative VOCs for Both Active and Control Compost Series.

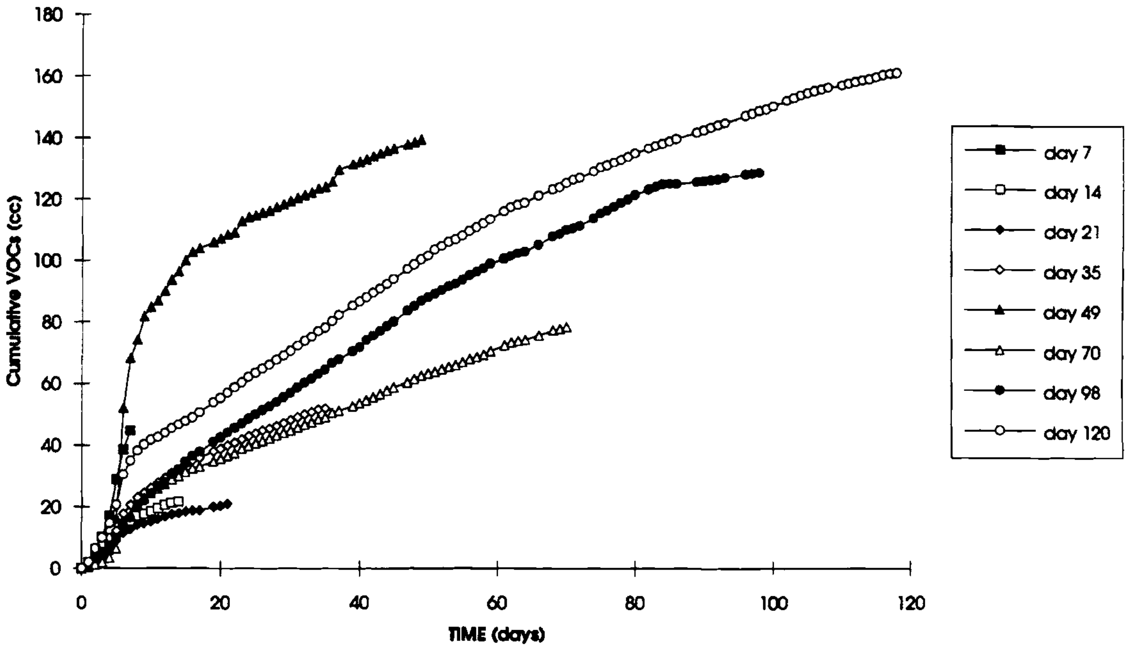


(c) Cumulative CO_2 of Pit 82093 Compost (Active)

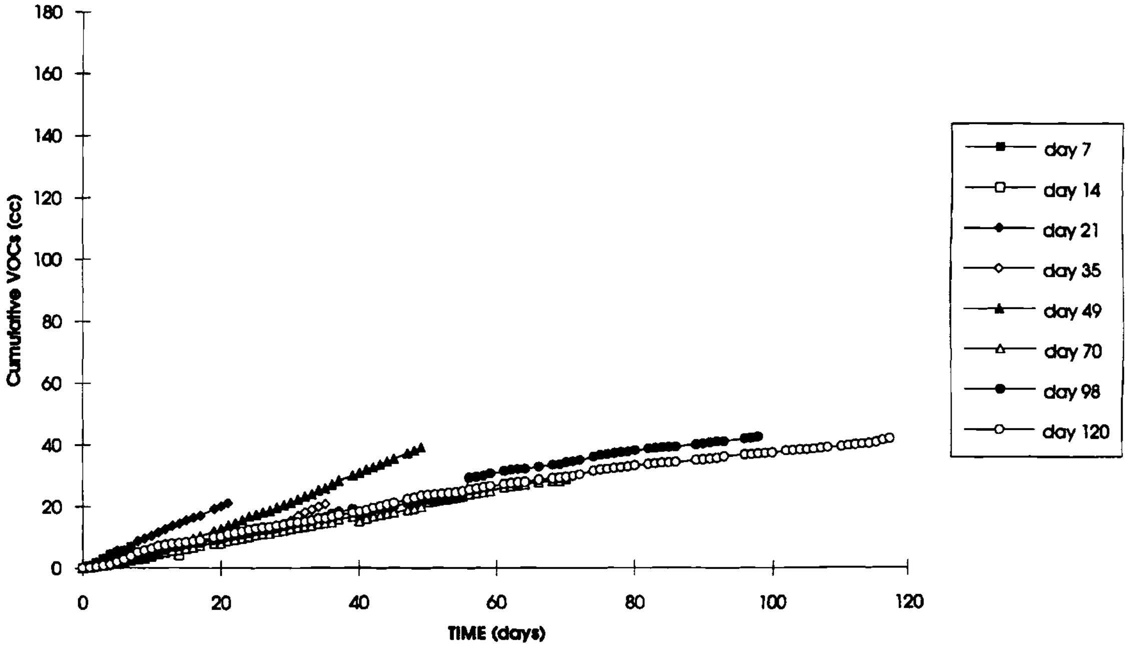


(d) Cumulative CO_2 of Pit 82093 Compost (Control)

Figure 17 (Cont'd). Daily and Cumulative CO_2 Production and Cumulative VOCs for Both Active and Control Compost Series.



(e) Cumulative VOC of Pit 82093 Compost (Active)



(f) Cumulative VOC of Pit 82093 Compost (Active)

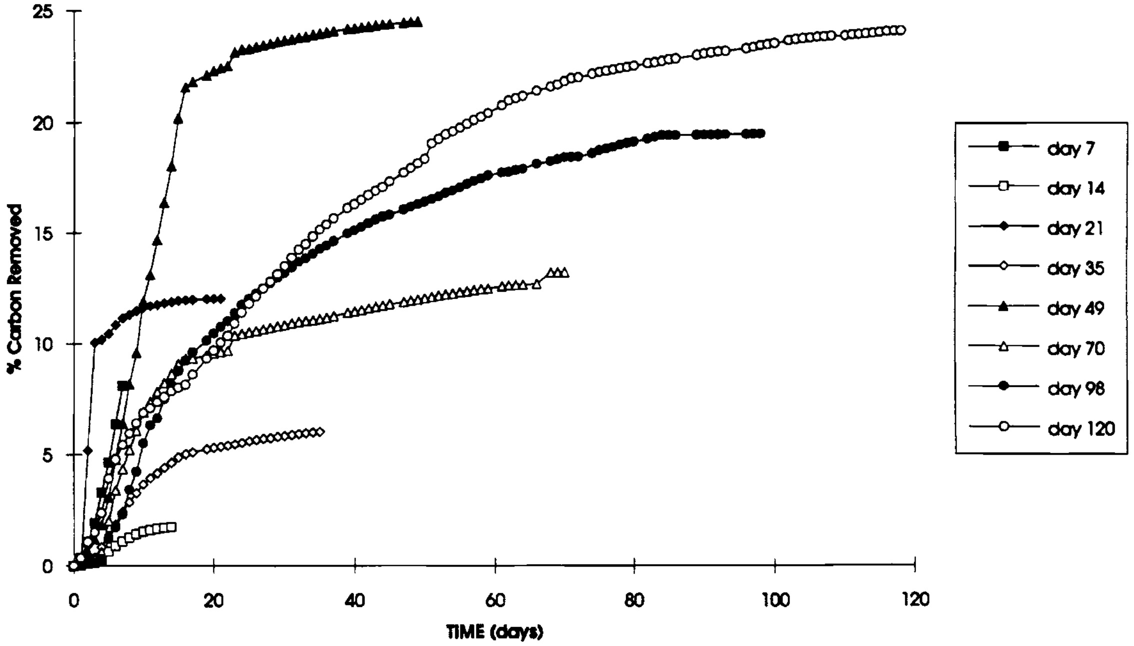
Figure 17 (Cont'd). Daily and Cumulative CO_2 Production and Cumulative VOCs for Both Active and Control Compost Series.

The amount of carbon that has been removed from the compost is shown in Figure 18. This is a calculated value from the monitoring data that were entered into the spreadsheet and is a percentage of the starting hydrocarbon concentration. Because the reactors were periodically withdrawn from the composting operation they cannot be compared to one another for end point performance. However, the CO_2 data that were compiled and plotted can indicate trends. From Figure 18 (a) it can be seen that the reactors did not all produce the same results even though every effort was made to keep the parameters identical. For easier reading, full page graphs have been included in Appendix H. Also included in the Appendix are prints of the spreadsheets for each reactor.

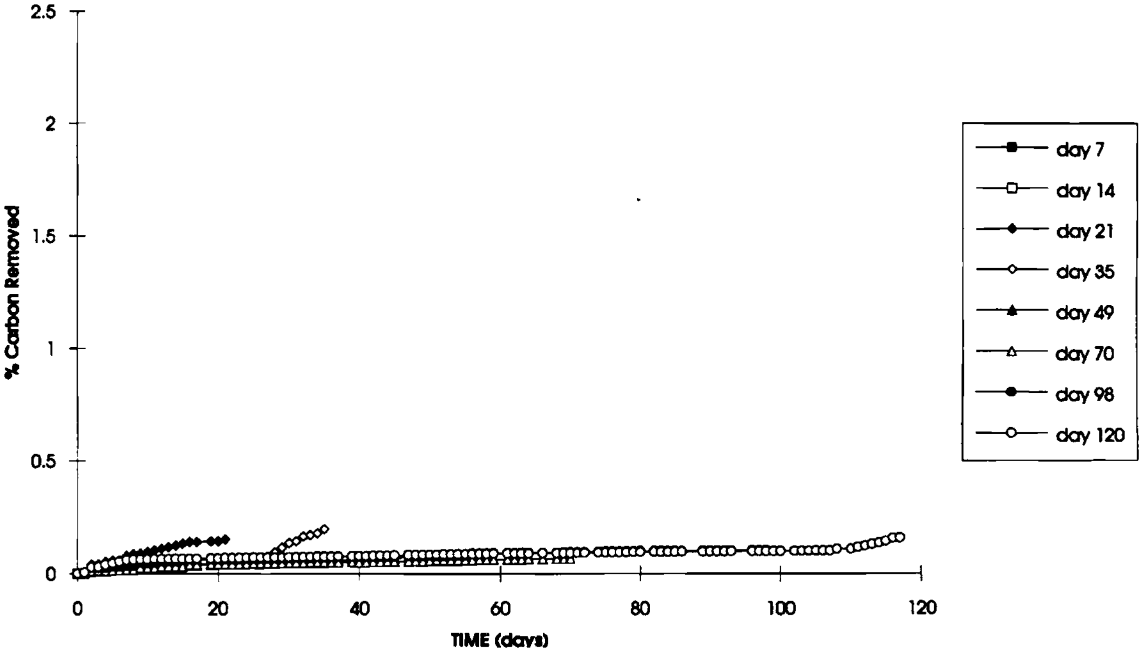
Moisture Content

Further investigation of the monitored parameters indicates that the one parameter that did not remain virtually the same for all reactors was the moisture content of the compost as recorded in the TDR readings. Figure 19 depicts the daily TDR moisture readings of each of the biologically active reactors. During the experiment water was added to any reactor that had a reading less than 50% of its day zero reading. Fluctuations in the TDR readings from start to end ranged from +20% to -79% (Table 8). Some reactors had patterns of wildly fluctuating moisture readings which may be an indication of channeling of air and moisture through the compost mixture within the reactor and in turn allowing dry areas within the compost. The reactor that maintained TDR readings above 8% also showed the higher % carbon reductions. This is significant because it shows the importance of controlling moisture content throughout the compost.

At the time that the compost was removed from the reactors, it was evident that the top portion of several of the reactors had dried out while the lowermost portion was sometimes very wet to the touch. The biologically active reactors had what appeared to be a white mold at the top of the reactor which increased in depth as the number of days in operation increased.



(a) % Carbon Removed from Pit 82093 Compost (Active)



(b) % Carbon Removed from Pit 82093 Compost (Control)

Figure 18. % Carbon Removed from (a) Biologically Active Compost and (b) Sterilized Control Compost as Calculated from Monitoring Data.

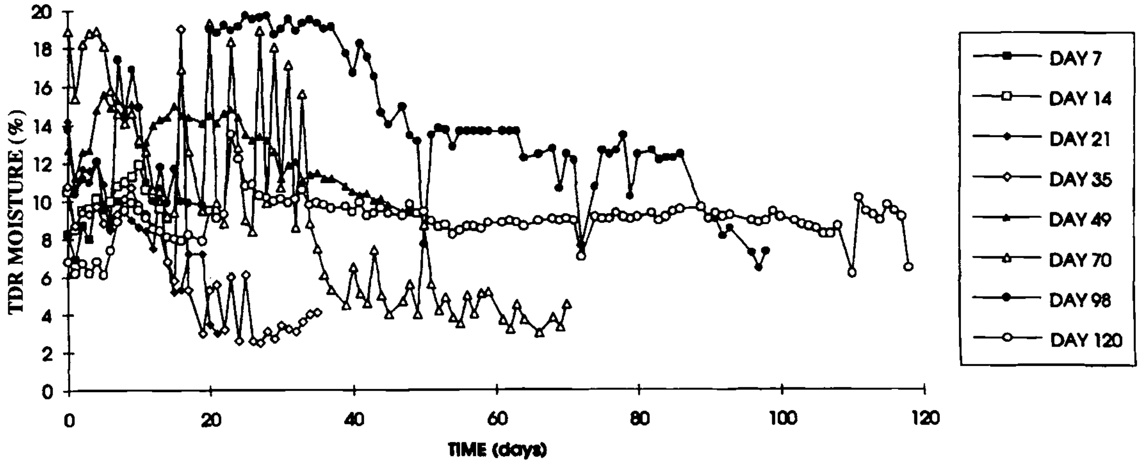


Figure 19. Daily Moisture Content of Pit 82093 Compost from TDR Reading.

TABLE 8

COMPARISON OF MOISTURE CONTENTS BY DENVER BALANCE AND TDR

	Denver Balance (wt%)			TDR (vol%)		
Series	Begin(%)	End (%)	% Change	Begin(%)	End (%)	% Change
Day 120	32.0	35.84	+12	6.8	6.4	-6
Day 98	32.0	33.55	+5	13.8	7.3	-47
Day 70	32.0	36.03	+13	18.0	4.5	-76
Day 49	32.0	36.70	+15	12.7	9.3	-27
Day 35	32.0	38.66	+21	10.8	4.1	-62
Day 21	32.0	39.50	+23	14.2	3.0	-79
Day 14	32.0	26.60	-17	10.5	9.1	-13
Day 7	32.0	30.50	-5	8.3	10.0	+20

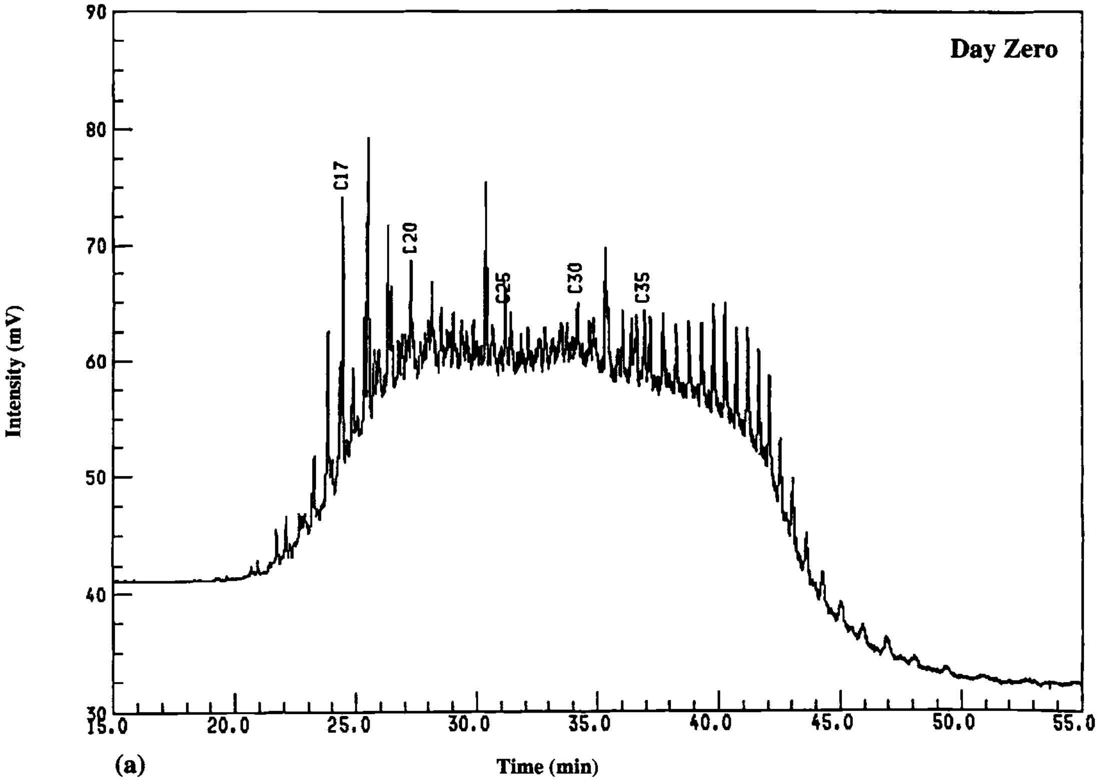
The moisture content was measured at the end of the run for each reactor with the Denver moisture balance. After the reactor contents had been emptied, the compost well mixed and sealed in a paint can and stored at 4°C for several days, sample containers were allowed to return to room temperature and opened. Samples were again well mixed, and two or three portions of the compost were analyzed in the Denver moisture balance. Changes in the starting to ending moisture contents of the composts ranged from +23% to -17%. As a point of interest, those reactors that showed the greater losses through the TDR readings and had the greatest amount of water added to them also had the highest Denver moisture balance readings. Table 8 is a compilation of the values determined through the Denver moisture balance and the TDR starting and ending readings. Fluctuations of the intermediate TDR readings are not considered in this table. The percent change in the moisture data for the TDR and Denver balance indicates that the reactors with the greatest TDR drops in moisture content, which had been given the greatest amount of added moisture, also had the greatest rise in moisture content as measured by the Denver balance. The conclusion that can be drawn from this information is that the moisture control problem is more one of distribution rather than total moisture content. An important fact to keep in mind when analyzing these data is that the TDR readings were taken from the compost in a static manner; the compost had not been turned or mixed so that there were dry and wet areas throughout the compost, while the Denver balance readings were from the compost after it had been well mixed and the available moisture evenly distributed. Relating this back to the CO_2 based calculated percent carbon removal shown in Figure 18, it may be postulated that the areas of the compost that became too wet or too dry were not conducive to the biodegradation of hydrocarbons in the soil. There is a close relationship between the time a reactor indicates a moisture problem and the time the CO_2 production dramatically decreases.

Reduction of Hydrocarbon

The reduction of hydrocarbon was also investigated through the methylene chloride extraction method described in Chapter III. Samples of the active and control composts were extracted and analyzed by GC analysis to establish a baseline concentration of hydrocarbons and a baseline hydrocarbon fingerprint that was used for comparison against the fingerprint of the aged compost.

Table 9 is a compilation of the extraction data for this compost. The first column defines the day the reactor was taken out of service and whether it was biologically active or a sterile control. The thimble label describes the position number of the reactor as it sat in the heater box and the sample that was taken from it. Three samples were taken from each reactor. The third column defines the moisture content of the compost as determined by the Denver moisture balance. The compost wet weight defines the sample mass of compost prior to mixing it with anhydrous magnesium sulfate which is used to sequester water. The extract weight is the gravimetrically determined mass of the extractable carbons remaining in the compost. The last column is an average of the three samples for each of the reactors. The TPH of the reactors which contained the sterilized control compost started at 3.67% and ranged between 2.67% and 4.01% with an average reading of 3.57%. The GC fingerprint identifies the concentration of the various carbon chains present in the compost at the time of the extraction as a percentage of the whole. Figure 20 shows the GC generated fingerprints of each reactor. Knowing the mass of compost that was extracted, the moisture content of that compost, the mass of the extract, and the fingerprint concentration of the carbon chains, another fingerprint was generated to illustrate the mass of hydrocarbon per mass of soil as a measure of the carbon number of the carbon chains within the compost. Individual fingerprints for each of the reactors are contained in Appendix I and a composite fingerprint of the initial active compost and the periodic composts is illustrated in Figure 21. Figure 21 is not normalized for detector response. In general, over time the hydrocarbons appear to be reduced with respect to length of carbon chain and mass of carbon in the soil, indicating that partial decomposition has taken place.

The extraction data for each of the compost reactors can be found in Appendix J and are summarized in Table 10 where they are also compared to the CO_2 based reduced hydrocarbon percentages. These averaged numbers are representative of the reactors that were removed from service on the day indicated. The percentages based on CO_2 production and extraction data do not follow the steadily increasing progression that was predicted. Nor does the extraction data correlate to the CO_2 data. The main factor in these varying results is that the CO_2 data represents complete decomposition to CO_2 and H_2O while the



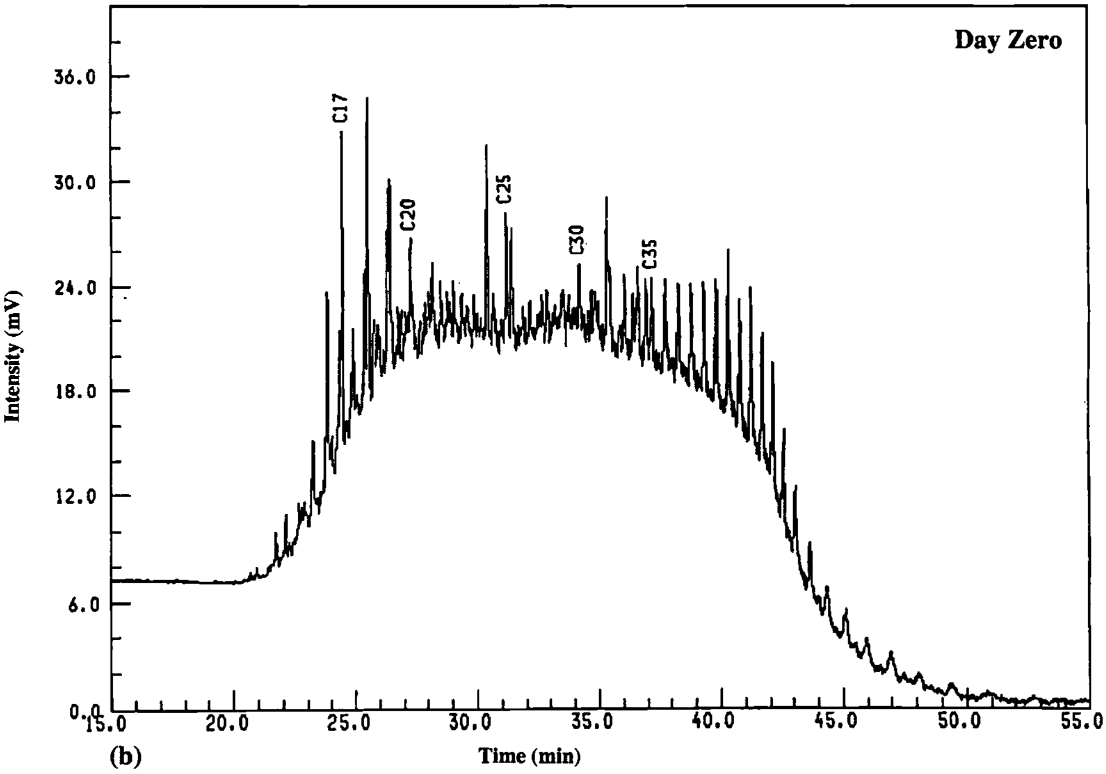


Figure 20. GC Generated Raw Fingerprints of P82093 Hydrocarbon Extract, (a) Active Baseline, (b) Sterile Control Baseline.

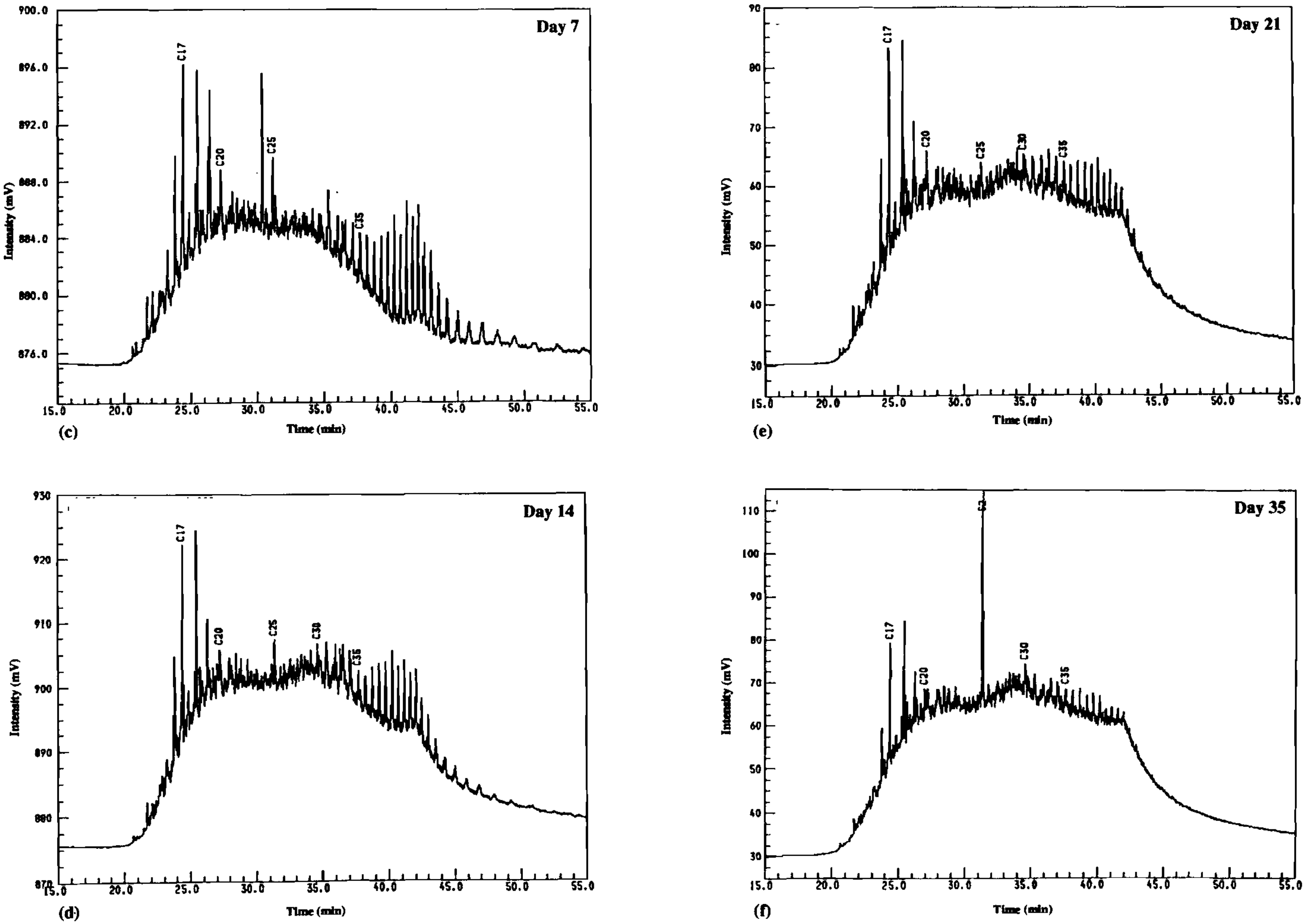


Figure 20 (Cont'd). (c) Active Day 7, (d) Active Day 14, (e) Active Day 21, (f) Active Day 35

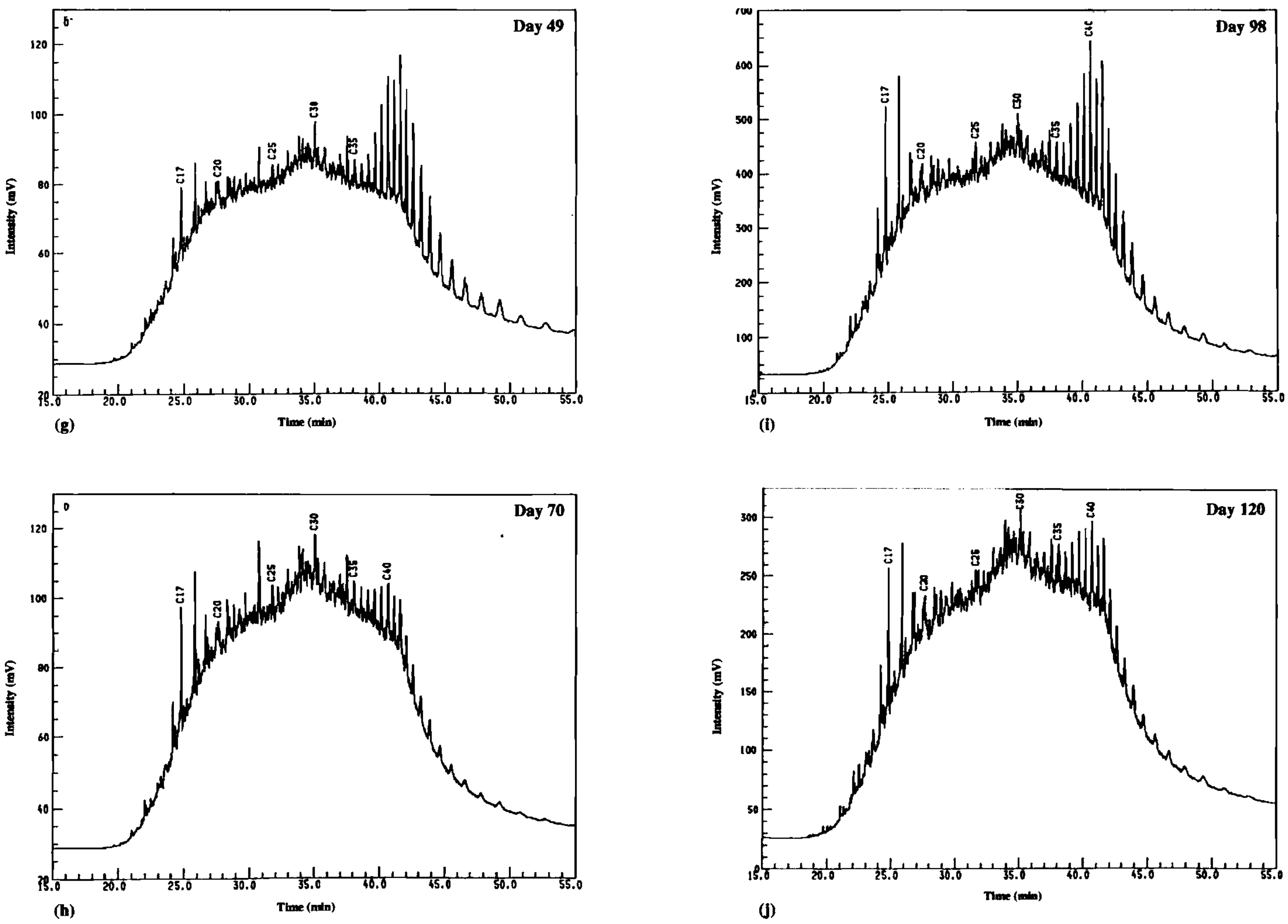


Figure 20 (Cont'd). (g) Active Day 49, (h) Active Day 70, (i) Active Day 98, (j) Active Day 120

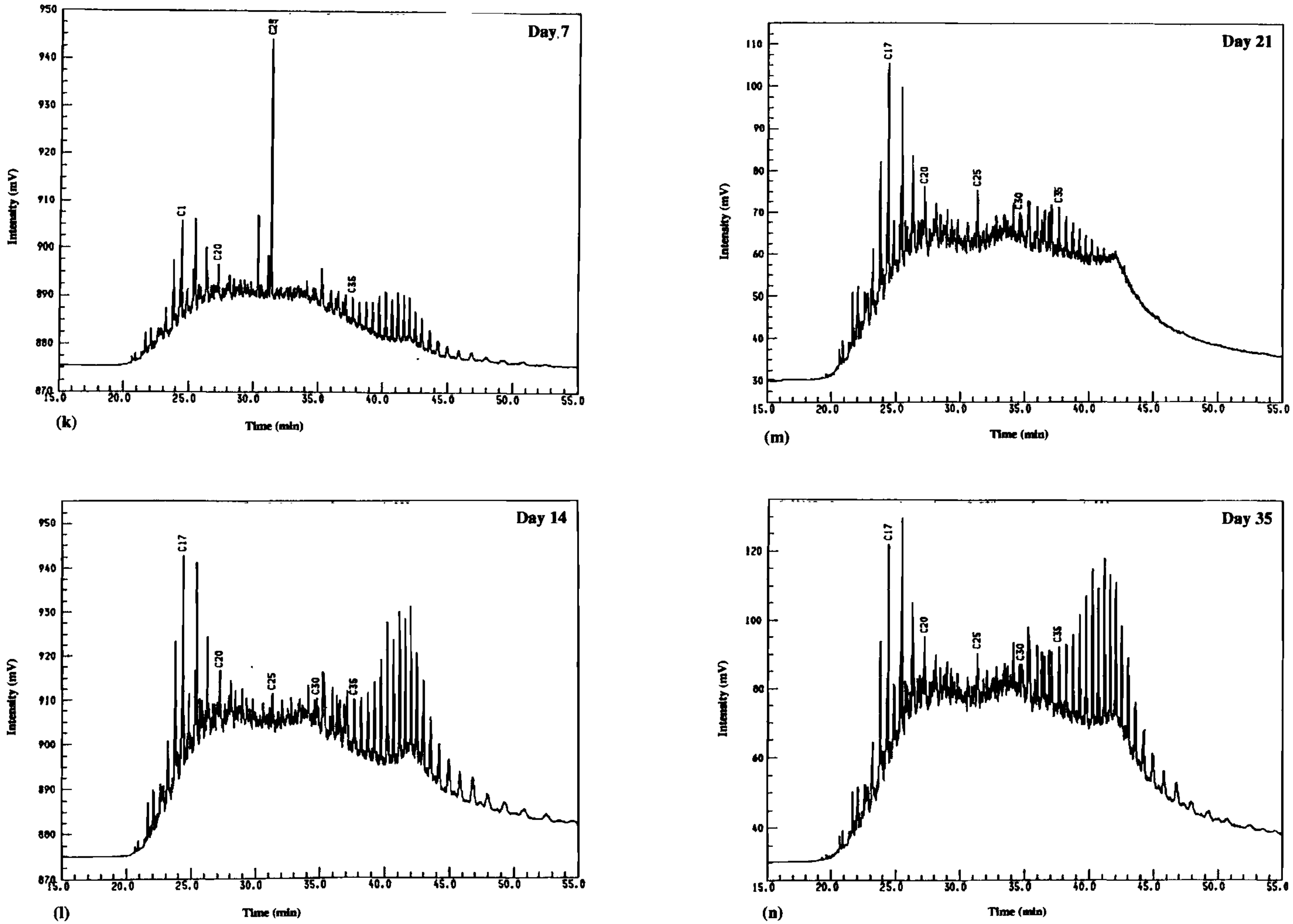


Figure 20 (Cont'd). (k) Control Day 7, (l) Control Day 14, (m) Control Day 21, (n) Control Day 35

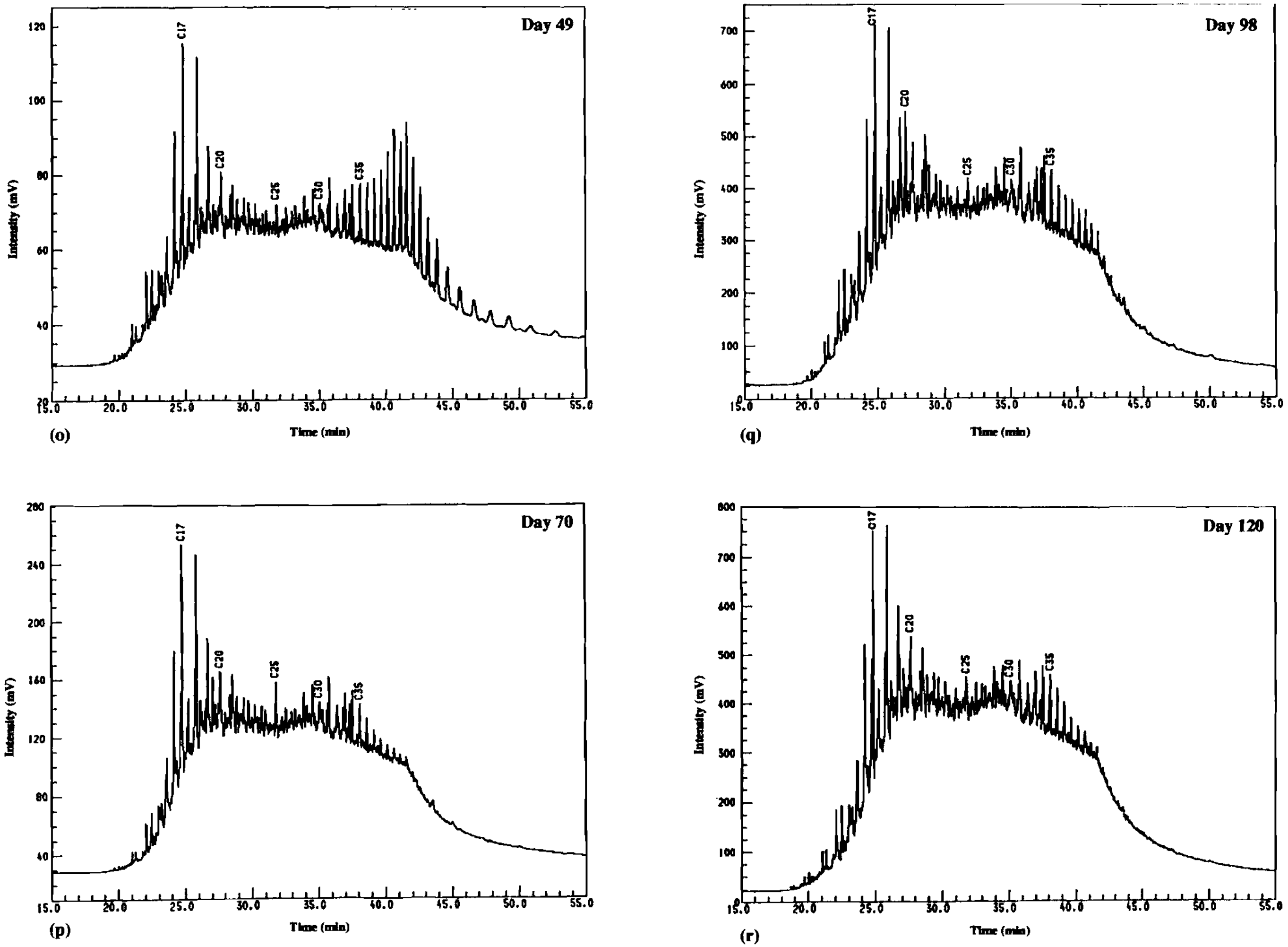


Figure 20 (Cont'd). (o) Control Day 49, (p) Control Day 70, (q) Control Day 98, (r) Control Day 120

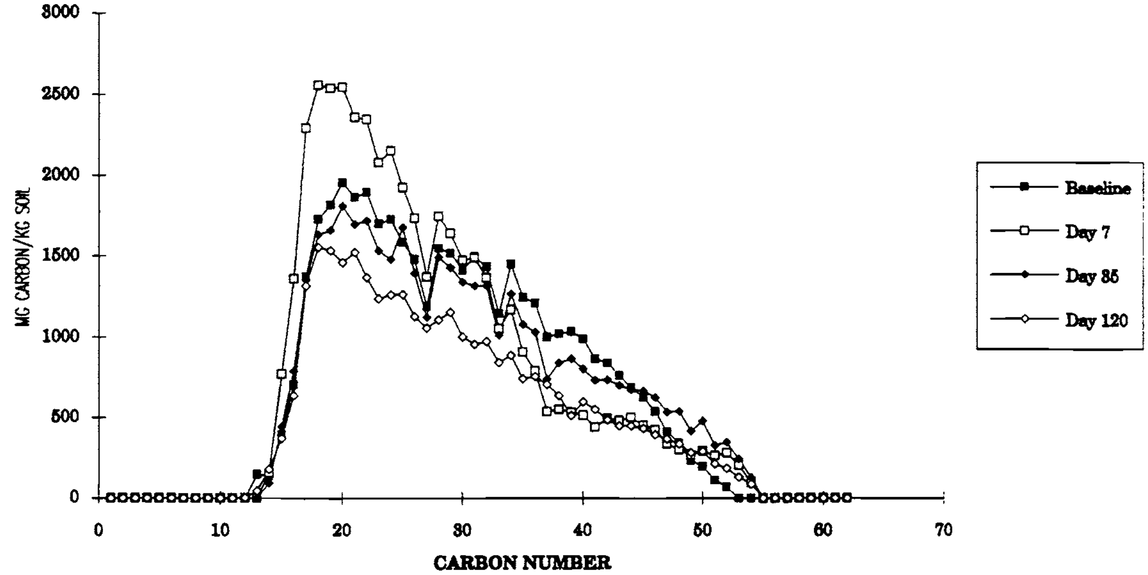


Figure 21. Aged GC Hydrocarbon Fingerprints of Pit 82093 Compost Extractions.

TABLE 9

TPH DATA FROM EXTRACTION OF AGED PIT SLUDGE COMPOST

Reactor #	Thimble Label	% Water	Compost Wet wt (gm)	Mix wt (gm)	Extract wt (gm)	Compost Dry wt (gm)	% Oil (Dry wt)	% Oil (Dry Inerts)	Avg. % Oil (Dry Inerts)
Baseline A	A1	30.36	1.76	17.42	0.0428	1.23	3.48	3.61	3.56
Baseline A	A2	30.36	1.65	16.32	0.0408	1.15	3.55	3.68	
Baseline A	A3	30.36	1.8	17.85	0.0411	1.25	3.29	3.4	
Baseline C	C1	34.31	2.52	24.98	0.0555	1.66	3.34	3.46	3.67
Baseline C	C2	34.31	2.52	24.97	0.0608	1.66	3.66	3.8	
Baseline C	C3	34.31	2.6	25.78	0.0619	1.71	3.62	3.76	
7 - Active	15-1	30.565	2.04	20.25	0.051	1.42	3.59	3.73	3.8
7 - Active	15-2	30.565	2.1	20.82	0.0536	1.46	3.67	3.81	
7 - Active	15-3	30.565	2.1	20.81	0.0544	1.46	3.73	3.87	
7 - Control	16-1	30.83	2.15	21.26	0.056	1.49	3.76	3.91	3.89
7 - Control	16-2	30.83	2.17	21.5	0.0554	1.5	3.69	3.83	
7 - Control	16-3	30.83	2.12	20.99	0.0555	1.47	3.78	3.92	
14 - Active	R1A	26.575	8.3	24.6	0.0725	6.09	1.19	1.2	2.5
14 - Active	R1B	26.575	8.33	24.68	0.1999	6.12	3.27	3.37	
14 - Active	R1C	26.575	8.52	25.24	0.1778	6.26	2.84	2.92	
14 - Control	R2A	27.325	8.65	24.95	0.2335	6.29	3.71	3.86	3.89
14 - Control	R2B	27.325	8.6	24.83	0.235	6.25	3.76	3.91	
14 - Control	R2C	27.325	8.61	24.85	0.2347	6.26	3.75	3.9	

TABLE 9 (CONTINUED)

TPH DATA FROM EXTRACTION OF AGED PIT SLUDGE COMPOST

Reactor #	Thimble Label	% Water	Compost Wet wt (gm)	Mix wt (gm)	Extract wt (gm)	Compost Dry wt (gm)	% Oil (Dry wt)	% Oil (Dry Inerts)	Avg. % Oil (Dry Inerts)
21 - Active	3A	39.505	8.71	25.83	0.2006	5.27	3.81	3.96	3.69
21 - Active	3B	39.505	8.52	25.26	0.1827	5.15	3.55	3.68	
21 - Active	3C	39.505	8.04	23.83	0.1609	4.86	3.31	3.42	
21 - Control	4A	27.235	8.62	25.42	0.21	6.27	3.35	3.47	3.56
21 - Control	4B	27.235	8.93	26.34	0.2337	6.5	3.6	3.73	
21 - Control	4C	27.235	8.47	25	0.2072	6.16	3.36	3.48	
35 - Active	5A	38.66	11.06	32.75	0.2459	6.78	3.63	3.76	3.88
35 - Active	5B	38.66	10.57	31.29	0.2581	6.48	3.98	4.15	
35 - Active	5C	38.66	8.67	25.66	0.1916	5.32	3.6	3.74	
35 - Control	6A	21.93	10.92	25.92	0.2203	8.53	2.58	2.65	2.67
35 - Control	6B	21.93	10.37	24.62	0.2277	8.1	2.81	2.89	
35 - Control	6C	21.93	10.44	24.8	0.1968	8.15	2.41	2.47	
49 - Active	11A	36.77	10.03	29.99	0.2301	6.34	3.63	3.77	3.7
49 - Active	11B	36.77	9.91	29.62	0.2098	6.27	3.35	3.46	
49 - Active	11C	36.77	10.07	30.12	0.2376	6.37	3.73	3.87	
49 - Control	14A	33.38	10.37	30.04	0.2638	6.91	3.82	3.97	4.01
49 - Control	14B	33.38	9.64	27.92	0.271	6.42	4.22	4.41	
49 - Control	14C	33.38	10.34	29.95	0.242	6.89	3.51	3.64	
70 - Active	9A	35.98	10.09	30.03	0.1767	6.46	2.74	2.81	2.82
70 - Active	9B	35.98	10.08	29.99	0.1849	6.45	2.87	2.95	
70 - Active	9C	35.98	10.51	31.26	0.1767	6.73	2.63	2.7	
70 - Control	10A	19.96	9.84	29.44	0.2673	7.88	3.39	3.51	3.45
70 - Control	10B	19.96	9.86	29.48	0.2655	7.89	3.37	3.48	
70 - Control	10C	19.96	9.66	28.9	0.2513	7.73	3.25	3.36	
98 - Active	7A	33.55	9.97	29.71	0.1645	6.63	2.48	2.54	2.88
98 - Active	7B	33.55	10.08	30.02	0.1953	6.7	2.91	3	
98 - Active	7C	33.55	9.8	29.19	0.195	6.51	3	3.09	
98 - Control	8A	20.69	9.73	28.85	0.2153	7.72	2.79	2.87	3.08
98 - Control	8B	20.69	9.84	29.16	0.2333	7.8	2.99	3.08	
98 - Control	8C	20.69	10.38	30.79	0.2612	8.23	3.17	3.28	
120 - Active	13A	33.57	8.41	25.12	0.1577	5.59	2.82	2.9	2.81
120 - Active	13B	33.57	8.44	25.2	0.1583	5.61	2.82	2.9	
120 - Active	13C	33.57	8.34	24.92	0.1417	5.54	2.56	2.62	
120 - Control	12A	27.77	8.42	25.18	0.2475	6.08	4.07	4.24	3.94
120 - Control	12B	27.77	8.38	25.05	0.2318	6.05	3.83	3.98	
120 - Control	12C	27.77	8.37	25.04	0.2096	6.05	3.46	3.59	

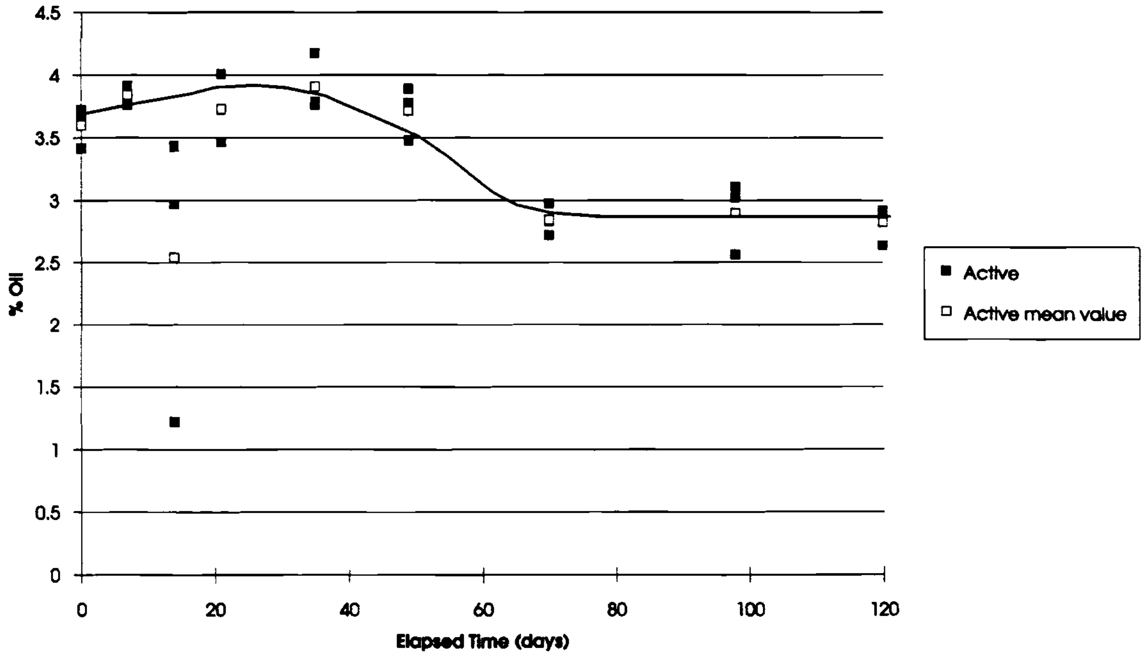
extraction data analysis with GC can give indication of partial decomposition which does not release CO_2. Mixing affects the distribution of nutrients which are necessary for increased activity of the microorganisms, which will in turn digest the hydrocarbons and release them as CO_2 and water. In heavy clayey soils, such as this, mixing is also crucial to the even distribution of the hydrocarbon and moisture. Clay type soils have a tendency to bind hydrocarbons inside the soil matrix and therefore make them unavailable for bioremediation.

TABLE 10

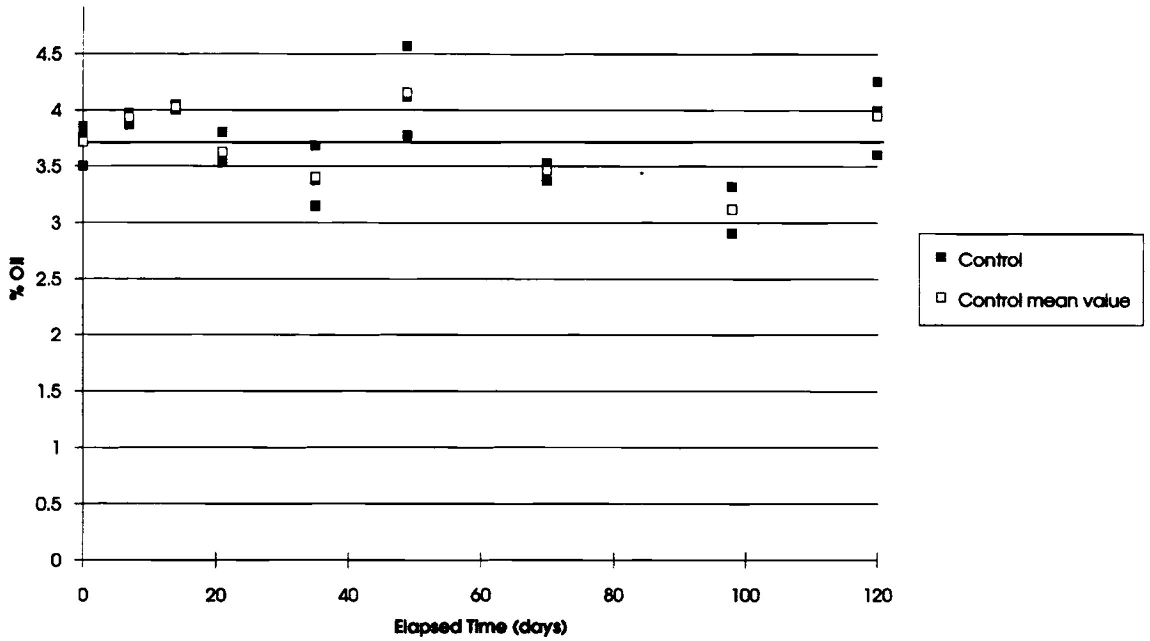
COMPARISON OF EXTRACTION VALUES TO MONITORING VALUES AS RELATED TO HYDROCARBON REDUCTION IN COMPOSTING

Elapsed Time (Days)	% Carbon Removed by Extraction	% Carbon Removed Based on CO_2 Production
7	0.00	8.089
14	24.24	1.745
21	8.88	12.029
35	2.92	6.017
49	4.57	24.500
70	25.76	13.206
98	21.32	19.498
120	42.39	24.108

The extraction data are graphically illustrated in Figure 22 where each of the individual samples and their average value are seen as the compost percentage of hydrocarbon remaining in the compost material. In Figure 22 (c), the average values can be compared between the biologically active compost and the sterilized control compost. Extraction values between active and control reactors are difficult to compare because they originated in two separately mixed batches. Additionally, they are taken out of service sequentially with no simultaneous sampling of all reactors for extractions.

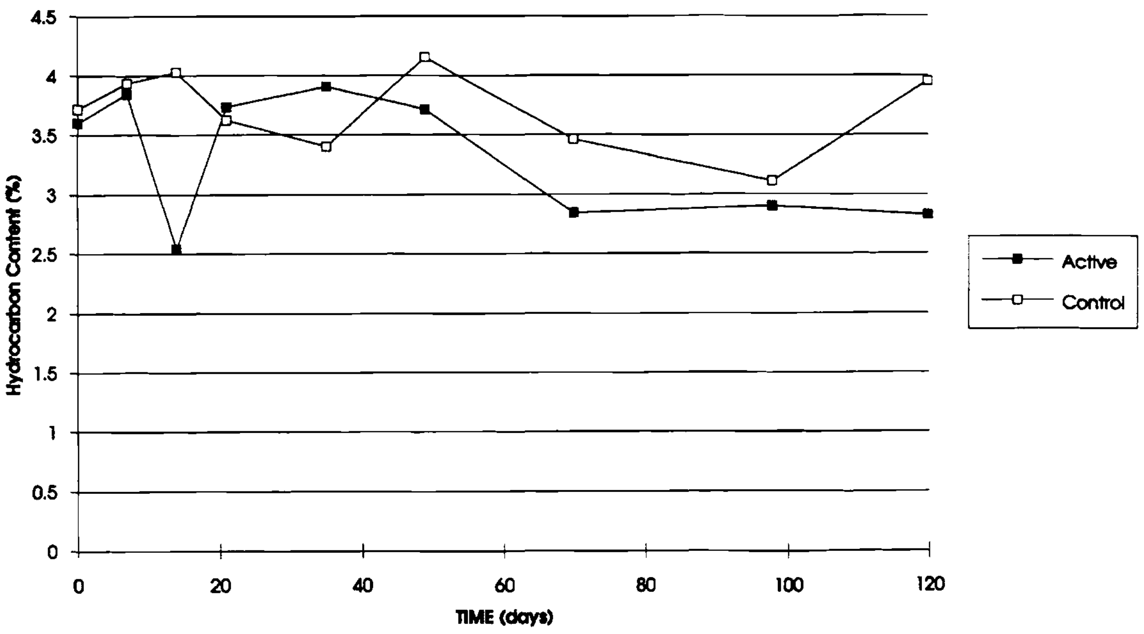


(a) P82093 Aged Active Compost - % Oil (Dry Inerts Basis)



(b) P82093 Aged Control Compost - % Oil (Dry Inerts Basis)

Figure 22. Percent Hydrocarbon in Extracted Aged Pit 82093 Compost.



(c) Average Hydrocarbon Content of Aged Pit 82093 Compost (Dry Inerts Basis)

Figure 22 (Cont'd). Percent Hydrocarbon in Extracted Aged Pit 82093 Compost.

When each set of reactors had run its allotted time, the compost was tested for pH, nitrogen, phosphorus, and moisture content. Table 11 lists these values along with the percent carbon reduction for evaluation purposes.

TABLE 11

pH, NH_3-N, PHOSPHORUS AND MOISTURE CONTENT OF COMPOST

Elapsed Time (Days)	Active					Control			
	- % C	pH	NH_3 mg/l	P mg/l	% H_2O	pH	NH_3 mg/l	P mg/l	% H_2O
7	8.1	7.43	197	115	30.56	6.44	96	148	30.83
14	1.7	8.10	154	110	26.60	6.71	29	129	27.33
21	12	8.15	111	1085	30.60	7.29	4	716	27.23
35	6.0	8.05	180	356	38.66	8.06	188	281	26.58
49	24	7.55	128	937	36.77	8.57	402	545	33.38
70	13	7.94	98	150	35.98	6.78	49.5	335	19.96
98	19	7.87	166	250	33.55	7.06	77.5	298	20.67
120	24	7.17	50	167	27.77	7.83	157	202	33.57

It is generally accepted that a pH between 6 and 8 is conducive to biodegradation. As can be seen in Table 11, most of the 100 gram grab samples of the compost tested within this range. An effort was made to keep the moisture content around 30%. These values are not far off the mark, but they are also values obtained after the compost was remixed and allowed to sit long enough to redistribute the moisture that was present. It does not allow for the wet and dry areas as they existed within the reactors.

To calculate the time required to reach a 1% contamination threshold recommended by the API Environmental Guidance Document for land disposal, the data generated by the monitoring of CO_2 production was used. The carbon reduction rate calculated was 0.15×10^{-4} gm carbon/gm compost•d, which gives an end point time of over 1000 days for this sludge under these plug flow conditions.

The companion pilot scale study conducted by Dan Denham investigated two composting methods. A static pile, which is similar to the plug flow of the bench scale reactors, and a window which is turned periodically. In his study, Denham states that the total organic carbon (TOC) in the two piles showed essentially no change and suggests that the biodegradation of petroleum hydrocarbons resulted in the formation of cellular biomass and polar compounds. The carbon reduction reported by Denham was 8 wt% for the static pile and 20% for the window over the 121 day pilot test period. He reported half-lives for the hydrocarbons of these systems as 4 years and 1 year, respectively. Because all of these calculated remediation times are more than a year, they are not likely to be economically feasible.

CHAPTER V

CONCLUSIONS

Bioremediation of Hydrocarbon Contaminated Soils Through Composting

This study suggests that the biodegradation of aged crude oil sludges by means of composting may not be practical due to low rates of biodegradation. The economic aspects of such a project are unattractive due to the length of time that would be required to reach the regulated endpoint of hydrocarbon contaminated soils. The best reduction of hydrocarbons over the 120 day experiment approached 25% by weight for the 4% hydrocarbon concentration compost and 18% by weight for the 21% hydrocarbon concentration compost. These systems would require at least a year to remediate.

Respirometry is not a comprehensive evaluation tool for determining the best parameters for the removal of hydrocarbons. It is a short-term technique that cannot estimate the hydrocarbon degradation kinetics and degradation endpoints. It relies solely on CO_2 evolution (or O_2 consumption) as a means of monitoring biological activity and does not directly evaluate hydrocarbon degradation. For hydrocarbon degradation to be correctly optimized using only respirometry, the ratio of hydrocarbon mineralized (i.e., converted to CO_2) to that converted to biomass would have to remain insensitive to changes in process parameters. The experiments conducted with the Farmington sludge show this not to be the case. Incomplete hydrocarbon degradation can be substantial when evaluated with extractive techniques such as those used in this study. If the goal were to adjust compost parameters to favor complete mineralization of hydrocarbons, then respirometry would be useful in correctly identifying those parameters.

CO_2 production, as reported in Table 5, was found to be a true indicator of "complete" hydrocarbon reduction in these experiments. However, monitoring CO_2 production will not reflect the carbon that is converted to biomass or to partially oxidized intermediates.

Bench scale studies performed better than the pilot scale studies performed in Phase III of this project (Denham, 1994) by 100 percent. The pilot study reported hydrocarbon reduction of 8% for the static pile, which is similar to the closed reactor, and 20% for the windrow using the extraction method of analysis. This study reports 24% reduction in hydrocarbon by CO_2 production and 42% reduction by extraction method. The ability to exert better control of temperature and moisture in the closed reactor produced much greater reduction in hydrocarbon concentrations than the pilot scale field applications tested in the Denham study. Therefore, if a time scale is to be projected from bench to field it would have to be multiplied by at least two based on these results.

Discussion of Conclusions

The X-ray diffraction mineralogy analysis conducted on the production pit sludge feedstock revealed that the soil consisted of about 30% clays with a large fraction composed of highly swelling and exchangeable smectite. Soils with a high clay content are highly adsorptive and may inhibit bioremediation of petroleum hydrocarbons by trapping the hydrocarbons inside the clay structures. Consequently, hydrocarbons that can be solvent extracted may not be as readily available to microorganisms for biodegradation if they are trapped in the solids matrix.

While temperature and air flow rates were consistent among the reactors, control of moisture content was perceived to be a major problem throughout the test period. In actuality, the moisture problem was one of distribution rather than total moisture content. TDR monitoring indicated that several of the reactors were losing moisture, and additional moisture was added in response to those readings. As the reactors were opened at the end of their respective run times, it was observed that the compost at the inlet end of the reactors was very dry while the compost at the exit end was very wet. It can be postulated that a lower saturated air flowrate could still supply adequate oxygen for microbial activity without displacing the needed moisture.

The addition of straw and chemical nutrients to a petroleum sludge based compost induces increased activity in the microbial community. The compost of sludge and straw will generally self heat, but the addition of chemical fertilizer is an inexpensive insurance policy by providing a guaranteed nutrient source for the microbes. This study had only the initial addition of nutrients and reached its peak CO_2 production within 14 days after which it tapered off dramatically. Periodic nutrient additions were not utilized so that a least maintenance method could be tested.

Homogeneity in the compost requires a great deal of effort and the use of mechanical mixing equipment. Homogeneity through thorough mixing will not only reduce hot spots but by providing even distribution of the hydrocarbons, will promote more complete bioremediation in a shorter period of time. Sampling results should also be more consistent.

Data gathered through the monitoring of CO_2 appear to be more reproducible than that garnered from extraction of grab samples which may not be representative of the system as a whole. However, while CO_2 evolution was found to be an indicator of complete decomposition, GC analysis of the residue procured through extractions indicated that partial mineralization of the hydrocarbons to biomass was also taking place. The use of small volume reactors (four liter, forced air reactors) to investigate the feasibility of a compost formulation and estimate the time required to reach a satisfactory endpoint cannot be relied upon completely but can be used to determine a best estimate. It can also indicate parameters that will give optimum initial conditions to stimulate microbial activity.

Scaling up from the respirometry study to the bench scale study is not possible because the microbial activity rate changes over time. In this case, the respirometry tests were run only for two weeks and the bench scale tests for 13 to 17 weeks. Only the first two weeks of these studies have the possibility of being similar.

It is also difficult to scale up from the bench scale studies to pilot scale studies even though they have equal run times. This is because the systems experience different operating parameters. The forced air plug flow reactors are a closed controlled system while the pilot scale static pile and windrow systems are open to the atmosphere.

Recommendations

The selection and design of a bioremediation system requires careful planning. The choice of an appropriate technology must be based on the assets of the facility in question, the targeted contaminants requiring action levels, the resistance of the contaminant to being degraded within its medium, and the time span required to reach satisfactory bioremediation levels. Laboratory tests are a valuable tool in determining the characteristics of the contaminant with respect to volatility, hydrocarbon distribution, background matrix and the degree of weathering of the targeted sludge. When choosing bioremediation to eliminate hydrocarbon contamination, tests should be conducted that include respirometry, investigation of mixing ratios, concentration of nutrient additions, moisture contents, and extraction. Once the parameters have been narrowed and the formulations chosen for further study, careful attention should be paid to the methods that will be used to analyze the progress and end results of the bioremediation. Extraction methods should be used to get an accurate evaluation of the hydrocarbon in a complex sludge system. Because of the high variability of a high solids system, it is necessary to find a balance between the number of samples that will be analyzed and the associated costs.

Since moisture distribution was observed to be a problem with the bench scale reactors when they were opened, it is recommended that reactors be designed that distribute the moisture evenly throughout the compost. As was discussed earlier, moisture measurements within the reactors were not a true indicator of the amount of water in the system. A monitoring system that would monitor the top, middle and bottom of the compost separately would give a better indication of moisture distribution and in turn provide the information required to address the problem of moisture distribution control.

Finally, addressing the question of scale up from lab to field: to achieve a better correlation between lab and field, the lab parameters should mirror the field parameters as closely as possible. Since the field scale composting system would be open to the atmosphere, the lab compost system should also be operated as an open system. A simulated windrow, static pile or land farm could be constructed using identical compost formulas determined by respirometric studies. CO_2/O_2 monitoring could be combined with an extraction method of hydrocarbon evaluation to monitor progress. Periodic addition of a nutrient solution might enable the microbial population to continue elevated levels of activity which would hopefully shorten bioremediation time requirements. Using identical methods in the lab that would be used in full scale field work should improve scale-up correlations.

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Appendix A: Soxtec Extraction Procedure

SOXTEC EXTRACTION PROCEDURE

A known amount of sample by weight is mixed with a known amount of Diatomaceous Earth (DE) or other water holding material in order to remove moisture from the sample. The ratio of sample to DE might vary depending on the moisture content of the sample.

The mixed sample is ground using mortar and pestle to obtain a homogeneous sample.

A known amount of the mixed sample is weighed into the extraction thimble and a known weight of methylene chloride (preferably 40-50 grams) is used as solvent.

The extraction in the Soxtec Extractor is done in two steps.

(i) boiling phase
(ii) rinsing phase

In order to achieve optimum extraction, aliquots of mixed sample can be extracted either with constant boiling time and varying rinsing time or with constant rinsing time and varying the boiling time.

After the extraction, the extract in the solvent cup is concentrated by letting the solvent evaporate. The concentrate is transferred to a preweighed glass vial. The weight of the extract in the vial is determined.

The aliquot of the extract is analyzed in GC to determine the quality and quantity of the hydrocarbons present.

Appendix B: Container Capacity Procedure

CONTAINER CAPACITY PROCEDURE

Container capacity (CC) is defined as the ratio of the mass of water retained against gravity to the dry mass of the material tested. The following steps detailing the determination of container capacity are adapted from Cassel & Nielson (1986).

1. The subject material is loaded and shaken down loosely into a 15 cm tall container with a perforated bottom and known mass.
2. The container is placed in a deep pan of shallow water and allowed to wet through capillary action. Over the next 12 hours the pan is gradually filled to submerge the container to saturation.
3. Once saturated, the container is set atop another to allow free drainage of water to air. The top is loosely covered to prevent evaporation.
4. Following six hours of drainage, the container and material are weighed.
5. The container is then placed in a drying oven at 105°C for 24 hours.
6. The container and dried mass are weighed to determine the mass of water which was previously held by the material. The dried material mass is determined by subtracting the original container weight.
7. Container capacity is the ratio of the mass of water held to the mass of dried material and has units of g H_2O/g dwt material.

Appendix C: Evans Mineral Medium for Hydrocarbon Oxidizing Bacteria

EVANS MINERAL MEDIUM FOR HYDROCARBON OXIDIZING BACTERIA

Constituents	Standard (gm/L)	50X Conc.
Ammonium Sulfate	1	50
Potassium Phosphate, Dibase	1	50
Magnesium Sulfate, $7H_2O$	0.3	15
Calcium Chloride	0.1	5
Ferrous Sulfate, $7H_2O$	0.02	1
Drews Trace Element Solution	1.0 ml	50 ml

Adjust pH to 7.0 - 7.2

DREWS TRACE ELEMENT SOLUTION

Constituents	gm/L
Manganous Sulfate - H_2O	0.12
Cobalt Chloride - $6H_2O$	0.02
Copper Sulfate - $5H_2O$	0.01
Sodium Molybdate - $2H_2O$	0.01
Zinc Sulfate	0.02
Lithium Chloride	0.005
Stannous Chloride - $2H_2O$	0.005
Phosphoric Acid	0.016
Potassium Bromide	0.02
Potassium Iodide	0.02
EDTA	8.0

Deionized H_2O required for 1 liter of 50X Conc.: 1000 ml - 50 ml (Drews) = 950 ml

After thorough mixing, the Evans Medium is sterilized in an autoclave.

Appendix D: Mineralogy Report

X-RAY DIFFRACTION MINERALOGY	
Amoco Production Company	
Catoosa Soil Feedback	
Mineralogy, Inc. Job No.: 94-265	
Sample Identification	**94-265-01**
MINERAL CONSTITUENTS	
Quartz	**66**
Plagioclase feldspar	**TRC**
K-Feldspar	**TRC**
Calcite	**1**
Dolomite	**TRC**
Hematite	**1**
Goethite	**2**
Kaolinite	**1**
Chlorite	**2**
Illite/Mica	**8**
Mixed-Layer Illite/Smectite	**19**
TOTAL	**100**

Appendix E: Farmington Extraction Data

Farmington Extractions

DAY 120
% Hydrocarbon is given on a dry inert basis

REACTORS 1 & 2 BA/S = 1:1 (vol) .7M NH3

	REACTOR 1			REACTOR 2		
Thimble	1	2	3	4	5	6
mixture wt	26.7302	28.5608	29.409	30.9042	37.7834	36.2817
compost wt	7.114243	7.601457	7.827205 dry wt.	8.341044	10.19774	9.792431 dry wt.
extract wt	1.3866	1.4631	1.0955	1.6212	1.8927	1.7159
% H.C.	24.20891	23.83537	16.27374	24.12556	22.78978	21.24551
Average H.C. %		21.43934			22.72028	

REACTORS 3 & 4 BA/S = 5.85:1 (vol) .07M NH3

	REACTOR 3			REACTOR 4		
Thimble	7	8	9	10	11	12
mixture wt	24.4828	25.5152	28.1263	30.0577	29.8361	30.5634
compost wt	7.617415	7.938629	8.751029 dry wt.	6.796046	6.745942	6.910385 dry wt.
extract wt	0.9878	0.9453	0.7164	0.7138	0.7503	0.7733
% H.C.	14.89981	13.51717	8.916404	11.7358	12.51409	12.60045
Average H.C. %		12.44446			12.28344	

REACTORS 5 & 6 BA/S = 5.85:1 (vol) .7M NH3 25C

	REACTOR 5			REACTOR 6		
Thimble	13	14	15	16	17	18
mixture wt	25.7943	25.1558	20.564	24.5673	24.0208	25.9388
compost wt	4.337741	4.230367	3.458179 dry wt.	4.325073	4.228862	4.566526 dry wt.
extract wt	0.5319	0.4886	0.2952	0.4375	0.3979	0.403
% H.C.	13.97588	13.058	9.332973	11.25381	10.38643	9.679296
Average H.C. %		12.12229			10.43984	

REACTORS 7 & 8 BA/S = 5.85:1 (vol) .7M 35C

	REACTOR 7			REACTOR 8		
Thimble	19	20	21	22	23	24
mixture wt	26.1407	26.2511	27.8921	26.9855	25.1483	26.5106
compost wt	5.660333	5.684238	6.039569 dry wt.	6.325401	5.894762	6.214085 dry wt.
extract wt	0.692	0.6891	0.597	0.7792	0.7083	0.6268
% H.C.	13.92821	13.79541	10.96908	14.04926	13.65671	11.21833
Average H.C. %		12.89757			12.97477	

REACTORS 9 & 10 BA/S = 5.85:1 (vol) CONTROL (2 WT% HgCl2)

	REACTOR 9				REACTOR 10	
Thimble	25	26	27	28	29	30
mixture wt	26.9313	25.8665	25.5403	32.182	28.7527	29.8011
compost wt	5.852171	5.62079	5.549907 dry wt.	9.934047	8.875479	9.199103 dry wt.
extract wt	0.9047	0.6527	0.9016	1.2066	1.3358	1.5288
% H.C.	18.28611	13.13784	19.39631	13.82535	17.71693	19.93142
Average H.C. %		16.94009			17.1579	

DAY ZERO
% Hydrocarbon is given on a dry inert basis

REACTORS 1 & 2 BA/S = 1:1 (vol) .7M NH3

Thimble	1	2	3
mixture wt	18.41387	24.6826	24.43245
compost wt	3.204013	4.294772	4.251246 dry wt.
extract wt	0.77495	1.00928	1.08022
% H.C.	31.90325	30.7193	34.06532 Dry Inert Basis
Average H.C. %		32.23	

REACTORS 3 & 4 BA/S = 5.85:1 (vol) .07M NH3

Thimble	7	8	9
mixture wt	19.2741	21.3202	20.30835
compost wt	4.308404	4.765775	4.539593 dry wt.
extract wt	0.06976	0.52979	0.68838
% H.C.	1.645809	12.50689	17.87437 Dry Inert Basis
Average H.C. %		15.19	

REACTORS 5-6 BA/S = 5.85:1 (vol) .7M NH3

Thimble	4	5	6
mixture wt	19.27774	17.36315	21.63842
compost wt	3.314807	2.985594	3.720726 dry wt.
extract wt	0.5236	0.33453	0.4914
% H.C.	18.75891	12.61871	15.2168 Dry Inert Basis
Average H.C. %		15.53	

REACTORS 9 & 10 BA/S = 5.85:1 (vol) CONTROL (2 WT% HgCl2)

Thimble	10	11	12
mixture wt	22.16223	21.79397	23.48483
compost wt	4.937745	4.855697	5.23242 dry wt.
extract wt	0.88514	0.81221	0.71934
% H.C.	21.84126	20.08687	15.939 Dry Inert Basis
Average H.C. %		19.29	

Note: Thimble 7 is considered to be insignificant and is not included in the calculation of the H.C. %

Hydrocarbon Reduction Due to Composting

Compost Parameters	%C Day Zero	%C Final	%C Removed
1:1, .7N, 35C	32.23	21.44	33.48
1:1, .7N, 35C	32.23	22.72	29.51
5.85:1, .07N, 35C	15.19	12.44	18.10
5.85:1, .07N, 35C	15.19	12.28	19.16
5.85:1, .7N, 25C	15.53	12.12	21.96
5.85:1, .7N, 25C	15.53	10.44	32.78
5.85:1, .7N, 35C	15.52	12.9	16.88
5.85:1, .7N, 35C	15.53	12.97	16.48
5.85:1, .7N, 35C, 2% HgC12	19.29	16.94	12.18
5.85:1, .7N, 35C, 2% HgC12	19.29	17.16	11.04

Appendix F: Calculations Used in Evaluation of Monitoring Data

Calculations Used in Evaluation of Monitoring Data

Flow Rate (cc/min) = (0.0486957 x setting) + (0.00287177 x setting ^{2}) + 7.5443956

Flow Rate (cc) = cc/min x 60 min/hr x hours

CO_2 (cc) = flow(cc) x (produced CO_2(%)/100)

Moles CO_2 = CO_2(cc)/R*T = cc/(82.05 x 308)

VOC (cc) = ppm x 0.000001 x flow(cc)

Moles VOC = VOC(cc)/R*T = cc/(82.05 x 308)

Moles Carbone Removed = Moles CO_2 + (2 x Moles VOC)

% Carbon Removed = (Moles C removed/moles C initial) x 100

Appendix G: Soil Analysis

Amoco Production Company

26

SUBJECT *Nitrogen Analysis of Straw* PROJECT NO.

BOOK NO. 11382

A sample of the shredded straw for composting was sent to SASI for nitrogen analysis. Results are listed below:

SASI

Soil Analytical Services, Inc.

Company : Amoco Production Research
Submitted by : Dan Denham
Date Received : 10/18/93
Reference # : 24101831
Report Date : 10/28/93

Sample	Straw	Straw, duplicate	Tech	Date	Time
TKN, ppm	4,704	4,480	JCR	10/27	16:30
STD Found	25,578				
STD TRUE	27,089 ± 2,453				

Avg 4592 ppm (0.46%)

Dan B Denham 4 Nov 93

Rita Vaughn
Rita Vaughn
Manager, Inorganic Laboratory

415 Graham Rd.
College Station, TX 77845
(409) 690-2280
Fax: (409) 690-0261

Appendix H: P82093 GC Fingerprints

Active Day Zero....100

Active Day 7....101

Active Day 14....102

Active Day 21....103

Active Day 35....104

Active Day 49....105

Active Day 70....106

Active Day 98....107

Active Day 120....108

Control Day Zero....109

Control Day 7....110

Control Day 14....111

Control Day 21....112

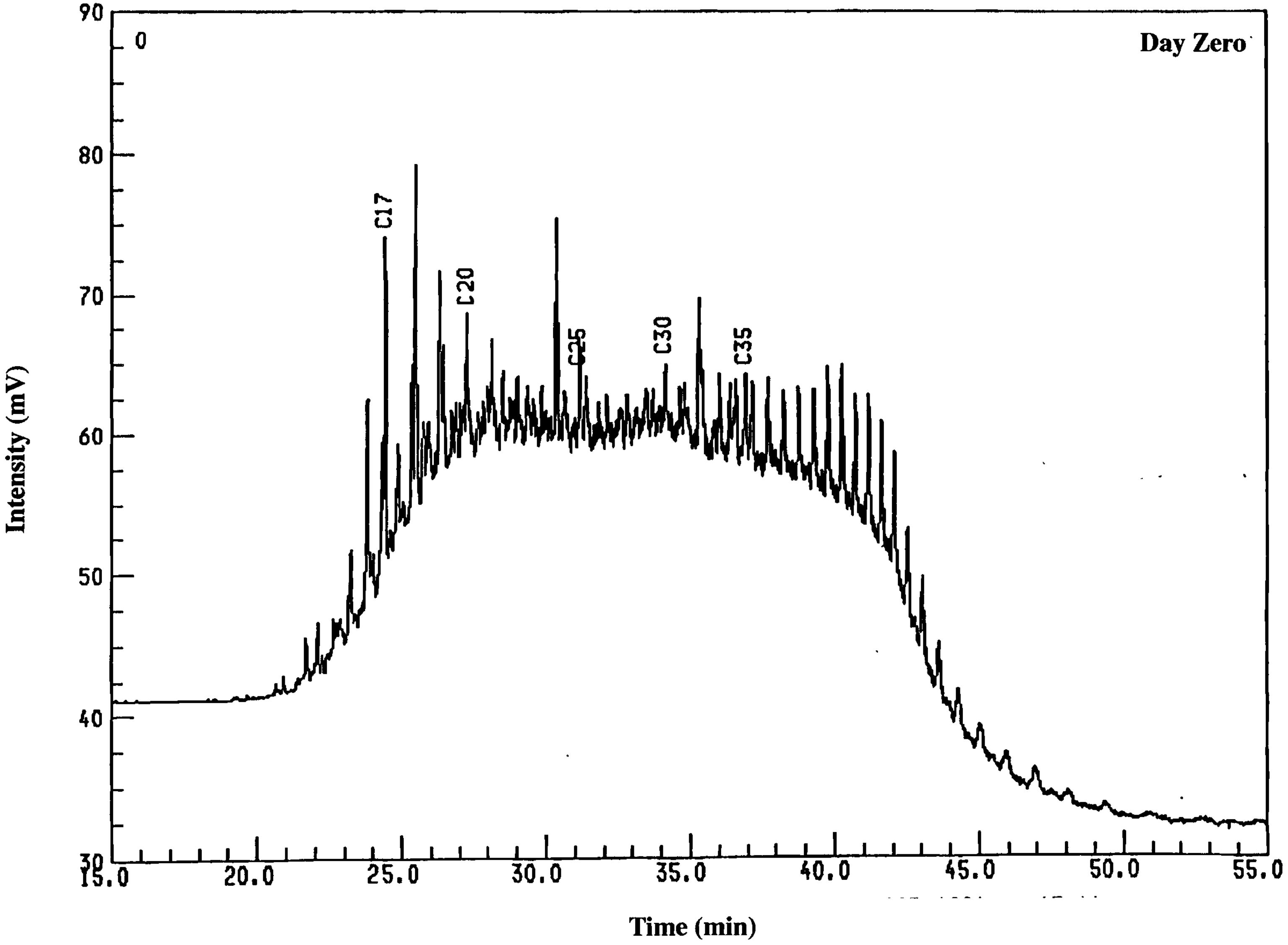
Control Day 35....113

Control Day 49....114

Control Day 70....115

Control Day 98....116

Control Day 120....117


Day Zero
0
C17
C20
C25
C30
C35
Intensity (mV)
90
80
70
60
50
40
30
Time (min)
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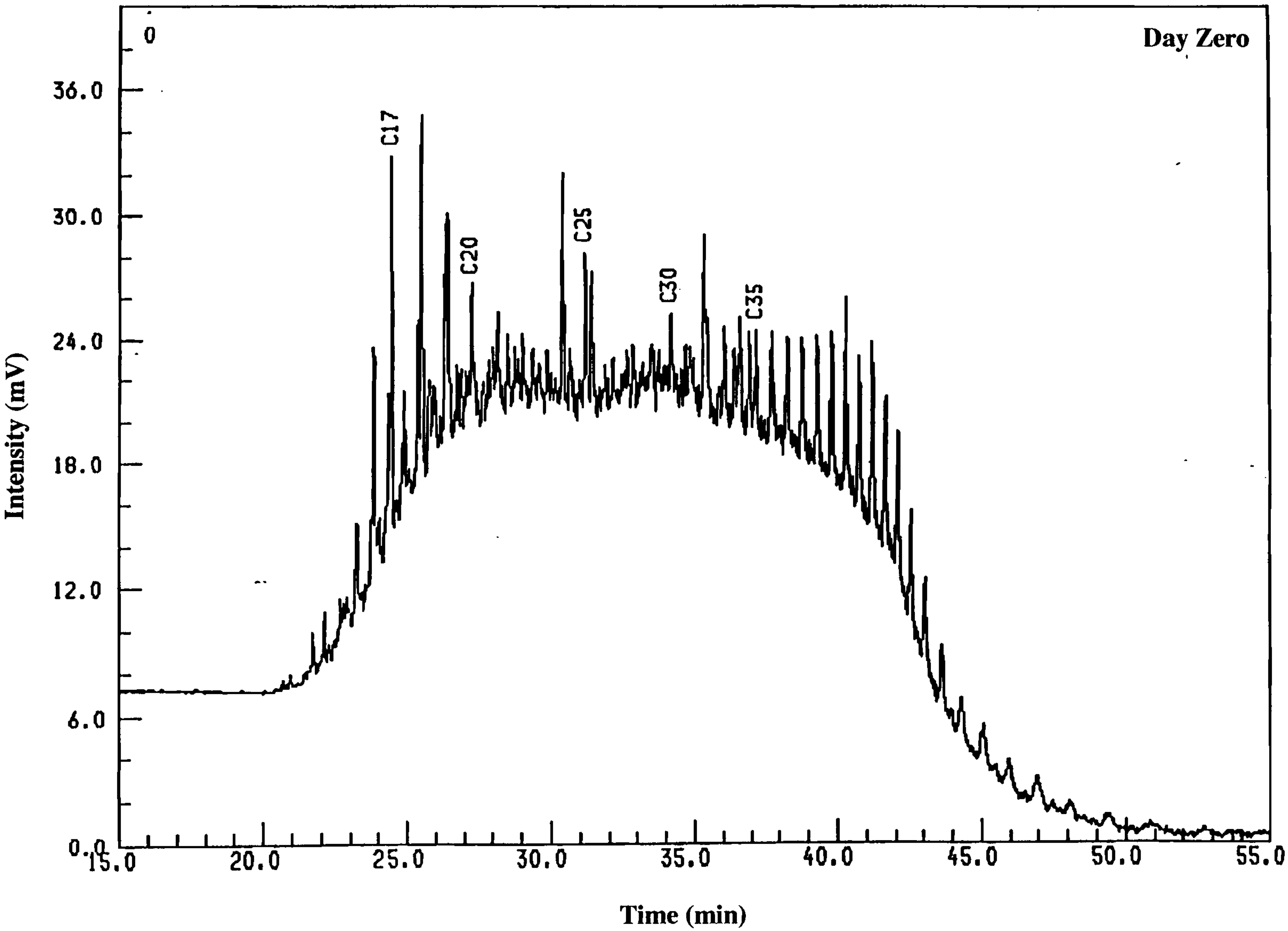
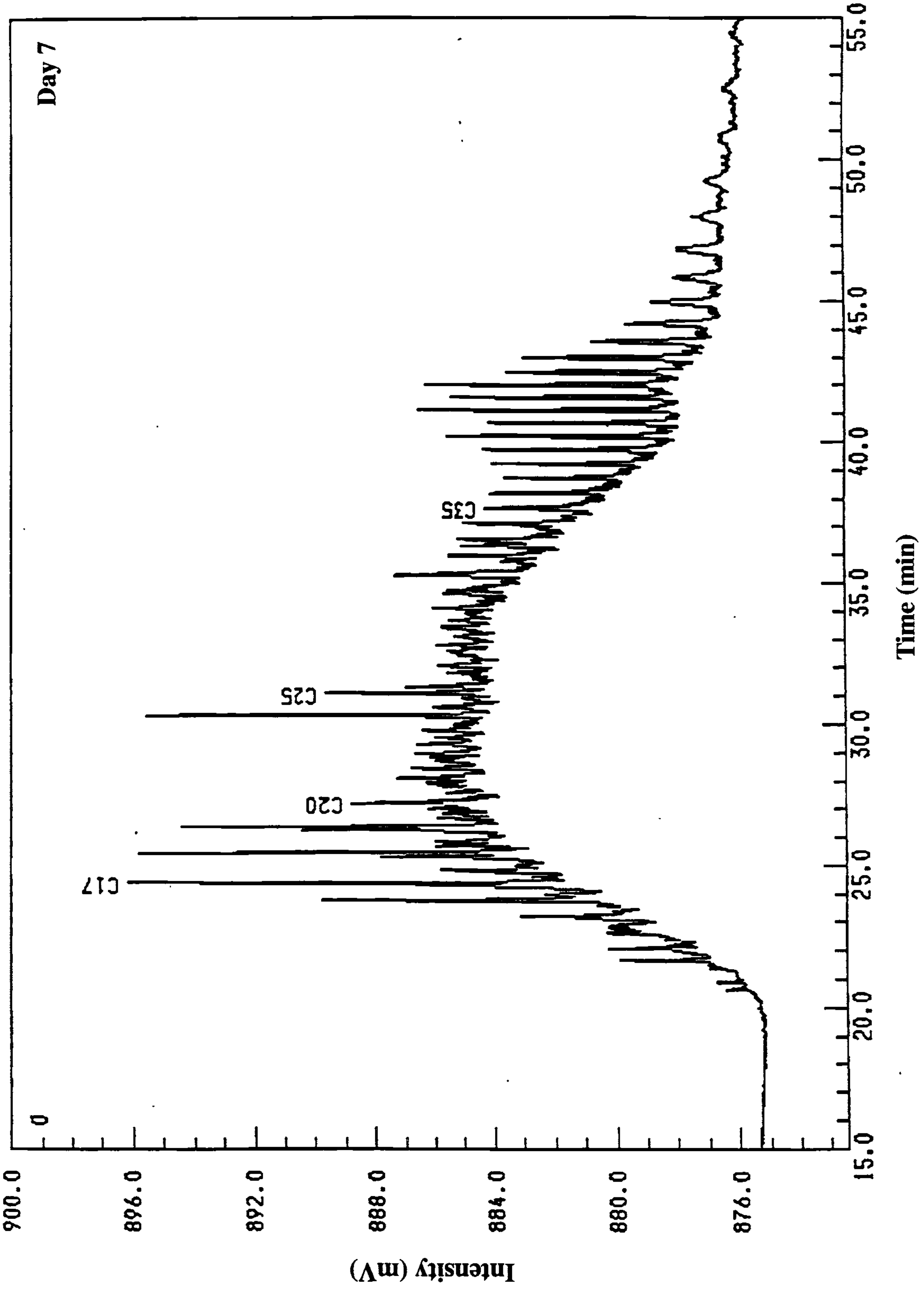
20.0
25.0
30.0
35.0
40.0
45.0
50.0
55.0


Day Zero
0
Intensity (mV)
36.0
30.0
24.0
18.0
12.0
6.0
0.0
C17
C20
C25
C30
C35
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
55.0
Time (min)


Day 7
C17
C20
C25
C35
Intensity (mV)
900.0
896.0
892.0
888.0
884.0
880.0
876.0
Time (min)
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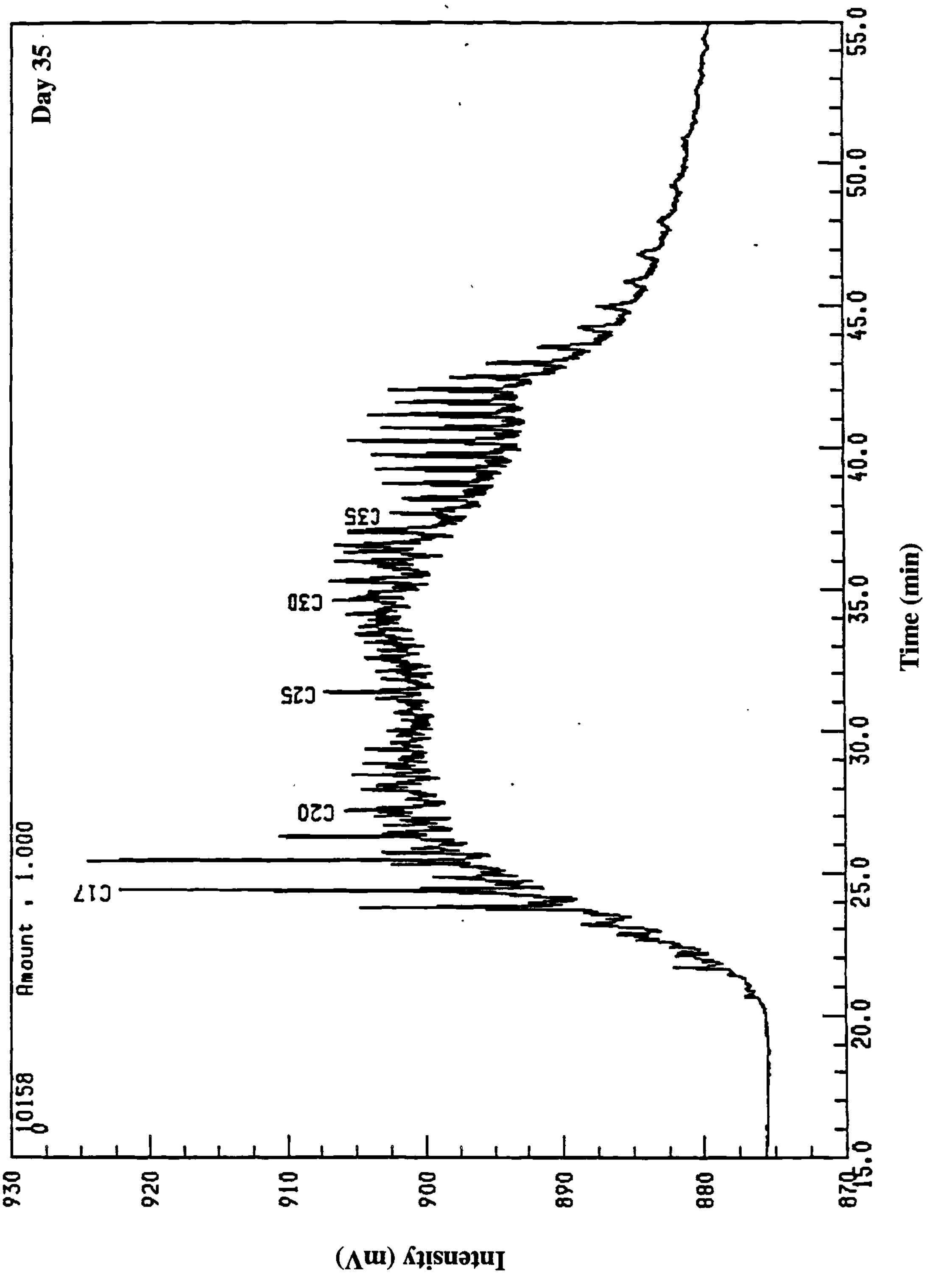
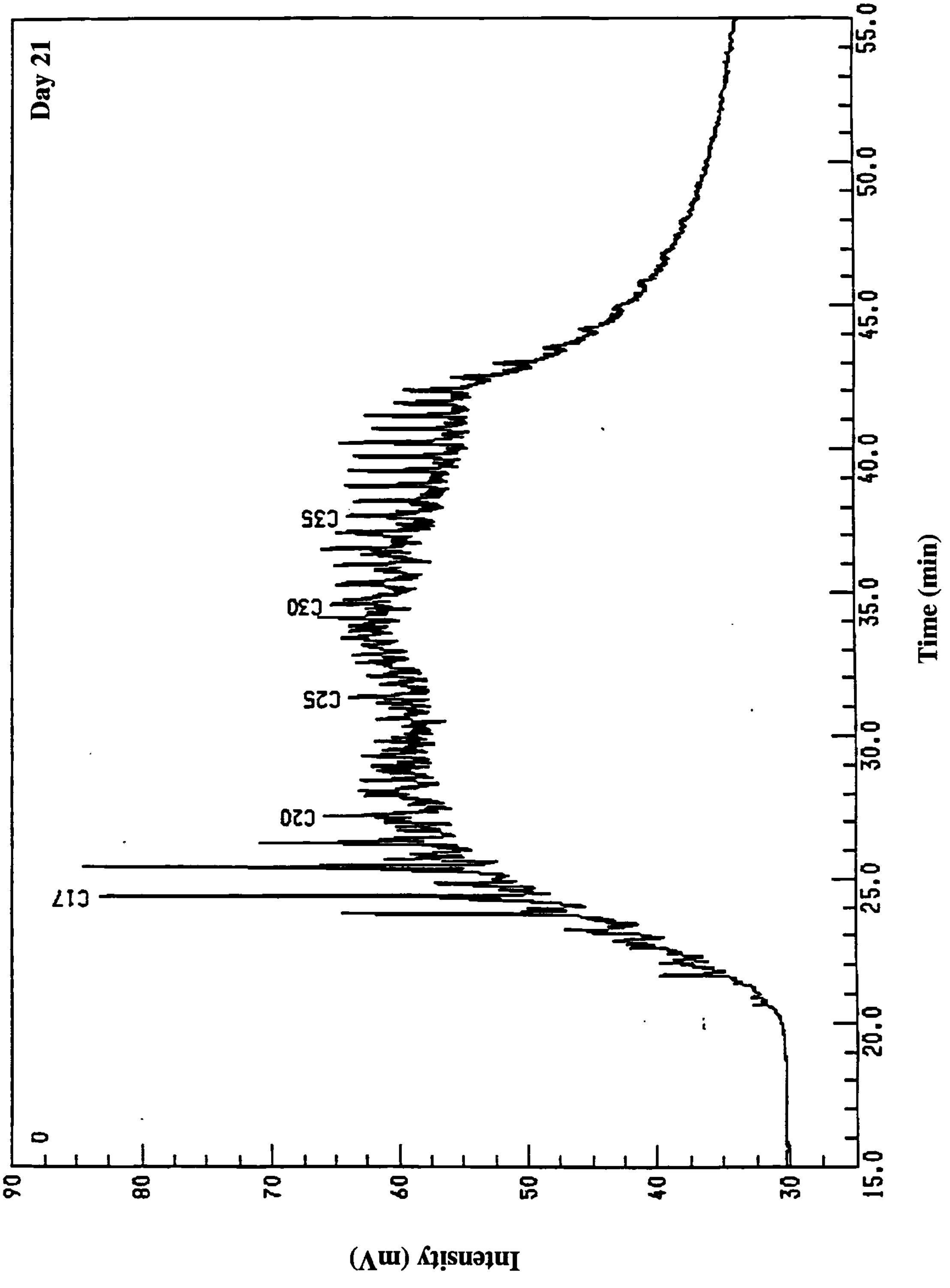
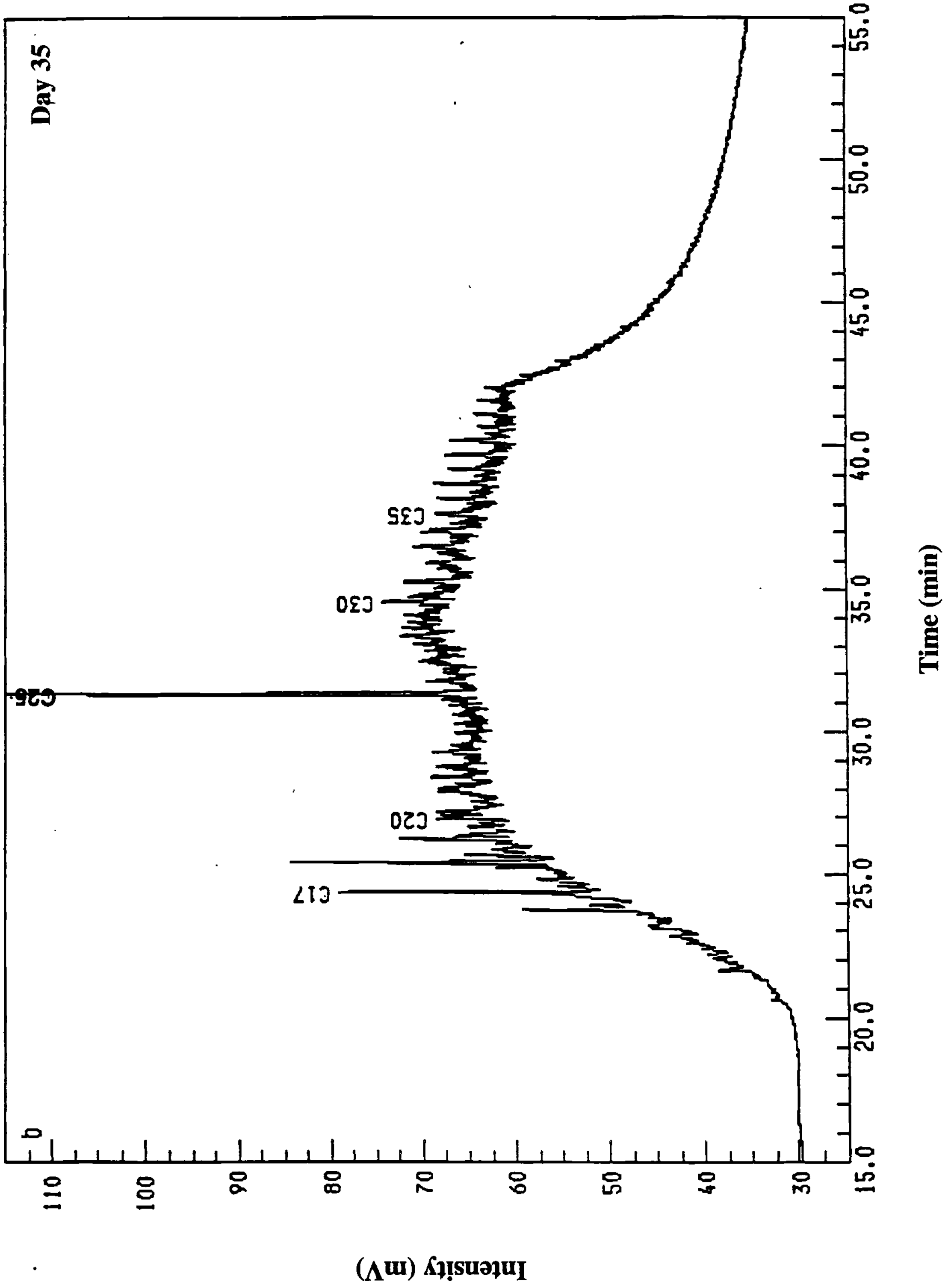
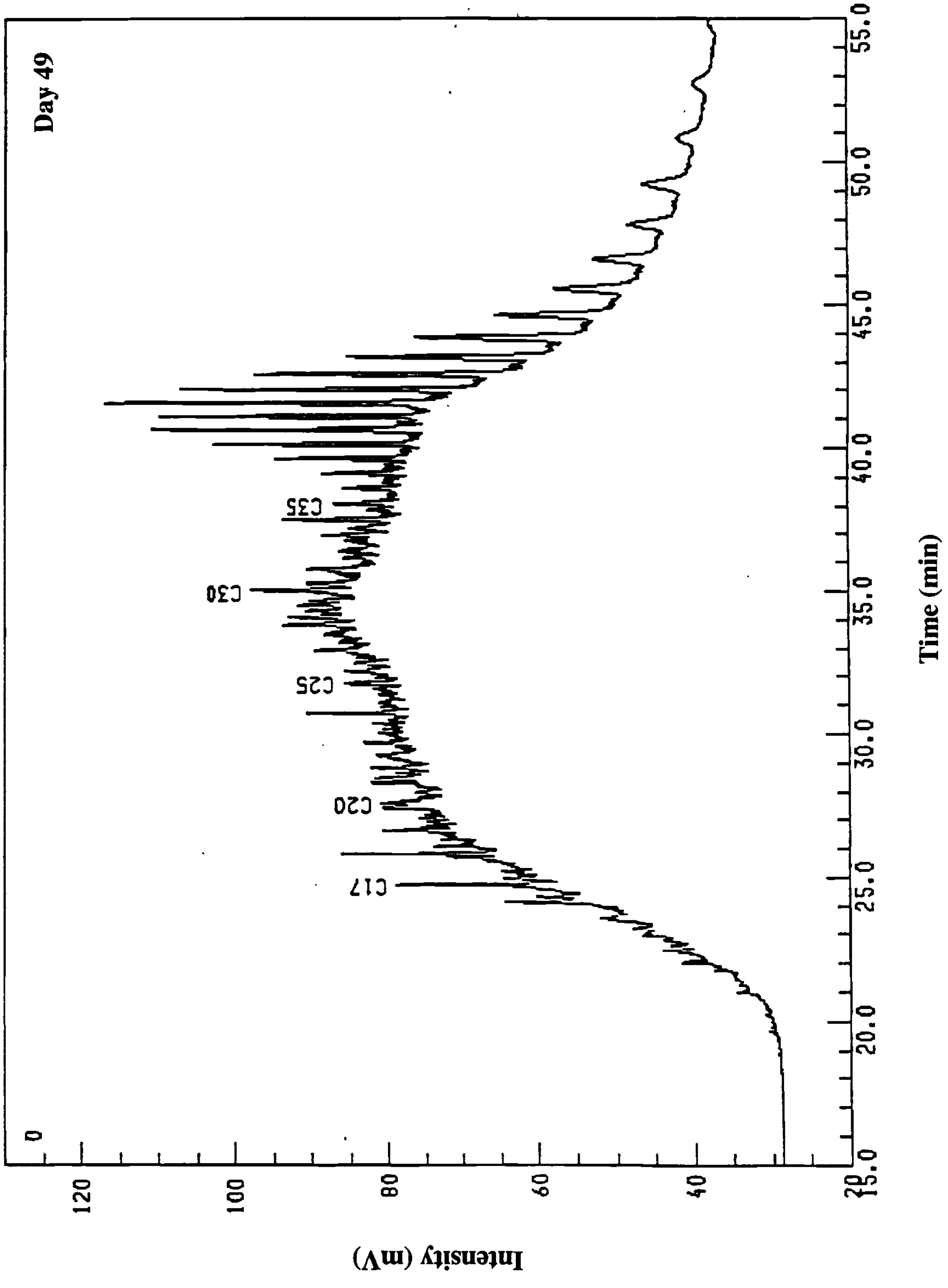
20.0
25.0
30.0
35.0
40.0
45.0
50.0
55.0


Day 35
10158
Amount = 1.000
C17
C20
C25
C30
C35
Intensity (mV)
930
920
910
900
890
880
870
Time (min)
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
55.0


Day 21
C17
C20
C25
C30
C35
0
Intensity (mV)
90
80
70
60
50
40
30
Time (min)
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
55.0


b
Day 35
C17
C20
C25
C30
C35
Intensity (mV)
110
100
90
80
70
60
50
40
30
Time (min)
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
55.0


Day 49
C17
C20
C25
C30
C35
Intensity (mV)
20
40
60
80
100
120
Time (min)
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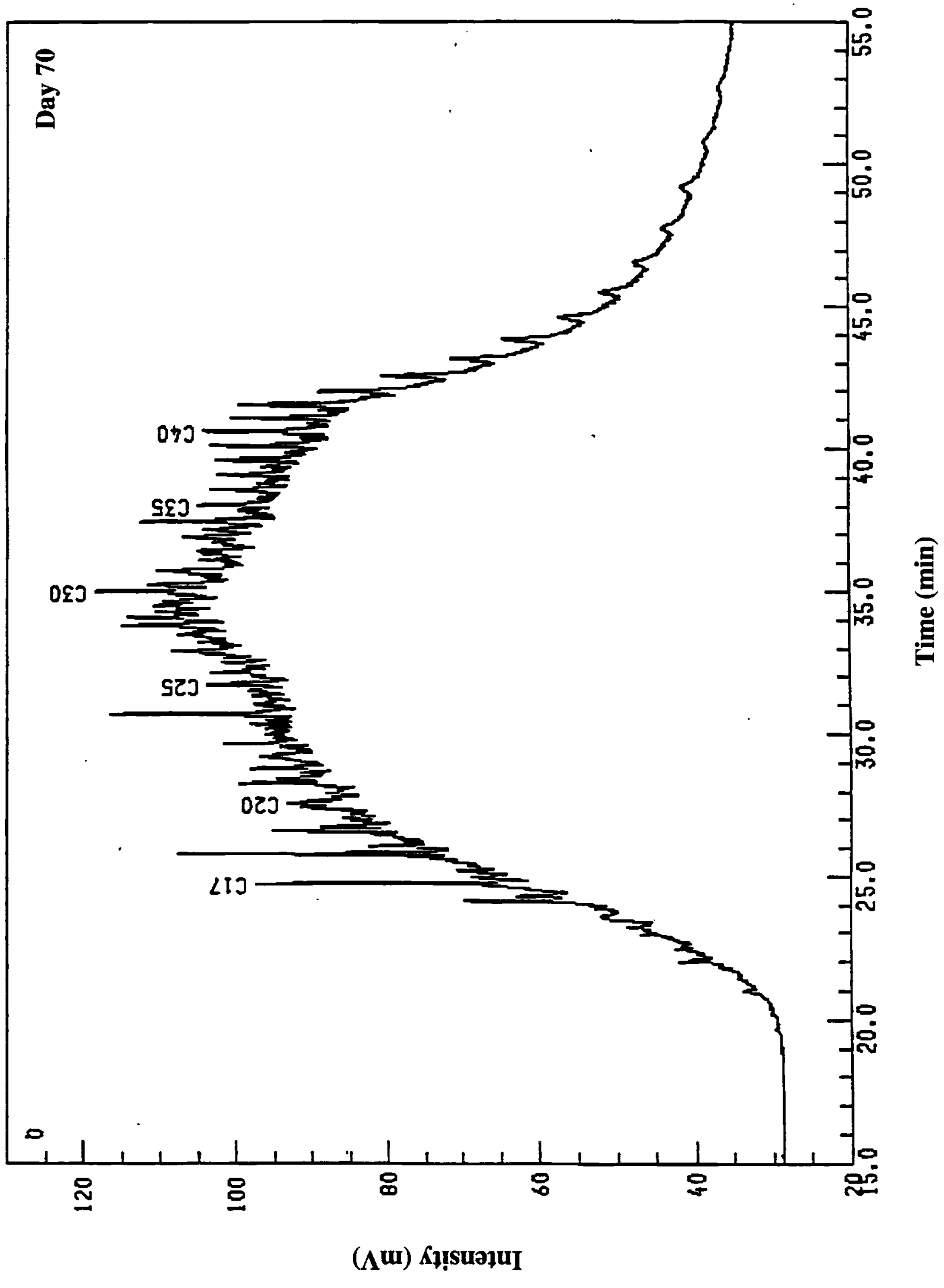
25.0
30.0
35.0
40.0
45.0
50.0
55.0


Day 70
C17
C20
C25
C30
C35
C40
Intensity (mV)
20
40
60
80
100
120
Time (min)
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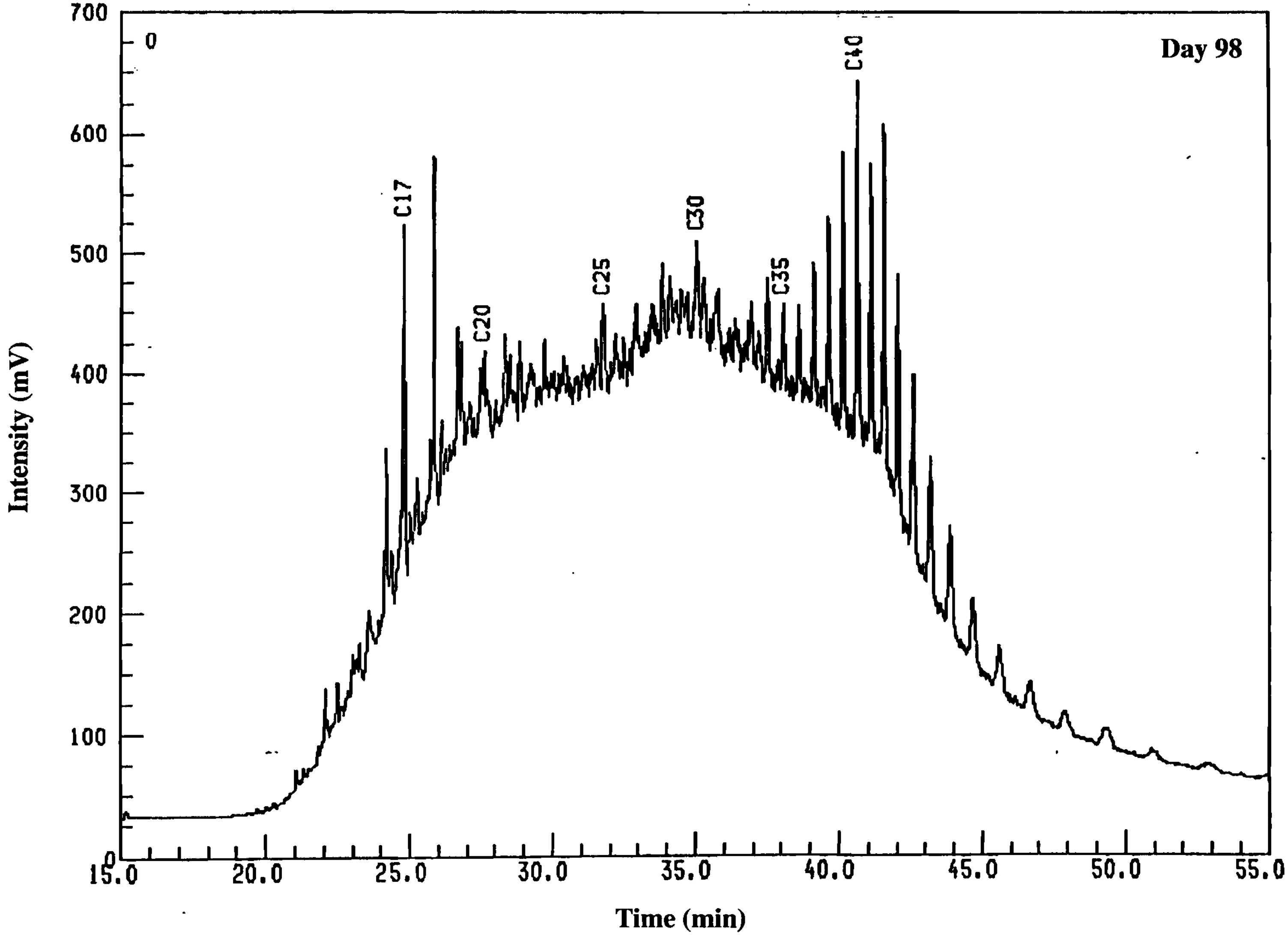
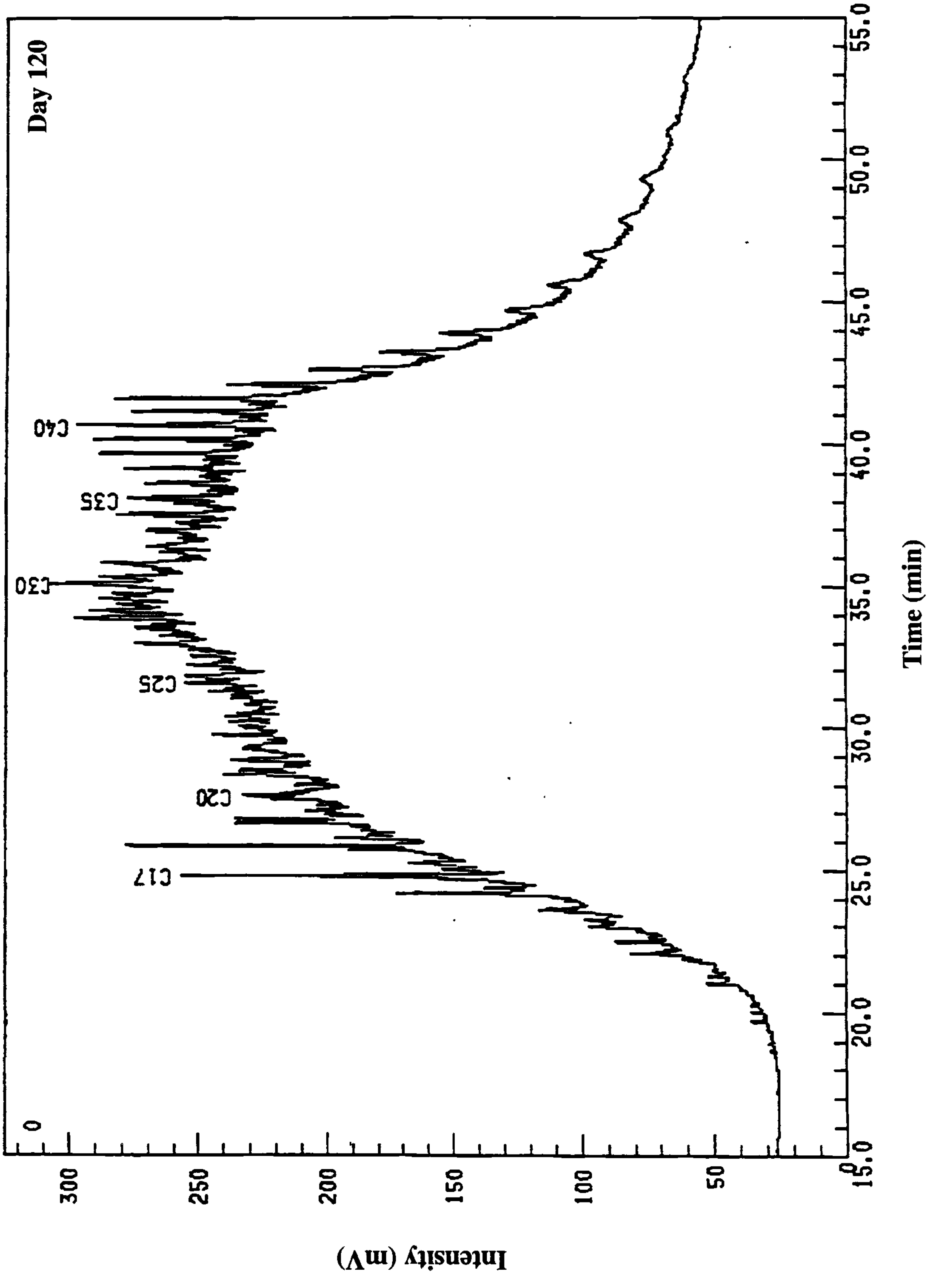
20.0
25.0
30.0
35.0
40.0
45.0
50.0
55.0


Day 98
Intensity (mV)
Time (min)
0
100
200
300
400
500
600
700
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
55.0
C17
C20
C25
C30
C35
C40


Day 120
C17
C20
C25
C30
C35
C40
Intensity (mV)
0
50
100
150
200
250
300
Time (min)
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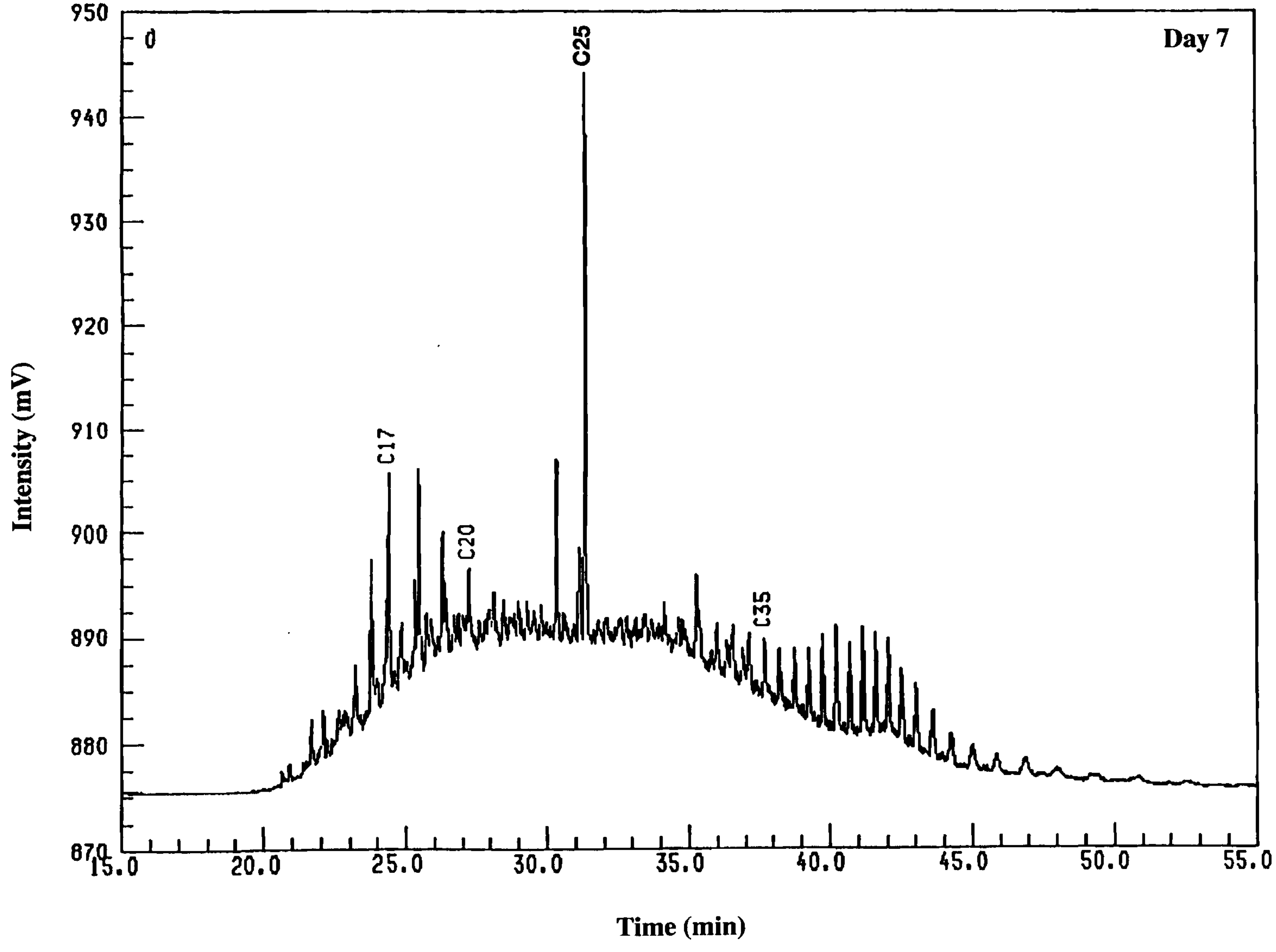
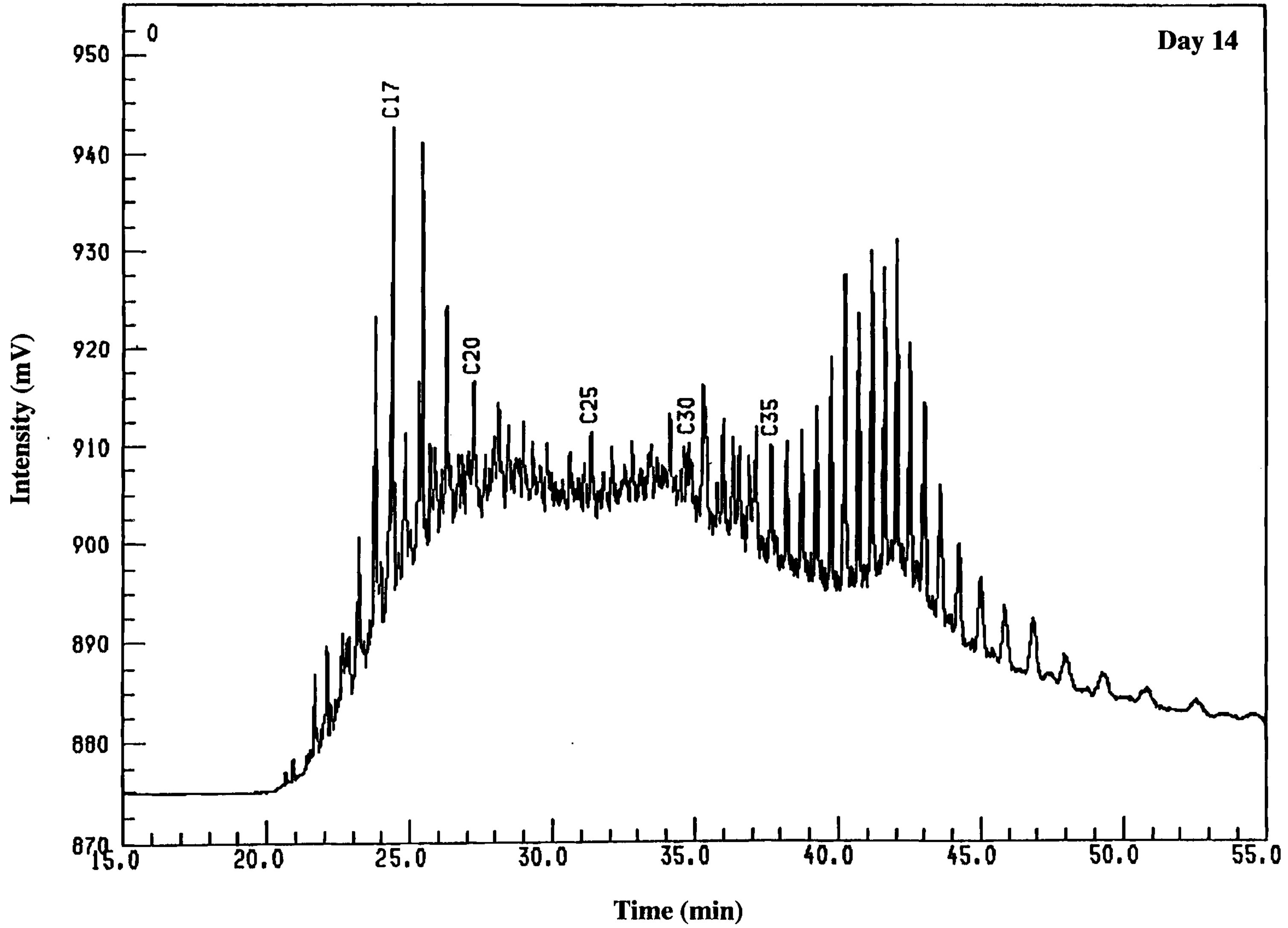
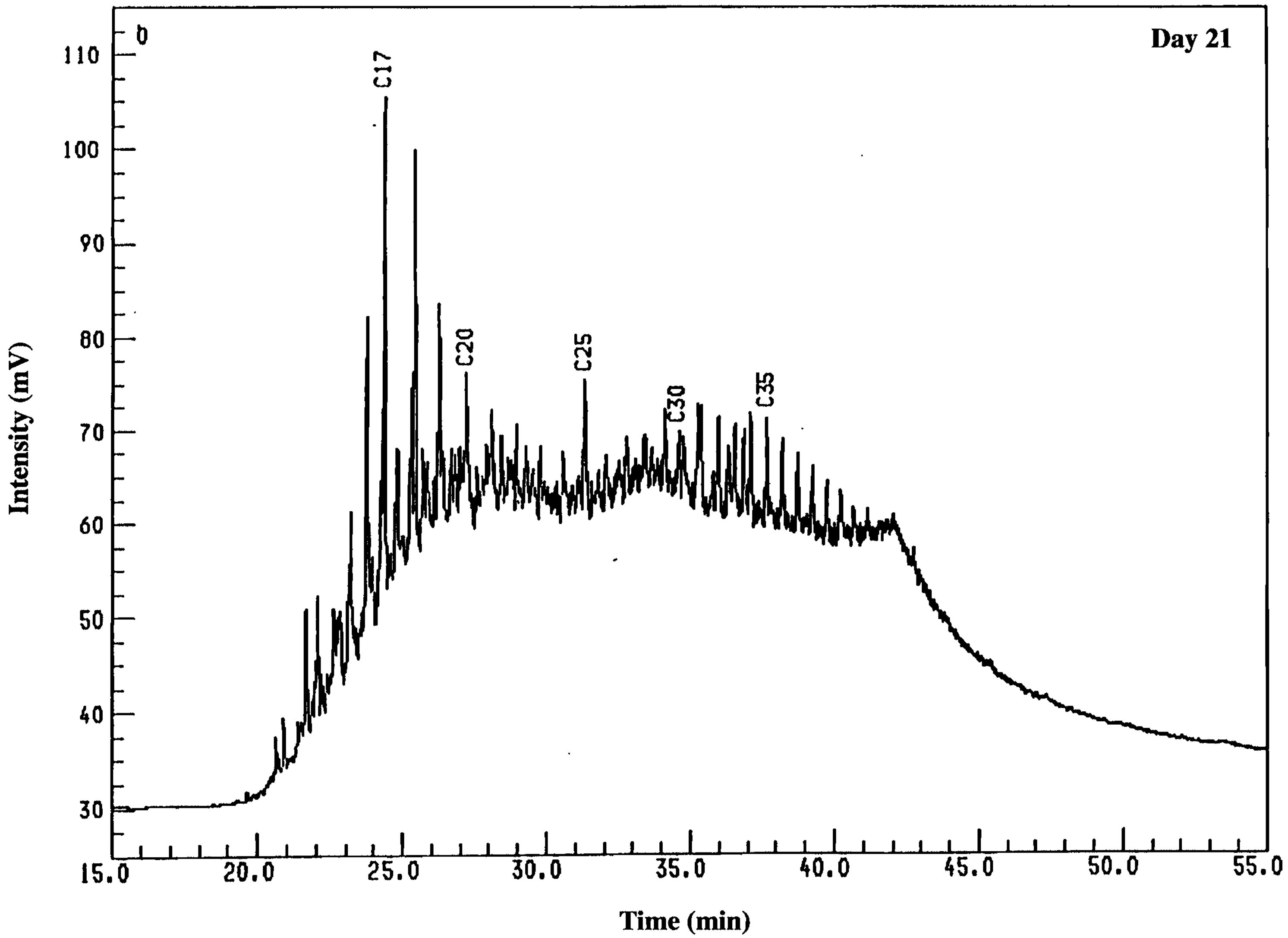
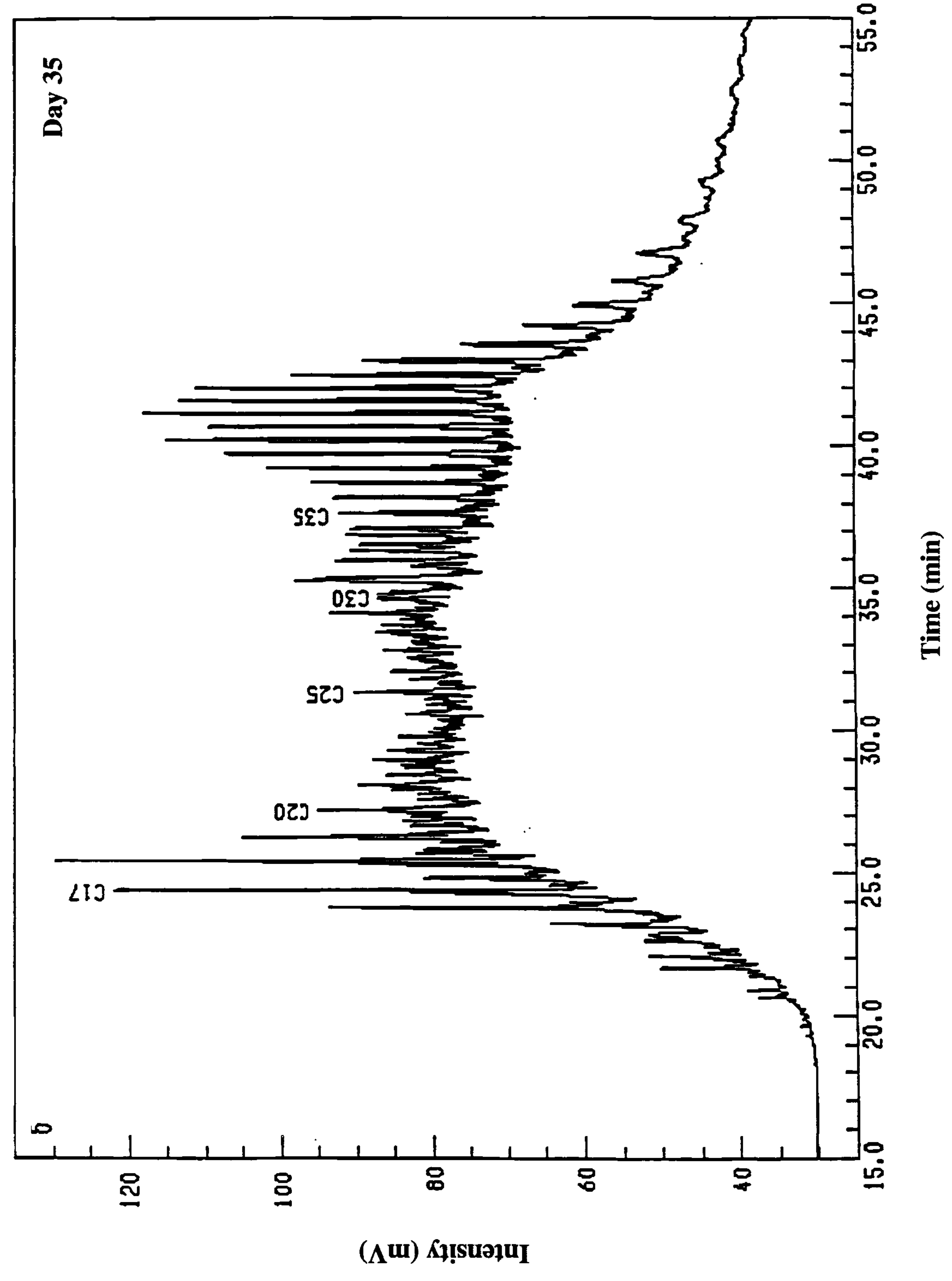
20.0
25.0
30.0
35.0
40.0
45.0
50.0
55.0


d
Day 7
C17
C20
C25
C35
Intensity (mV)
950
940
930
920
910
900
890
880
870
Time (min)
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
55.0



Day 14
0
C17
C20
C25
C30
C35
Intensity (mV)
950
940
930
920
910
900
890
880
870
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
55.0
Time (min)


b
Day 21
C17
C20
C25
C30
C35
Intensity (mV)
110
100
90
80
70
60
50
40
30
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
55.0
Time (min)


b
Day 35
C17
C20
C25
C30
C35
Intensity (mV)
40
60
80
100
120
Time (min)
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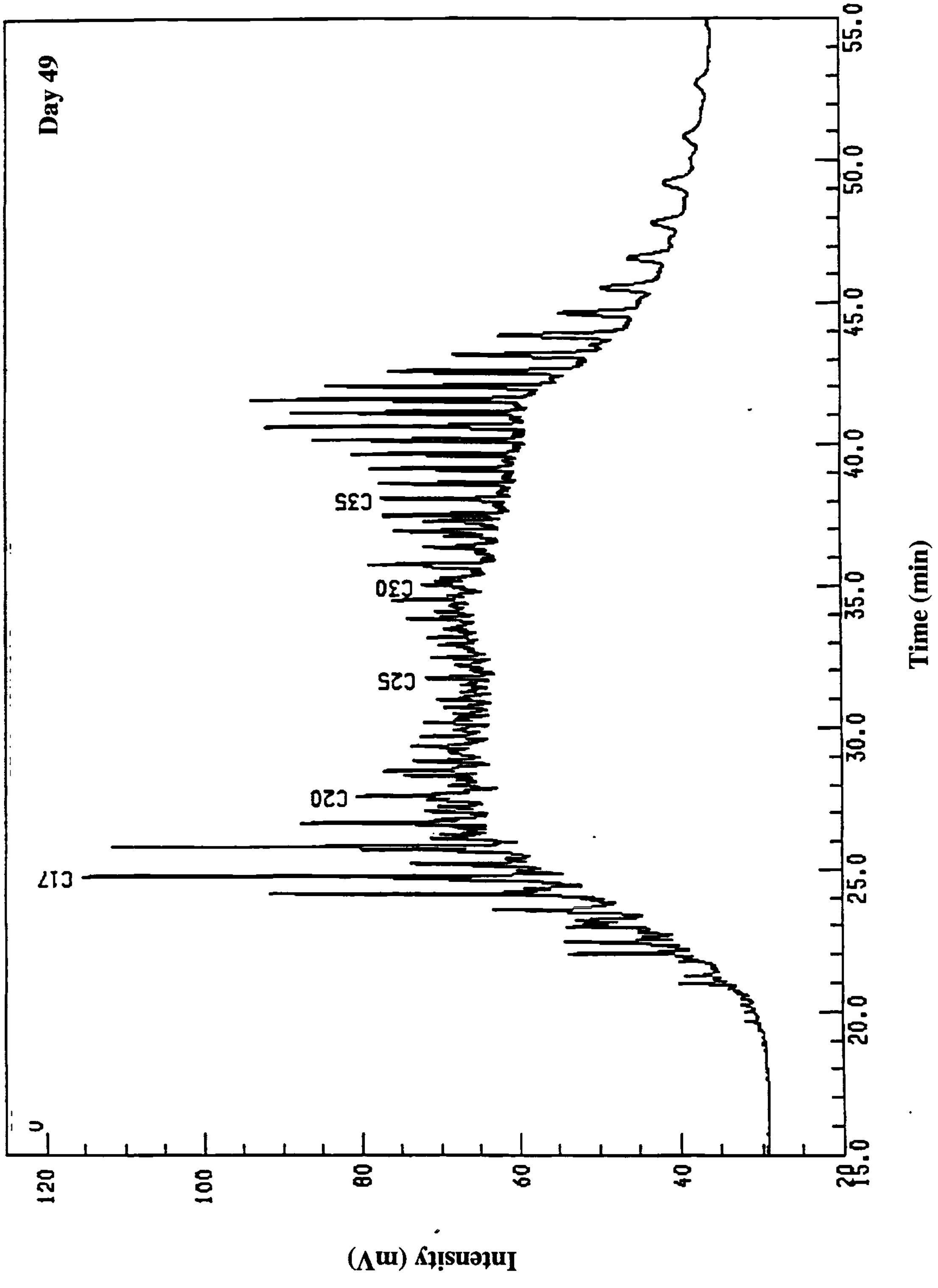
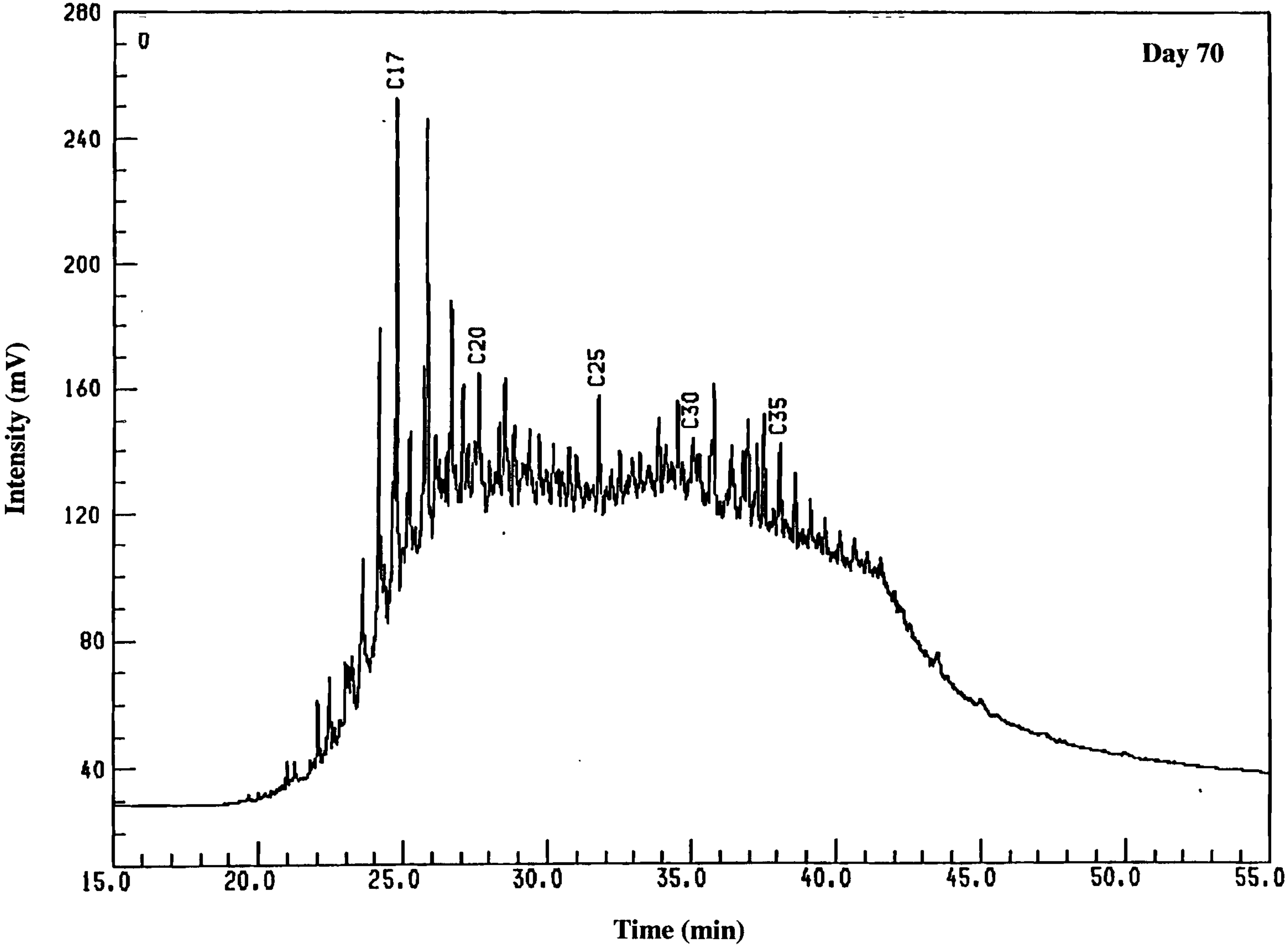
40.0
45.0
50.0
55.0


Day 49
C17
C20
C25
C30
C35
Intensity (mV)
120
100
80
60
40
20
Time (min)
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
55.0


0
Day 70
C17
C20
C25
C30
C35
280
240
200
160
120
80
40
Intensity (mV)
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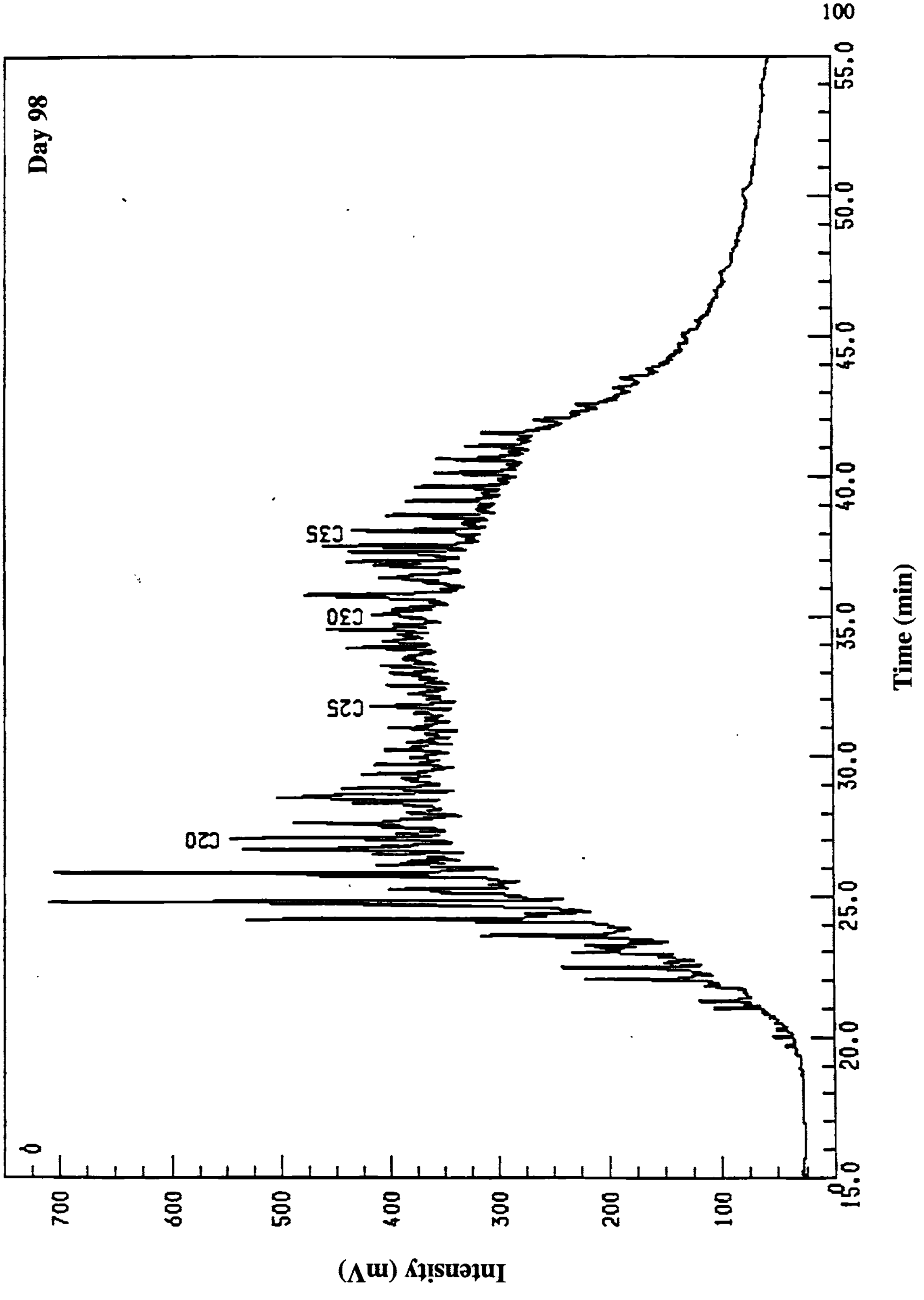
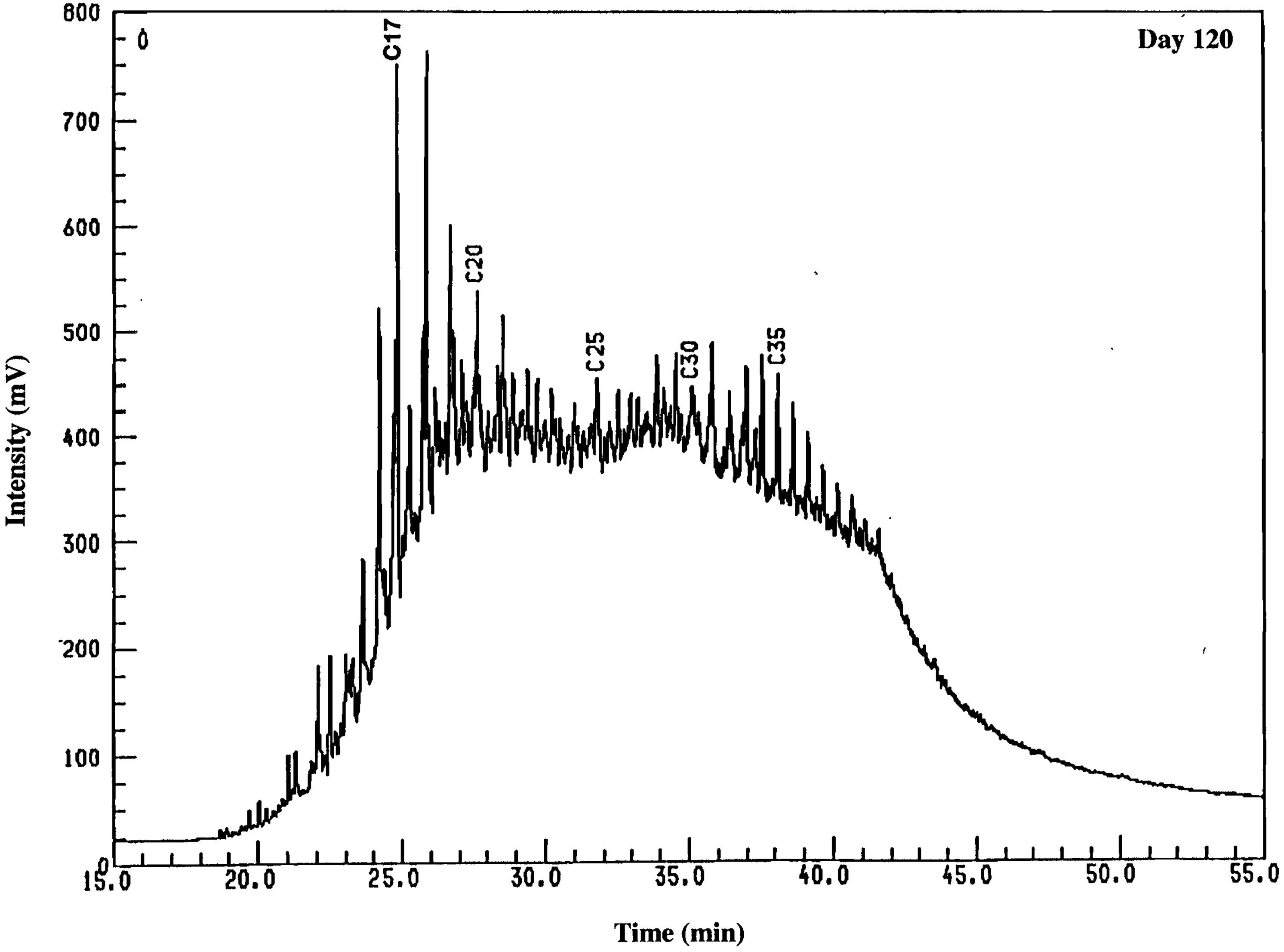
20.0
25.0
30.0
35.0
40.0
45.0
50.0
55.0
Time (min)


Day 98
C20
C25
C30
C35
Intensity (mV)
Time (min)
700
600
500
400
300
200
100
0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
55.0
100


Day 120
C17
C20
C25
C30
C35
0
Intensity (mV)
800
700
600
500
400
300
200
100
0
Time (min)
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
55.0

Appendix I: P82093 Extraction Data

		Thimble		Compost	Compost	% Dry	Thimble	Thimble			Compost	% Oil	% Oil	AVG.
Reactor #	LBN #	label	% Water	Wet wt	+ DE (gm)	Compost	weight	+ Mix wt.	Mix wt	Extract wt	Dry wt	Compost (Dry	Compost	Inerts (Dry
Baseline A	11412-07	A1	30.36	5.2073	52.0792	0.069632	29.1128	46.5279	17.4151	0.0428	1.212643	3.529480116	3.65861	
Baseline A	11412-07	A2	30.36	5.2073	52.0792	0.069632	29.9339	46.2535	16.3196	0.0408	1.136362	3.590406293	3.724117	3.600689
Baseline A	11412-07	A3	30.36	5.2073	52.0792	0.069632	29.0508	46.9031	17.8523	0.0411	1.243086	3.306287298	3.419341	
Baseline C	11412-07	C1	34.31	7.6367	76.3711	0.065686	30.5729	55.5509	24.978	0.0555	1.640717	3.382668006	3.501099	
Baseline C	11412-07	C2	34.31	7.6367	76.3711	0.065686	28.9983	53.9695	24.9712	0.0608	1.64027	3.706706676	3.849392	3.714657
Baseline C	11412-07	C3	34.31	7.6367	76.3711	0.065686	30.3108	56.0946	25.7838	0.0619	1.693647	3.654835033	3.79348	
7 - Active	11412-14	15-1	30.565	6.2412	62.4249	0.069421	30.1924	50.4428	20.2504	0.051	1.405796	3.627838001	3.764404	
7 - Active	11412-14	15-2	30.565	6.2412	62.4249	0.069421	28.8501	49.6673	20.8172	0.0536	1.445144	3.708974015	3.851838	3.843095
7 - Active	11412-14	15-3	30.565	6.2412	62.4249	0.069421	29.3024	50.1121	20.8097	0.0544	1.444623	3.765688534	3.913041	
7 - Control	11412-14	16-1	30.83	6.4325	64.3276	0.069167	30.1302	51.3919	21.2617	0.056	1.470612	3.807937565	3.958682	
7 - Control	11412-14	16-2	30.83	6.4325	64.3276	0.069167	29.3786	50.8742	21.4956	0.0554	1.486791	3.726146885	3.870362	3.934809
7 - Control	11412-14	16-3	30.83	6.4325	64.3276	0.069167	29.6848	50.6715	20.9867	0.0555	1.451591	3.82339006	3.975385	
14 - Active	11412-21	R1A	26.575	25.157	75.6825	0.244066	27.7402	52.3404	24.6002	0.0725	6.004073	1.207513607	1.222273	
14 - Active	11412-21	R1B	26.575	25.157	75.6825	0.244066	28.2188	52.8963	24.6775	0.1999	6.022939	3.318977423	3.432915	2.542239
14 - Active	11412-21	R1C	26.575	25.157	75.6825	0.244066	27.4057	52.6499	25.2442	0.1778	6.161252	2.885777274	2.971529	
14 - Control	11412-21	R2A	27.325	25.8602	77.2096	0.243414	26.8692	51.8237	24.9545	0.2335	6.074276	3.844079803	3.997757	
14 - Control	11412-21	R2B	27.325	25.8602	77.2096	0.243414	27.837	52.665	24.828	0.235	6.043484	3.888485719	4.045806	4.026561
14 - Control	11412-21	R2C	27.325	25.8602	77.2096	0.243414	26.6336	51.4871	24.8535	0.2347	6.049691	3.879537153	4.03612	
21 - Active	11412-27	3A	39.505	25.27	75.84	0.20157	27.1	52.93	25.83	0.2006	5.206559	3.852832457	4.007224	
21 - Active	11412-27	3B	39.505	25.27	75.84	0.20157	27.81	53.07	25.26	0.1827	5.091664	3.588217851	3.721763	3.731593
21 - Active	11412-27	3C	39.505	25.27	75.84	0.20157	27.32	51.15	23.83	0.1609	4.803419	3.349697608	3.465791	
21 - Control	11412-27	4A	27.235	26.02	78.12	0.242364	27.57	52.99	25.42	0.21	6.160886	3.408600923	3.528887	
21 - Control	11412-27	4B	27.235	26.02	78.12	0.242364	27.09	53.43	26.34	0.2337	6.38386	3.660794502	3.799901	3.623174
21 - Control	11412-27	4C	27.235	26.02	78.12	0.242364	27.26	52.26	25	0.2072	6.059093	3.419653879	3.540735	
35 - Active	11412-41	5A	38.66	30.3	90.3	0.205825	27.76	60.51	32.75	0.2459	6.740777	3.647947459	3.786061	
35 - Active	11412-41	5B	38.66	30.3	90.3	0.205825	27.08	58.37	31.29	0.2581	6.440272	4.007594681	4.174908	3.908435
35 - Active	11412-41	5C	38.66	30.3	90.3	0.205825	26.95	52.61	25.66	0.1916	5.281476	3.627773824	3.764335	
35 - Control	11412-41	6A	21.93	31.73	95.16	0.260315	27.91	53.83	25.92	0.2203	6.747374	3.264973659	3.375172	
35 - Control	11412-41	6B	21.93	31.73	95.16	0.260315	27.77	52.39	24.62	0.2277	6.408965	3.552836026	3.683712	3.401049
35 - Control	11412-41	6C	21.93	31.73	95.16	0.260315	27.94	52.74	24.8	0.1968	6.455821	3.048411527	3.144262	
49 - Active	11412-53	11A	36.765	30.01	90.03	0.210783	26.5041	56.4949	29.9908	0.2301	6.321561	3.639923866	3.777419	
49 - Active	11412-53	11B	36.765	30.01	90.03	0.210783	26.8211	56.4421	29.621	0.2098	6.243613	3.360233827	3.477072	3.714311
49 - Active	11412-53	11C	36.765	30.01	90.03	0.210783	26.9865	57.1028	30.1163	0.2376	6.348014	3.742902839	3.888444	
49 - Control	11412-53	14A	33.375	30.34	91.01	0.222108	27.5815	57.6171	30.0356	0.2638	6.671139	3.954347168	4.117154	
49 - Control	11412-53	14B	33.375	30.34	91.01	0.222108	27.3958	55.3149	27.9191	0.271	6.201048	4.370228979	4.569946	4.15399
49 - Control	11412-53	14C	33.375	30.34	91.01	0.222108	26.861	56.8141	29.9531	0.242	6.652815	3.637557821	3.774871	
70 - Active	11412-66	9A	35.975	30.68	92.04	0.213417	27.99	58.02	30.03	0.1767	6.408903	2.757102328	2.835274	
70 - Active	11412-66	9B	35.975	30.68	92.04	0.213417	27.54	57.53	29.99	0.1849	6.400366	2.888897366	2.974837	2.843596
70 - Active	11412-66	9C	35.975	30.68	92.04	0.213417	27.48	58.74	31.26	0.1767	6.671405	2.648617495	2.720678	
70 - Control	11412-66	10A	19.96	29.36	88.08	0.2668	26.99	56.43	29.44	0.2673	7.854592	3.403104833	3.522996	
70 - Control	11412-66	10B	19.96	29.36	88.08	0.2668	27.43	56.91	29.48	0.2655	7.865264	3.375601887	3.49353	3.461837

70 - Control	11412-66	10C	19.96	29.36	88.08	0.2668	28.01	56.91	28.9	0.2513	7.71052	3.259183557	3.368985	
98 - Active	11412-73	7A	33.55	29.85	89.5542	0.22149	27.23	56.944	29.714	0.1645	6.581342	2.499490101	2.563566	
98 - Active	11412-73	7B	33.55	29.85	89.5542	0.22149	27.295	57.3178	30.0228	0.1953	6.649738	2.936957676	3.025825	2.899682
98 - Active	11412-73	7C	33.55	29.85	89.5542	0.22149	27.9271	57.1194	29.1923	0.195	6.465791	3.015872212	3.109655	
98 - Control	11412-73	8A	20.69	29.946	89.8391	0.264363	28.1883	57.0338	28.8455	0.2153	7.625695	2.8233491	2.905378	
98 - Control	11412-73	8B	20.69	29.946	89.8391	0.264363	28.2216	57.3865	29.1649	0.2333	7.710133	3.025888143	3.120305	3.113616
98 - Control	11412-73	8C	20.69	29.946	89.8391	0.264363	26.9972	57.7887	30.7915	0.2612	8.140147	3.20878744	3.315164	
120 - Active	11412-78	13A	33.57	25.1923	75.5786	0.221428	27.1543	52.2745	25.1202	0.1577	5.562325	2.835145629	2.917872	
120 - Active	11412-78	13B	33.57	25.1923	75.5786	0.221428	27.1537	52.3501	25.1964	0.1583	5.579197	2.837325699	2.920181	2.82445
120 - Active	11412-78	13C	33.57	25.1923	75.5786	0.221428	27.9834	52.9066	24.9232	0.1417	5.518703	2.567632231	2.635297	
120 - Contr	11412-78	12A	27.77	25.1704	75.5126	0.240762	27.15	52.3263	25.1763	0.2475	6.061501	4.08314676	4.256965	
120 - Contr	11412-78	12B	27.77	25.1704	75.5126	0.240762	26.9176	51.9723	25.0547	0.2318	6.032225	3.84269501	3.996259	3.951498
120 - Contr	11412-78	12C	27.77	25.1704	75.5126	0.240762	28.2821	53.3266	25.0445	0.2096	6.029769	3.476086735	3.60127	

P82093 EXTRACTIONS

DAY ZERO

BASELINE - ACTIVE COMPOST 2:1 (vol)

Thimble	A1	A2	A3	
mixture wt	17.4151	16.3196	17.8523	
compost	1.212643	1.136362	1.243086	Dry Wt.
extract wt	0.0428	0.0408	0.0411	
% H.C.	3.6586106	3.724116	3.419341	Dry Inert Basis
Average H.C. %		3.600689		

DAY 7 - ACTIVE

Thimble	15-1	15-2	15-3	
mixture wt	20.2504	20.8172	20.8097	
compost	1.405796	1.445144	1.444623	Dry Weight
extract wt	0.051	0.0536	0.0544	
% H.C.	3.76440438	3.851837	3.913041	Dry Inert Basis
Average H.C. %		3.843094		

DAY 14 - ACTIVE

Thimble	R1A	R1B	R1C	
mixture wt	24.6002	24.6775	25.2442	
compost	6.004073	6.022939	6.161252	Dry Weight
extract wt	0.0725	0.1999	0.1778	
% H.C.	1.22227274	3.432915	2.971529	Dry Inert Basis
Average H.C. %		2.542239		

DAY 21 - ACTIVE

Thimble	3A	3B	3C	
mixture wt	25.83	25.36	23.83	
compost	5.206559	5.091664	4.803419	Dry Weight
extract wt	0.2006	0.1827	0.1609	
% H.C.	4.00722419	3.721763	3.465791	Dry Inert Basis
Average H.C. %		3.731593		

DAY 35 - ACTIVE

Thimble	5A	5B	5C	
mixture wt	32.75	31.29	25.66	
compost	6.740777	6.440272	5.281476	Dry Weight
extract wt	0.2459	0.2581	0.1916	
% H.C.	3.78606092	4.174908	3.764335	Dry Inert Basis
Average H.C. %		3.908435		

DAY 49 - ACTIVE

Thimble	11A	11B	11C	
mixture wt	29.9908	29.621	30.1163	
compost	6.321561	6.243613	6.348014	Dry Weight
extract wt	0.2301	0.2098	0.2376	
% H.C.	3.77741891	3.477072	3.888444	Dry Inert Basis
Average H.C. %		3.714311		

DAY 70 - ACTIVE

Thimble	9A	9B	9C	
mixture wt	30.03	29.99	31.26	
compost	6.408903	6.400366	6.671405	Dry Weight
extract wt	0.1767	0.1849	0.1767	
% H.C.	2.8352735	2.974837	2.720678	Dry Inert Basis
Average H.C. %		2.843596		

BASELINE - CONTROL COMPOST 2:1 (vol)

Thimble	C1	C2	C3	
mixture wt	24.978	24.9712	25.7838	
compost	1.640717	1.64027	1.693647	Dry Wt.
extract wt	0.0555	0.0608	0.0619	
% H.C.	3.501098	3.849393	3.79348	Dry Inert Basis
Average H.C. %		3.714657		

DAY 7 - CONTROL

Thimble	16-1	16-2	16-3	
mixture wt	21.2617	21.4956	20.9867	
compost	1.470612	1.486791	1.451591	Dry Weight
extract wt	0.056	0.0554	0.0555	
% H.C.	3.958683	3.870361	3.975386	Dry Inert Basis
Average H.C.%		3.93481		

DAY 14 - CONTROL

Thimble	R2A	R2B	R2C	
mixture wt	24.9545	24.828	24.8535	
compost	6.074276	6.043484	6.049691	Dry Weight
extract wt	0.2335	0.235	0.2347	
% H.C.	3.997756	4.045806	4.03612	Dry Inert Basis
Average H.C.%		4.026561		

DAY 21 - CONTROL

Thimble	4A	4B	4C	
mixture wt	25.42	26.34	25	
compost	6.160886	6.38386	6.059093	Dry Weight
extract wt	0.21	0.2337	0.2072	
% H.C.	3.528886	3.799901	3.540735	Dry Inert Basis
Average H.C.%		3.623174		

DAY 35 - CONTROL

Thimble	6A	6B	6C	
mixture wt	25.92	24.62	24.8	
compost	6.747374	6.408965	6.455821	Dry Weight
extract wt	0.2203	0.2277	0.1968	
% H.C.	3.375172	3.683712	3.144262	Dry Inert Basis
Average H.C.%		3.401049		

DAY 49 - CONTROL

Thimble	14A	14B	14C	
mixture wt	30.0356	27.9191	29.9531	
compost	6.671139	6.201048	6.652815	Dry Weight
extract wt	0.2638	0.271	0.242	
% H.C.	4.117154	4.569946	3.774871	Dry Inert Basis
Average H.C.%		4.15399		

DAY 70 - CONTROL

Thimble	10A	10B	10C	
mixture wt	29.44	29.48	28.9	
compost	7.854592	7.865264	7.71052	Dry Weight
extract wt	0.2673	0.2655	0.2513	
% H.C.	3.522996	3.49353	3.368985	Dry Inert Basis
Average H.C.%		3.461837		

DAY 98 - ACTIVE

Thimble	7A	7B	7C	
mixture wt	29.714	30.0228	29.1923	
compost	6.581342	6.649738	6.465791	Dry Weight
extract wt	0.1645	0.1953	0.195	
% H.C.	2.56356632	3.025825	3.109656	Dry Inert Basis
Average H.C. %		2.899682		

DAY 120 - ACTIVE

Thimble	13A	113B	13C	
mixture wt	25.1202	25.1964	24.9232	
compost	5.562325	5.579197	5.518703	Dry Weight
extract wt	0.1577	0.1583	0.1417	
% H.C.	2.91787127	2.920181	2.635297	Dry Inert Basis
Average H.C. %		2.82445		

DAY 98 - CONTROL

Thimble	8A	8B	8C	
mixture wt	28.8455	29.1649	30.7915	
compost	7.625695	7.710133	8.140147	Dry Weight
extract wt	0.2153	0.2333	0.2612	
% H.C.	2.905378	3.120305	3.315164	Dry Inert Basis
Average H.C.%		3.113616		

DAY 120 - CONTROL

Thimble	12A	12B	12C	
mixture wt	25.1763	25.0547	25.0445	
compost	6.061501	6.032225	6.029769	Dry Weight
extract wt	0.2475	0.2318	0.2096	
% H.C.	4.256965	3.996259	3.60127	Dry Inert Basis
Average H.C.%		3.951498		

Appendix J: CO2 Monitoring Data

DAY7A.XLS

Date	Elapsed Ti	Elapsed Ti	VOC, ppm	CO2, %	Temperatu	Flowrate, s	Flowrate, c	Cumulative	Moisture, T	CO2, cc	Cum CO2,	Moles CO2	VOC, cc	Cum VOC,	Cum VOC,	Total moles	% Total C Removed	
2/16/94	0	0	2300	1.5	74.1	0	0	0	6.3	0	0	0	0	0	0	0	0	
2/17/94	1	20	120	3.6	74.5	40	14.08706	16904.47	6.9	600.1066	600.1066	0.023747	2.026536	8.03E-05	2.026536	0.023807	0.359505	
2/18/94	2	44	220	6.3	94.1	38	13.54167	36404.47	6.7	1179.75	1779.856	0.07043	4.29	0.00025	6.316536	0.07093	1.066614	
2/19/94	3	68	209	7.6	94.7	38	13.54167	55904.47	6	1433.25	3213.109	0.127144	3.9	0.000404	10.21654	0.127953	1.924102	
2/20/94	4	96	250	8.5	111.8	48	16.49635	83621.69	10.2	2286.671	5499.78	0.217629	6.929306	0.000679	17.14784	0.218966	3.293018	
2/21/94	5	118	560	11.5	113.1	44	15.24675	103747.4	9.5	2264.143	7763.923	0.307222	11.67291	0.00114	28.82076	0.309503	4.654175	
2/22/94	6	142	480	14.3	113.1	40	14.08706	124032.8	9.9	2850.093	10614.02	0.429001	9.736973	0.001526	38.55773	0.423053	6.361083	
2/23/94	7	166	300	14.5	112.9	40	14.08706	144318.1	10	2890.664	13504.66	0.534366	6.085606	0.001767	44.64334	0.537919	8.089008	

DAY14A.XLS

Date	Elapsed Ti	Elapsed Ti	VOC, ppm	CO2, %	Temperatu	Flowrate, s	Flowrate, c	Cumulative	Moisture, T	CO2, cc	Cum CO2,	Moles CO2	VOC, cc	Cum VOC,	Cum VOC,	Total moles	% Total C Removed	
2/16/94	0	0	2100	7	73.8	0	0	0	10.5	0	0	0	0	0	0	0	0	
2/17/94	1	20	60	0.4	73.9	40	14.06706	16904.47	8.5	25.3567	25.3567	0.001003	1.014268	4.01E-05	1.014268	0.001064	0.016295	
2/18/94	2	44	94	0.8	93.9	46	15.86106	39744.4	9.5	125.6196	150.9763	0.005974	2.146954	1.25E-04	3.161222	0.006224	0.0936	
2/19/94	3	68	85	0.5	94.4	50	17.15661	64452.79	9.8	61.77096	212.7473	0.008419	2.100213	2.06E-04	5.261435	0.008635	0.132656	
2/20/94	4	96	120	0.9	111.5	47	16.17683	91629.87	10.1	176.651	389.3983	0.015409	3.26125	3.37E-04	8.522684	0.016063	0.241652	
2/21/94	5	118	110	3.8	114.5	42	14.65542	110975	9.8	686.7529	1076.151	0.042584	2.127967	4.21E-04	10.65065	0.043427	0.653032	
2/22/94	6	142	170	2.2	116.3	42	14.65542	132078.8	10	411.5241	1487.675	0.058888	3.587646	5.63E-04	14.2383	0.059995	0.902177	
2/23/94	7	166	68	2.3	114.1	28	11.15934	148148.3	10.8	329.4236	1817.099	0.071903	1.092723	6.07E-04	15.33102	0.073117	1.099499	
2/24/94	8	190	87	1.7	113.1	40	14.06706	168433.6	11	294.1377	2111.237	0.083543	1.764626	6.76E-04	17.09565	0.084698	1.276624	
2/25/94	9	214	30	1.5	112.6	40	14.06706	188719	11.3	253.567	2364.804	0.093576	0.608561	7.01E-04	17.70441	0.094977	1.428232	
2/26/94	10	244	32	1	112	38	13.54167	213094	11.9	182.8126	2547.616	0.10081	0.78	7.31E-04	18.48441	0.102273	1.537942	
2/27/94	11	266	52	0.9	112.2	40	14.06706	231688.9	10.8	120.8669	2668.483	0.105593	0.966936	7.70E-04	19.45134	0.107132	1.611014	
2/28/94	12	287	63	0.8	111.5	40	14.06706	249436.6	10.4	97.6233	2766.107	0.109456	1.11823	8.14E-04	20.56957	0.111084	1.670435	
3/1/94	13	311	34	0.6	111.3	40	14.06706	269724	9.6	70.99676	2837.105	0.112265	0.689702	8.41E-04	21.25928	0.113946	1.713503	
3/2/94	14	336	18	0.5	110.9	40	14.06706	290654.5	9.1	52.82646	2889.932	0.114356	0.380351	8.56E-04	21.63963	0.116066	1.74539	

DAY21A.XLS

Date	Elapsed Ti	Elapsed Ti	VOC, ppm	CO2, %	Temperatu	Flowrate, s	Flowrate, c	Cumulative	Moisture, T	CO2, cc	Cum CO2,	Moles CO2	VOC, cc	Cum VOC,	Cum VOC,	Total moles	% Total C Removed	
2/16/94	0	0	1600	8.8	71.1	0	0	0	14.2	0	0	0	0	0	0	0	0	
2/17/94	1	20	70	0.3	73.9	40	14.06706	16904.47	10.6	8.452233	8.452233	0.000334	1.183313	4.68E-05	1.183313	0.000428	0.008436	
2/18/94	2	44	90	20.2	94.1	44	15.24675	36869.79	11.7	4380.087	4388.539	0.173658	1.975979	1.25E-04	3.159292	0.173908	5.188136	
2/19/94	3	68	77	20.5	94.1	40	14.06706	59145.15	11.6	4107.786	8496.325	0.336203	1.561973	1.87E-04	4.721265	0.336577	10.04107	
2/20/94	4	96	110	0.7	111	43	14.94821	84256.15	12.1	113.0086	8609.333	0.340675	2.76243	2.96E-04	7.483694	0.341267	10.181	
2/21/94	5	118	80	1.5	116.5	38	13.54167	102133.2	10.9	223.4375	8832.771	0.349516	1.43	3.53E-04	8.913695	0.350222	10.44615	
2/22/94	6	142	120	1.8	115.5	42	14.65542	123237	9.2	327.1069	9159.88	0.36246	2.532458	4.53E-04	11.44615	0.363366	10.84028	
2/23/94	7	166	58	1.5	113.2	40	14.06706	143522.3	9.2	253.567	9413.447	0.372494	1.176551	4.99E-04	12.6227	0.373493	11.14239	
2/24/94	8	190	70	0.9	112.6	40	14.06706	163807.7	9.4	131.8548	9545.302	0.377712	1.419975	5.56E-04	14.04268	0.378823	11.3014	
2/25/94	9	214	28	1	112.4	35	12.76666	182191.7	9	137.88	9683.182	0.383168	0.514752	5.76E-04	14.55743	0.38432	11.46536	
2/26/94	10	244	28	0.8	111.8	35	12.76666	205171.7	8.6	126.39	9809.572	0.388169	0.64344	6.02E-04	15.20087	0.389372	11.61611	
2/27/94	11	268	44	0.6	111.3	40	14.06706	223766.6	8.4	65.0822	9874.654	0.390744	0.818176	6.34E-04	16.01904	0.392012	11.69487	
2/28/94	12	287	48	0.5	110.3	40	14.06706	241516.3	7.5	44.37423	9919.028	0.3925	0.851985	6.68E-04	16.87103	0.393836	11.74926	
3/1/94	13	311	35	0.5	110.5	40	14.06706	261801.6	10.7	50.7134	9969.741	0.394507	0.709988	6.96E-04	17.58102	0.395899	11.81081	
3/2/94	14	336	16	0.5	110.4	40	14.06706	282932.2	6.7	52.82646	10022.57	0.396597	0.338089	7.09E-04	17.91911	0.398015	11.87397	
3/3/94	15	360	18	0.4	109	60	20.60451	312890.7	5.2	44.93774	10067.51	0.398375	0.539253	7.30E-04	18.45836	0.399836	11.92829	
3/4/94	16	384	14	0.4	107.9	35	12.76666	331274.7	5.3	27.57599	10095.08	0.399467	0.257376	7.41E-04	18.71574	0.400948	11.96145	
3/5/94	17	406	5	0.3	106.5	47	16.17683	352628.1	7.2	10.67671	10105.76	0.399889	0.106767	7.45E-04	18.8225	0.401379	11.97431	
3/7/94	19	454	28	0.3	106.3	42	14.65542	394835.7	7.2	21.1038	10126.86	0.400724	1.181813	7.92E-04	20.00432	0.402307	12.00201	
3/8/94	20	478	12	0.3	106.7	42	14.65542	415938.5	3.5	10.5519	10137.41	0.401142	0.253246	8.02E-04	20.25756	0.402746	12.01506	
3/9/94	21	502	34	0.3	106.6	40	14.06706	436224.9	3	10.14268	10147.56	0.401543	0.689702	8.29E-04	20.94726	0.403201	12.02867	

DAY35A.XLS

Date	Elapsed Ti	Elapsed Ti	VOC, ppm	CO2, %	Temperatu	Flowrate, s	Flowrate, c	Cumulative	Moisture, T	CO2, cc	Cum CO2,	Moles CO2	VOC, cc	Cum VOC,	Cum VOC,	Total moles	% Total C Removed	
2/16/94	0	0	2100	4	71.1	0	0	0	10.8	0	0	0	0	0	0	0	0	0 time = 1
2/17/94	1	20	66	0.75	73.6	40	14.06706	18904.47	6.7	84.52233	84.52233	0.003345	1.115685	4.41E-05	1.115685	0.003433	0.051622	
2/18/94	2	44	92	1.5	93.9	45	15.55104	39297.96	9.4	279.9167	364.441	0.014421	2.060201	0.000126	3.175886	0.014672	0.220636	
2/19/94	3	68	94	1.5	94.1	46	16.49835	63055.56	9.3	296.9703	661.4112	0.026172	2.233216	0.000214	5.409112	0.0266	0.400006	
2/20/94	4	96	120	2.2	111.2	64	22.42369	100727.4	9.7	734.6001	1396.011	0.055241	4.520616	0.000393	9.929728	0.056027	0.842505	
2/21/94	5	118	120	4.8	116.2	42	14.65542	120072.5	8.8	880.2044	2276.216	0.090071	2.321418	0.000485	12.25115	0.09104	1.369028	
2/22/94	6	142	260	4.2	116	42	14.65542	141176.3	8.5	833.6001	3109.816	0.123057	5.486968	0.000702	17.73813	0.124461	1.871567	
2/23/94	7	166	140	5	113.8	40	14.06706	161461.7	9.3	963.5546	4073.37	0.161185	2.83995	0.000814	20.57809	0.162814	2.448324	
2/24/94	8	190	120	3.8	113.1	39	13.81149	181350.2	10.1	706.0434	4779.414	0.189123	2.386625	0.000909	22.96471	0.190841	2.871291	
2/25/94	9	214	80	3.6	112.6	38	13.01925	200098	10.7	665.5443	5444.958	0.215459	1.499816	0.000966	24.46453	0.217395	3.269104	
2/26/94	10	244	66	3	112	38	13.54167	224473	9.6	670.3128	6115.271	0.241964	1.60875	0.001032	26.07328	0.244047	3.669684	
2/27/94	11	268	90	2.7	111.9	40	14.06706	243067.9	9.3	455.5754	6570.846	0.260011	1.673542	0.001098	27.74682	0.262207	3.942963	
2/28/94	12	287	83	2.3	111.8	40	14.06706	260617.6	8.6	363.8686	6934.715	0.27441	1.473224	0.001156	29.22005	0.276722	4.161235	
3/1/94	13	311	76	2.2	111.6	43	14.94621	282343	8.4	419.7458	7354.461	0.291019	1.635932	0.001221	30.85598	0.293461	4.412948	
3/2/94	14	336	49	1.9	110.9	42	14.65542	304326.1	6.8	362.7216	7717.182	0.305372	1.077173	0.001264	31.93315	0.307699	4.630066	
3/3/94	15	360	60	1.6	110.8	60	20.80451	334264.6	5.8	404.4397	8121.622	0.321376	1.79751	0.001335	33.73066	0.324045	4.872864	
3/4/94	16	384	60	1.3	10.2	43	14.94621	355810	19	226.017	8347.639	0.33032	1.291526	0.001366	35.02219	0.333091	5.008692	
3/5/94	17	408	40	0.9	110.3	42	14.65542	375155.2	5.3	125.7436	8473.382	0.335295	0.773806	0.001416	35.79599	0.338128	5.084635	
3/7/94	19	454	52	0.8	109.2	43	14.94621	418296	3	236.7797	8710.162	0.344865	2.238644	0.001505	38.03464	0.347675	5.228194	
3/8/94	20	478	36	0.6	109.2	40	14.06706	436491.4	5.3	111.5695	8821.731	0.34908	0.730273	0.001534	38.76491	0.352148	5.295452	
3/9/94	21	502	55	0.7	109.1	40	14.06706	458776.8	5.6	91.28412	8913.016	0.352692	1.115685	0.001578	39.8806	0.355648	5.351098	
3/10/94	22	523	46	0.6	109.2	40	14.06706	478528.5	3.2	62.12392	8975.139	0.35516	0.816486	0.00161	40.69709	0.358371	5.369036	
3/11/94	23	548	58	0.8	109.7	35	12.76666	495876.5	6	105.325	9080.464	0.359318	1.1107	0.001654	41.80779	0.362627	5.45303	
12-Mar	24	576	42	0.7	109.1	40	14.06706	521033.2	2.6	114.1052	9194.57	0.363633	1.064961	0.001696	42.87277	0.367226	5.522195	
3/13/94	25	599	52	0.6	109.5	40	14.06706	538782.8	6.1	97.6233	9292.193	0.367696	0.922964	0.001733	43.79576	0.371182	5.561384	
3/14/94	26	621	46	0.8	108.9	42	14.65542	558128	2.6	106.3963	9398.591	0.371906	0.869877	0.001768	44.66563	0.375443	5.645755	
3/15/94	27	645	26	0.6	106.9	47	16.17883	581422.6	2.5	81.53124	9480.122	0.375132	0.605661	0.001792	45.29129	0.378717	5.68499	
3/16/94	28	669	43	0.5	109.2	40	14.06706	601706	3.1	50.7134	9530.836	0.377139	0.87227	0.001827	46.16356	0.380793	5.726205	
3/17/94	29	693	42	0.7	109.3	44	15.24675	623663.3	2.7	98.79696	9629.635	0.381049	0.922124	0.001863	47.08569	0.384775	5.786092	
3/18/94	30	717	45	0.5	109.4	42	14.65542	644767.1	3.4	52.7595	9682.394	0.383136	0.949671	0.001901	48.03536	0.386938	5.818617	
3/19/94	31	744	42	0.6	109.2	42	14.65542	668506.9	3.2	83.09622	9765.491	0.386425	0.997155	0.00194	49.03251	0.390305	5.869249	
3/20/94	32	770	36	0.6	108.8	42	14.65542	691371.3	3.1	80.01658	9845.509	0.389591	0.868773	0.001975	49.90129	0.39354	5.917698	
3/21/94	33	788	48	0.5	109.1	40	14.06706	706565.4	3.6	38.03505	9883.544	0.391096	0.730273	0.002004	50.63156	0.395103	5.941399	
3/22/94	34	812	44	0.6	109.3	42	14.65542	727689.2	4	73.8633	9957.407	0.394019	0.928567	0.00204	51.56013	0.398099	5.966456	
3/23/94	35	836	16	0.5	106.9	40	14.06706	747974.5	4.1	50.7134	10008.12	0.396028	0.324566	0.002053	51.88469	0.400132	6.017019	

DAY49A.XLS

Date	Elapsed Ti	Elapsed Ti	VOC, ppm	CO2, %	Temperatu	Flowrate, s	Flowrate, c	Cumulative	Moisture, T	CO2, cc	Cum CO2,	Moles CO2	VOC, cc	Cum VOC,	Cum VOC,	Total mole	% Total C Removed	
2/16/94	0	0	2400	4.6	72.9	0	0	0	12.7	0	0	0	0	0	0	0	0	0 = 1 pm
2/17/94	1	20	50	2.8	74.8	40	14.06706	16904.47	11.3	431.0639	431.0639	0.017057	0.845223	3.34E-05	0.845223	0.017124	0.257506	
2/18/94	2	44	66	3.5	94.4	42	14.65542	38008.27	12.6	685.8736	1116.937	0.044196	1.392851	8.86E-05	2.238074	0.044375	0.66729	
2/19/94	3	68	75	4.91	95.2	37	13.27759	57128	12.7	890.9794	2007.917	0.079454	1.43396	0.000145	3.672054	0.079745	1.199169	
2/20/94	4	96	75	3.5	111.8	57	19.65043	90140.72	14.6	1072.914	3080.83	0.12191	2.475954	0.000243	6.148008	0.122396	1.840546	
2/21/94	5	118	570	12	112.5	37	13.27759	107867.1	15.6	2059.354	5140.185	0.203399	9.990056	0.000639	16.13807	0.204676	3.077641	
2/22/94	6	142	1800	14.27	112.9	39	13.81149	127555.7	14.9	2786.374	7926.559	0.313736	35.79938	0.002055	51.93745	0.317847	4.779651	
2/23/94	7	166	840	14	112.9	38	13.54167	147056.7	15.3	2681.25	10609.81	0.419835	16.38	0.002703	68.31745	0.425241	6.394606	
2/24/94	8	190	290	14.8	112.6	40	14.06706	167341	14.8	2951.52	13561.33	0.536628	5.882754	0.002936	74.20021	0.5425	8.157692	
2/25/94	9	214	465	15	112.4	28	11.15934	183410.5	15.1	2370.244	15931.57	0.630419	7.472296	0.003232	81.6725	0.636883	9.577164	
2/26/94	10	244	115	15.11	112.6	42	14.65542	209790.3	13	3920.031	19851.6	0.785536	3.033671	0.003352	84.70617	0.79224	11.91339	
2/27/94	11	266	155	14.47	112.2	25	10.55864	223725	13.1	1981.524	21833.13	0.863946	2.159869	0.003437	86.86606	0.870821	13.09505	
2/28/94	12	287	170	14.37	112.9	43	14.94821	242559.8	14	2659.467	24492.6	0.969182	3.201907	0.003564	90.06797	0.97631	14.68136	
3/1/94	13	311	160	12.84	112.7	45	15.56104	264953.3	14.3	2819.341	27311.94	1.080745	3.582959	0.003706	93.65093	1.088156	16.36326	
3/2/94	14	336	120	12.71	112.1	43	14.94821	287375.6	14.4	2793.821	30105.76	1.191296	2.690678	0.003812	96.34161	1.196922	18.0289	
3/3/94	15	360	110	11.14	111.8	65	22.84284	320269.3	15	3562.123	33667.88	1.333044	3.618307	0.003955	99.95991	1.340955	20.16473	
3/4/94	16	384	120	10.95	111.3	43	14.94821	341794.7	14.5	2303.221	35991.1	1.424183	2.583051	0.004056	102.543	1.432296	21.53832	
3/5/94	17	406	66	2.5	112.3	40	14.06706	360399.6	14.4	418.3856	36409.49	1.440739	1.264454	0.004106	103.8074	1.448954	21.78879	
3/7/94	19	454	52	1.5	111.3	40	14.06706	400960.3	14.1	507.134	36916.62	1.460806	2.109677	0.004191	105.9171	1.469189	22.09306	
3/8/94	20	478	52	1.8	111.2	40	14.06706	421245.7	14.5	314.4231	37231.04	1.473248	1.054839	0.004233	106.9719	1.481714	22.28141	
3/9/94	21	502	66	1.3	111.1	40	14.06706	441531.1	14.1	212.9963	37444.04	1.481677	1.338834	0.004286	108.3108	1.490246	22.40975	
3/10/94	22	523	42	1.1	111.2	42	14.65542	458996.9	14.6	156.9596	37601	1.487887	0.775565	0.004317	109.0863	1.496521	22.50407	
3/11/94	23	548	210	6	111.1	30	11.59986	477381.7	14.8	999.6254	38600.62	1.527443	3.650606	0.004461	112.7371	1.536365	23.10324	
12-Mar	24	578	50	1.2	111.1	40	14.06706	502736.4	14.4	240.8887	38841.51	1.536975	1.267835	0.004511	114.005	1.545996	23.24808	
3/13/94	25	599	32	0.5	110.4	40	14.06706	520466.1	13.5	44.37423	38885.89	1.538731	0.56799	0.004534	114.573	1.547798	23.27516	
3/14/94	26	621	48	1	110.6	42	14.65542	539633.2	13.2	145.0866	39030.98	1.544472	0.928567	0.00457	115.5015	1.553613	23.3626	
3/15/94	27	645	34	0.9	110.6	40	14.06706	560118.6	13.4	131.8546	39162.83	1.54969	0.689702	0.004596	116.1912	1.558865	23.44186	
3/16/94	28	669	53	0.8	110.9	40	14.06706	580403.9	13.2	111.5695	39274.4	1.554105	1.075124	0.00464	117.2664	1.563386	23.50955	
3/17/94	29	693	44	0.9	110.7	39	13.81149	600292.5	12.6	129.2755	39403.68	1.55922	0.875096	0.004675	118.1415	1.56867	23.58752	
3/18/94	30	717	50	0.8	110.8	40	14.06706	620577.8	11.2	111.5695	39515.25	1.563635	1.014266	0.004715	119.1557	1.573065	23.65511	
3/19/94	31	744	46	0.7	111	40	14.06706	643398.9	11.9	102.6946	39617.94	1.567699	1.049767	0.004757	120.2055	1.577212	23.71747	
3/20/94	32	770	41	0.8	110.8	40	14.06706	665374.7	12.1	120.6669	39738.61	1.572461	0.901008	0.004792	121.1065	1.582066	23.79046	
3/21/94	33	788	54	0.7	110.7	42	14.65542	681202.5	11.1	71.22533	39810.03	1.5753	0.854704	0.004826	121.9612	1.584952	23.83366	
3/22/94	34	812	60	0.8	110.7	42	14.65542	702306.3	11.4	116.0709	39926.1	1.579893	1.266228	0.004876	123.2274	1.589645	23.90444	
3/23/94	35	836	30	0.7	110.2	44	15.24675	724261.7	11.5	96.79696	40024.9	1.583802	0.65866	0.004902	123.8861	1.593607	23.96401	
3/24/94	36	860	46	0.5	110.6	70	25.02477	760297.3	11.2	90.06916	40114.99	1.587367	1.657641	0.004966	125.5437	1.597303	24.01959	
3/25/94	37	884	110	0.5	110.6	70	25.02477	796333	11.2	90.06916	40205.06	1.590932	3.963923	0.005125	129.5077	1.601181	24.07792	
3/27/94	39	934	38	0.6	110.6	42	14.65542	840299.2	10.8	153.6619	40358.96	1.597021	1.670716	0.005191	131.1784	1.607403	24.17147	
3/28/94	40	958	42	0.5	110.5	41	14.36836	859265.5	10.6	47.4156	40406.36	1.598898	0.796582	0.005222	131.975	1.609342	24.20063	
3/29/94	41	981	46	0.6	110.6	35	12.76666	878415.5	10.3	67.02496	40473.4	1.60155	0.8809	0.005257	132.8559	1.612064	24.24156	
3/30/94	42	1005	56	0.6	110.6	36	13.01925	897163.2	10.4	65.61704	40539.02	1.604146	1.049673	0.005299	133.9057	1.614744	24.28186	
3/31/94	43	1029	42	0.6	110.3	44	15.24675	919118.5	10	76.84364	40615.86	1.607187	0.922124	0.005335	134.8278	1.617657	24.32868	
4/1/94	44	1053	44	0.5	110.5	45	15.55104	941512	10.1	55.96373	40671.85	1.609402	0.985314	0.005374	135.8132	1.620151	24.36317	
4/2/94	45	1080	34	0.4	110.6	43	14.94821	965728.1	9.8	36.32418	40708.17	1.61084	0.823348	0.005407	136.6365	1.621653	24.38576	
4/4/94	47	1125	32	0.5	110.3	40	14.06706	1003783	9.4	95.06763	40803.26	1.614602	1.217122	0.005455	137.8536	1.625512	24.44379	

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Date	Elapsed Ti	Elapsed Ti	VOC, ppm	CO2, %	Temperatu	Flowrate, s	Flowrate, c	Cumulative	Moisture, T	CO2, cc	Cum CO2,	Moles CO2	VOC, cc	Cum VOC,	Cum VOC,	Total mole	% Total C Removed	
4/5/94	48	1150	32	0.5	110.1	45	15.55104	1027090	9.4	58.31639	40661.58	1.61691	0.74645	0.005484	138.8001	1.627879	24.47936	
4/6/94	49	1174	42	0.4	110.2	45	15.55104	1049483	9.3	33.59024	40695.17	1.618239	0.940527	0.005522	139.5406	1.629282	24.50049	

Date	Elapsed Ti	Elapsed Ti	VOC, ppm	CO2, %	Temperatu	Flowrate, s	Flowrate, c	Cumulative	Moisture, T	CO2, cc	Cum CO2,	Moles CO2	VOC, cc	Cum VOC,	Cum VOC,	Total mole	% Total C Removed
2/16/94	0	0	2500	6	72	0	0	0	18.9	0	0	0	0	0	0	0	0
2/17/94	1	20	30	0.9	74.2	40	14.06706	16904.47	15.4	109.879	109.879	0.004346	0.507134	2.01E-05	0.507134	0.004366	0.065966
2/18/94	2	44	40	1.4	93.9	37	13.27759	36024.2	16.2	219.8769	329.7559	0.013049	0.764789	5.03E-05	1.271923	0.013149	0.197733
2/19/94	3	68	40	1.8	94.4	25	10.55664	51225.78	18.8	235.6243	565.3802	0.022372	0.608063	7.44E-05	1.879986	0.022521	0.338683
2/20/94	4	96	48	1.8	111.5	52	17.84184	81200.05	18.9	464.6015	1029.982	0.040757	1.436766	0.000131	3.316752	0.041019	0.616834
2/21/94	5	118	180	14.28	115.4	36	12.76686	96052.05	18.1	2364.335	3394.317	0.134315	3.033359	0.000251	6.352111	0.134817	2.027327
2/22/94	6	142	360	10.5	114.6	45	15.55104	120445.5	15.6	2295.333	5689.65	0.225142	8.061657	0.00057	14.41377	0.226283	3.402745
2/23/94	7	166	160	8.9	113.2	36	12.76686	136629.5	14.6	1590.216	7279.866	0.288067	2.941439	0.000687	17.35521	0.289441	4.352494
2/24/94	8	190	160	7.3	112.8	40	14.06706	159114.9	14.1	1430.116	8709.983	0.344656	3.245656	0.000815	20.60087	0.346266	5.20734
2/25/94	9	214	96	6.8	112.9	43	14.94821	180640.3	14.6	1409.915	10119.9	0.400449	2.109492	0.000899	22.71036	0.402246	6.046612
2/26/94	10	244	66	5.8	112	40	14.06706	205997	13.2	1407.297	11527.2	0.456136	1.724256	0.000967	24.43461	0.45607	6.866267
2/27/94	11	266	60	4.8	111.9	36	12.76686	222649	12.6	766.7656	12293.96	0.486477	1.34616	0.00102	25.78277	0.488518	7.346131
2/28/94	12	287	83	4.6	111.8	40	14.06706	240596.7	10.6	772.1115	13066.07	0.51703	1.473224	0.001079	27.256	0.519187	7.807325
3/1/94	13	311	74	3.7	111.6	38	13.54167	260096.7	10.5	672.7501	13738.82	0.543651	1.443	0.001136	28.699	0.545922	8.209358
3/2/94	14	336	52	3.5	111.2	40	14.06706	281229.3	9.2	686.744	14425.57	0.570626	1.09879	0.001179	29.79779	0.573184	8.619306
3/3/94	15	360	58	3.2	111.3	50	17.15661	306937.7	9.4	728.8976	15154.46	0.599689	1.433087	0.001236	31.23087	0.60214	9.05474
3/4/94	16	384	52	1.9	110.7	47	16.17683	329232.3	16.9	384.3616	15538.83	0.614678	1.211321	0.001284	32.44219	0.617446	9.284694
3/5/94	17	408	28	0.5	110.3	40	14.06706	347827.2	12.6	46.48728	15585.31	0.616717	0.520658	0.001304	32.96285	0.619326	9.313175
3/7/94	19	454	40	0.8	110.3	43	14.94821	390878.1	9.5	236.7797	15822.09	0.626087	1.722034	0.001372	34.68489	0.628632	9.456119
3/8/94	20	478	40	0.9	110.1	42	14.65542	411981.9	19.3	137.1747	15959.27	0.631515	0.844152	0.001406	35.52904	0.634327	9.536749
3/9/94	21	502	48	0.8	110	40	14.06706	432257.3	9.9	111.5695	16070.84	0.63593	0.973697	0.001444	36.50274	0.638619	9.606296
3/10/94	22	523	40	0.8	110.3	42	14.65542	450733.1	8.8	101.562	16172.4	0.639949	0.738633	0.001474	37.24137	0.642896	9.667609
3/11/94	23	548	94	6.6	110.6	30	11.56866	468117.9	18.3	1138.704	17311.1	0.685006	1.63417	0.001536	38.87554	0.686064	10.34713
12-Mar	24	578	32	0.7	110.3	40	14.06706	493474.6	12.8	114.1052	17425.21	0.689523	0.811414	0.00157	39.68695	0.692664	10.416
3/13/94	25	599	50	1	110.1	40	14.06706	511224.3	9	133.1227	17558.33	0.694791	0.887485	0.001606	40.57444	0.696002	10.49627
3/14/94	26	621	40	0.8	110	39	13.81149	529455.4	8.4	100.2714	17658.6	0.698756	0.729247	0.001634	41.30368	0.702027	10.5566
3/15/94	27	645	30	0.8	109.8	47	16.17683	552750.1	16.9	128.1205	17786.72	0.703828	0.698839	0.001662	42.00252	0.707152	10.63367
3/16/94	28	669	51	0.8	110.1	40	14.06706	573035.4	9.9	111.5695	17898.29	0.708243	1.034563	0.001703	43.03708	0.711649	10.70149
3/17/94	29	693	40	0.8	110.2	40	14.06706	593320.8	18	111.5695	18009.86	0.712658	0.811414	0.001735	43.84849	0.716128	10.76664
3/18/94	30	717	42	0.7	110.2	38	13.54167	612820.8	10.7	87.75001	18097.61	0.71613	0.819	0.001766	44.66749	0.719665	10.82203
3/19/94	31	744	42	0.8	110.1	42	14.65542	636562.6	17.1	130.5796	18228.19	0.721297	0.997155	0.001807	45.66465	0.724911	10.90092
3/20/94	32	770	40	0.8	110.2	41	14.36836	658977.2	8.6	123.2806	18351.47	0.726176	0.896586	0.001842	46.56123	0.72966	10.97534
3/21/94	33	788	50	0.8	110	41	14.36836	674495	15.6	85.34809	18436.82	0.729553	0.775892	0.001873	47.33712	0.733299	11.02705
3/22/94	34	812	48	0.4	110.1	40	14.06706	694780.4	8.8	30.42804	18467.25	0.730757	0.973697	0.001912	48.31082	0.73468	11.04632
3/23/94	35	836	30	0.7	109.6	42	14.65542	715884.2	7.5	94.9671	18562.22	0.734515	0.633114	0.001937	48.94394	0.736366	11.10356
3/24/94	36	860	46	0.5	109.8	64	22.42369	748174.3	6.1	80.72529	18642.94	0.737709	1.485345	0.001996	50.42928	0.7417	11.15336
3/25/94	37	884	24	0.8	109.7	55	18.90976	775404.4	5.3	149.7653	18792.71	0.743635	0.653521	0.002021	51.0828	0.747676	11.24328
3/27/94	39	934	34	0.8	110.1	43	14.94821	820249	4.5	246.6455	19039.35	0.753395	1.524718	0.002062	52.60752	0.757569	11.39166
3/28/94	40	958	46	0.8	110.2	39	13.81149	838460.2	6.5	100.2714	19139.62	0.757363	0.875096	0.002116	53.48262	0.761596	11.45257
3/29/94	41	981	50	0.8	110	38	13.54167	856792.7	5.1	111.7168	19251.34	0.761764	1.015625	0.002157	54.49824	0.766097	11.52025
3/30/94	42	1005	56	0.8	110	38	13.54167	876292.7	4.6	107.25	19358.59	0.766028	1.0725	0.002199	55.57074	0.770428	11.58535
3/31/94	43	1029	46	0.8	110	42	14.65542	898396.5	7.4	116.0709	19474.66	0.770621	0.970775	0.002237	56.54152	0.775095	11.65567
4/1/94	44	1053	54	0.7	110.2	41	14.36836	920086.9	5	93.107	19567.77	0.774305	1.117264	0.002282	57.6588	0.778668	11.7123
4/2/94	45	1080	42	0.7	110.2	45	15.55104	945279.6	4	113.3671	19681.14	0.778791	1.056093	0.002323	58.71689	0.783436	11.78102
4/4/94	47	1125	42	0.7	110	40	14.06706	983314.7	4.7	171.1577	19852.29	0.785584	1.597472	0.002367	60.31436	0.790337	11.88477

Date	Elapsed Ti	Elapsed Ti	VOC, ppm	CO2, %	Temperatu	Flowrate, s	Flowrate, c	Cumulative	Moisture, T	CO2, cc	Cum CO2,	Moles CO2	VOC, cc	Cum VOC,	Cum VOC,	Total mole	% Total C Removed	
4/5/94	48	1150	48	0.6	110.1	45	15.55104	1006641	5.6	81.64294	19933.94	0.788794	1.119675	0.002431	61.43404	0.793656	11.93466	
4/6/94	49	1174	48	0.6	110	42	14.65542	1027745	4	73.8633	20007.8	0.791717	1.012962	0.002471	62.44702	0.796659	11.97984	
4/7/94	50	1198	40	0.8	110.5	37	13.27759	1046665	8.7	105.1585	20112.96	0.795878	0.764789	0.002501	63.21181	0.800881	12.04332	
4/8/94	51	1222	30	0.7	110.4	37	13.27759	1065984	5.6	86.03678	20199	0.799283	0.573592	0.002524	63.7854	0.804331	12.0952	
4/9/94	52	1248	38	0.7	110.1	42	14.65542	1087088	4.2	94.9871	20293.96	0.803041	0.801944	0.002556	64.58735	0.808152	12.15267	
4/10/94	53	1274	32	0.6	110.7	43	14.94821	1112201	4.9	87.89549	20381.86	0.806519	0.803616	0.002588	65.39096	0.811694	12.20592	
4/11/94	54	1294	35	0.6	105.9	36	12.76666	1127521	3.8	53.61999	20435.48	0.808641	0.5362	0.002609	65.92716	0.813858	12.23847	power outa
4/12/94	55	1318	44	0.7	110.2	43	14.94821	1149047	3.5	96.86442	20532.34	0.812474	0.947119	0.002646	66.87428	0.817766	12.29723	
4/13/94	56	1343	46	0.6	110.8	45	15.55104	1172373	5	81.64294	20613.99	0.815704	1.073022	0.002689	67.9473	0.821082	12.34709	
4/14/94	57	1367	32	0.6	110.4	42	14.65542	1193477	4	73.8633	20687.85	0.818627	0.675322	0.002715	68.62262	0.824058	12.39185	
4/15/94	58	1391	34	0.6	110.4	47	16.17683	1216772	6.1	81.53124	20769.38	0.821853	0.792018	0.002747	69.41464	0.827347	12.4413	
4/16/94	59	1417	47	0.4	109.9	44	15.24675	1240557	5.2	35.6774	20805.06	0.823265	1.117892	0.002791	70.53253	0.828847	12.46387	
4/18/94	61	1470	40	0.6	110.4	43	14.94821	1286092	3.7	166.3736	20971.43	0.829848	1.901413	0.002866	72.43395	0.835581	12.56513	
4/19/94	62	1503	32	0.5	110	40	14.06706	1315984	3.2	69.73093	21041.16	0.832608	0.892556	0.002902	73.3265	0.838411	12.60768	
4/20/94	63	1518	36	0.4	110.4	43	14.94821	1329438	4.5	20.16009	21061.34	0.833406	0.484322	0.002921	73.81083	0.839248	12.62027	
4/21/94	64	1531	30	0.4	110	43	14.94821	1341087	3.7	17.46941	21078.83	0.834098	0.349786	0.002935	74.16061	0.839968	12.63109	
4/23/94	66	1582	34	0.4	110.1	40	14.06706	1384204	3	64.65959	21143.49	0.836657	1.465617	0.002993	75.62623	0.842642	12.67131	
4/25/94	68	1632	60	3.2	110.4	20	9.667016	1413205	3.8	855.5311	21999.02	0.870511	1.740063	0.003061	77.36629	0.876634	13.18246	
4/26/94	69	1650	22	0.4	110.1	45	15.55104	1430000	3.3	25.19266	22024.22	0.871506	0.369493	0.003076	77.73579	0.87766	13.19789	
4/27/94	70	1676	26	0.3	110.4	43	14.94821	1453319	4.5	11.85961	22035.88	0.871969	0.6063	0.0031	78.34209	0.878169	13.20555	

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Date	Elapsed Ti	Elapsed Ti	VOC, ppn	CO2, %	Temperat	Flowrate,	Flowrate,	Cumulativ	Moisture,	CO2, cc	Cum CO2	Moles CO	VOC, cc	Cum VOC	Cum VOC	Total mole	% Total C
2/16/94	0	0	1800	5	71.1	0	0	0	13.8	0	0	0	0	0	0	0	0
2/17/94	1	20	62	0.5	74.2	40	14.08706	16904.47	10.4	42.26117	42.26117	0.001672	1.048077	4.15E-05	1.048077	0.001755	0.026395
2/18/94	2	44	98	0.9	94.1	40	14.08706	37189.83	11.2	131.8548	174.116	0.00689	1.987965	0.00012	3.036042	0.00713	0.10722
2/19/94	3	68	80	0.7	94.4	34	12.51982	55218.36	11	81.1284	255.2444	0.0101	1.442283	0.000177	4.478325	0.010455	0.157211
2/20/94	4	96	110	1.22	111.2	42	14.65542	79839.46	12.1	238.8247	494.0691	0.019551	2.708321	0.000284	7.186646	0.020119	0.302546
2/21/94	5	118	140	8.5	113.9	41	14.36836	98805.7	9.8	1564.715	2058.784	0.081467	2.655274	0.000389	9.84192	0.082246	1.23678
2/22/94	6	142	220	4.5	119.3	38	13.54167	118305.7	8.5	828.7501	2887.534	0.114261	4.29	0.000559	14.13192	0.115379	1.735028
2/23/94	7	166	110	5.12	114.6	40	14.08706	138591.1	17.4	987.897	3875.431	0.153352	2.23139	0.000648	16.36331	0.154647	2.325526
2/24/94	8	190	160	9.3	113.5	40	14.08706	158876.4	14.5	1835.825	5711.256	0.225997	3.245658	0.000776	19.60897	0.227549	3.421785
2/25/94	9	214	110	7.21	113.2	38	13.54167	178376.4	16.9	1357.2	7068.456	0.279702	2.145	0.000861	21.75397	0.281423	4.231931
2/26/94	10	244	100	8.98	112.3	38	13.54167	202751.4	14.9	2127.938	9196.394	0.363905	2.4375	0.000957	24.19147	0.36582	5.501049
2/27/94	11	266	120	7.7	112.5	38	13.54167	220626.4	11	1331.688	10528.08	0.416601	2.145	0.001042	26.33647	0.418685	6.296014
2/28/94	12	287	86	3.2	112.3	40	14.08706	238376.1	10	523.6159	11051.7	0.43732	1.526473	0.001103	27.86294	0.439525	6.609405
3/1/94	13	311	120	6.96	111.9	43	14.94821	259901.5	11.8	1444.356	12496.05	0.494474	2.583051	0.001205	30.44599	0.496884	7.471935
3/2/94	14	336	78	5.5	111.5	40	14.08706	281032.1	9.9	1109.356	13605.41	0.538372	1.648186	0.00127	32.09418	0.540912	8.134012
3/3/94	15	360	80	3.7	111.6	60	20.80451	310990.6	11.7	1033.568	14638.98	0.579271	2.39668	0.001365	34.49086	0.582	8.751882
3/4/94	16	384	94	3.9	111.3	42	14.65542	332094.4	10	770.2887	15409.27	0.609751	1.983757	0.001443	36.47462	0.612638	9.212599
3/5/94	17	406	68	3.5	111.1	42	14.65542	351439.6	9.9	628.7174	16037.98	0.63463	1.31547	0.001495	37.79009	0.637621	9.588279
3/7/94	19	454	74	2.3	110.9	43	14.94821	394490.4	9.8	882.5425	16920.53	0.669552	3.185763	0.001621	40.97585	0.672795	10.11722
3/8/94	20	478	68	2.8	110.7	42	14.65542	415594.2	19	538.1469	17458.67	0.690847	1.435058	0.001678	42.41091	0.694204	10.43915
3/9/94	21	502	80	2.7	110.8	40	14.08706	435879.6	18.8	496.9913	17955.66	0.710513	1.622829	0.001742	44.03374	0.713998	10.73681
3/10/94	22	523	74	2.5	110.9	43	14.94821	454714.3	19.2	423.7819	18379.45	0.727282	1.393771	0.001798	45.42751	0.730878	10.99064
3/11/94	23	548	78	3.5	110.8	35	12.76666	473864.3	18.9	622.3748	19001.82	0.75191	1.4937	0.001857	46.92121	0.755623	11.36276
12-Mar	24	578	62	2.7	110.6	40	14.08706	499221	19.1	621.2392	19623.06	0.776493	1.572115	0.001919	48.49332	0.780331	11.73429
3/13/94	25	599	78	2.7	110.4	40	14.08706	516970.7	19.7	434.8674	20057.93	0.793701	1.384476	0.001974	49.8778	0.797648	11.99471
3/14/94	26	621	73	2.3	110.6	40	14.08706	535565.6	19.5	381.1957	20439.12	0.808785	1.357429	0.002027	51.23523	0.81284	12.22315
3/15/94	27	645	50	2.1	110.3	47	16.17683	558860.3	19.6	430.9508	20870.07	0.825838	1.164732	0.002073	52.39996	0.829985	12.48097
3/16/94	28	669	72	2.2	110.3	40	14.08706	579145.6	19.7	395.5645	21265.64	0.84149	1.460546	0.002131	53.8605	0.845753	12.71809
3/17/94	29	693	74	2.2	110.7	42	14.65542	600249.4	18.7	411.5241	21677.16	0.857775	1.561681	0.002193	55.42219	0.862161	12.96482
3/18/94	30	717	71	2	110.6	40	14.08706	620534.8	19	354.9938	22032.16	0.871822	1.440261	0.00225	56.86245	0.876322	13.17777
3/19/94	31	744	75	2	110.4	42	14.65542	644276.6	19.5	415.4811	22447.64	0.888263	1.780633	0.002321	58.64308	0.892904	13.42712
3/20/94	32	770	66	2.1	110.5	42	14.65542	667139	18.9	422.9553	22870.59	0.904999	1.508922	0.00238	60.152	0.90976	13.68059
3/21/94	33	788	78	2	110.3	42	14.65542	682966.9	19.3	276.9874	23147.58	0.91596	1.234572	0.002429	61.38657	0.920818	13.84688
3/22/94	34	812	74	1.9	110.4	42	14.65542	704070.7	19.5	348.2127	23495.79	0.929738	1.561681	0.002491	62.94826	0.93472	14.05594
3/23/94	35	836	67	2	110.1	42	14.65542	725174.5	19.3	369.3165	23865.11	0.944352	1.413955	0.002547	64.36221	0.949446	14.27739
3/24/94	36	860	68	1	110.3	65	22.84284	758068.2	19	246.7027	24111.81	0.954115	2.236771	0.002635	66.59898	0.959385	14.42685
3/25/94	37	884	38	1.3	110.2	63	22.01028	789763	19.1	332.7954	24444.61	0.967283	1.204403	0.002683	67.80338	0.972649	14.62631
3/27/94	39	934	56	1.5	110.3	45	15.55104	836416.1	17.7	583.1639	25027.77	0.99036	2.612574	0.002786	70.41596	0.995932	14.97643
3/28/94	40	956	72	1.5	110.2	40	14.08706	855011	16.7	232.4364	25260.21	0.999557	1.338834	0.002839	71.75479	1.005236	15.11633
3/29/94	41	981	110	1.4	110.3	40	14.08706	876141.6	18.2	243.0017	25503.21	1.009173	2.324364	0.002931	74.07916	1.015035	15.26369
3/30/94	42	1005	76	1.7	110.3	40	14.08706	896426.9	17.5	294.1377	25797.35	1.020812	1.541687	0.002992	75.62084	1.026797	15.44055

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Date	Elapsed Ti	Elapsed Ti	VOC, ppn	CO2, %	Temperat	Flowrate,	Flowrate,	Cumulativ	Moisture,	CO2, cc	Cum CO2	Moles CO	VOC, cc	Cum VOC	Cum VOC	Total mole	% Total C
3/31/94	43	1029	66	1.5	110.3	42	14.65542	917530.7	16.5	263.7975	26061.14	1.031251	1.392851	0.003047	77.01369	1.037345	15.59918
4/1/94	44	1053	80	1.3	110.5	42	14.65542	938634.5	14.6	221.5899	26282.73	1.040019	1.688304	0.003114	78.702	1.046247	15.73304
4/2/94	45	1080	52	0.8	110.5	45	15.55104	963827.2	14	138.5597	26421.29	1.045502	1.310019	0.003166	80.01202	1.051834	15.81705
4/4/94	47	1125	86	1.2	110.3	45	15.55104	1005815	14.9	398.8841	26820.18	1.061286	3.610951	0.003309	83.62297	1.067904	16.0587
4/5/94	48	1150	62	1.1	110.1	45	15.55104	1029142	13.4	198.2757	27018.45	1.069132	1.446246	0.003366	85.06921	1.075864	16.17841
4/6/94	49	1174	74	1.1	110.5	45	15.55104	1051535	13.1	190.3447	27208.8	1.076664	1.657118	0.003432	86.72633	1.083527	16.29364
4/7/94	50	1198	68	1.2	110.5	35	12.76666	1069919	7.7	174.648	27383.45	1.083575	1.250112	0.003481	87.97644	1.090537	16.39905
4/8/94	51	1222	58	1.3	110.1	37	13.27759	1089039	13.4	200.7572	27584.2	1.091519	1.108944	0.003525	89.08539	1.098569	16.51983
4/9/94	52	1246	58	1.2	110.4	42	14.65542	1110143	13.8	200.4861	27784.69	1.099452	1.22402	0.003574	90.30941	1.106599	16.64059
4/10/94	53	1274	50	1.3	110.4	43	14.94821	1135256	13.7	263.6865	28048.38	1.109886	1.25565	0.003623	91.56506	1.117133	16.79899
4/11/94	54	1294	54	1.3	107.3	39	13.81149	1151829	12.8	174.0248	28222.4	1.116772	0.894985	0.003659	92.46004	1.12409	16.90361
4/12/94	55	1318	52	1.3	110.4	45	15.55104	1174223	13.6	235.1317	28457.53	1.126077	1.164462	0.003705	93.62451	1.133486	17.0449
4/13/94	56	1343	64	1.4	110.6	45	15.55104	1197549	13.6	268.2554	28725.79	1.136692	1.492899	0.003764	95.1174	1.144219	17.20631
4/14/94	57	1367	50	1.3	110.6	45	15.55104	1219943	13.6	235.1317	28960.92	1.145996	1.119675	0.003808	96.23708	1.153612	17.34755
4/15/94	58	1391	52	1.1	110.4	45	15.55104	1242336	13.6	190.3447	29151.26	1.153528	1.164462	0.003854	97.40154	1.161236	17.4622
4/16/94	59	1417	66	1.3	110.2	41	14.36836	1264751	13.6	235.3538	29386.62	1.162841	1.479367	0.003913	98.88091	1.170666	17.60401
4/18/94	61	1470	37	0.7	110	40	14.08706	1309548	13.6	201.5858	29588.2	1.170818	1.657483	0.003978	100.5384	1.178774	17.72593
4/19/94	62	1503	30	0.4	110	40	14.08706	1337440	13.6	41.83856	29630.04	1.172473	0.836771	0.004011	101.3752	1.180496	17.75182
4/20/94	63	1518	59	1.2	110.4	44	15.24675	1351162	13.6	130.3597	29760.4	1.177632	0.809603	0.004043	102.1848	1.185719	17.83036
4/21/94	64	1531	46	1.2	110.1	44	15.24675	1363055	12.2	112.9784	29873.38	1.182102	0.547054	0.004065	102.7318	1.190233	17.89824
4/23/94	66	1582	52	1.1	110.4	42	14.65542	1407900	12.4	381.1874	30254.57	1.197186	2.33197	0.004157	105.0638	1.205501	18.12783
4/25/94	68	1632	26	0.4	110.2	90	35.18835	1513465	12.7	158.3476	30412.92	1.203452	2.744691	0.004266	107.8085	1.211984	18.22532
4/26/94	69	1650	45	1.2	110.1	44	15.24675	1529932	10.6	156.4317	30569.35	1.209642	0.740992	0.004295	108.5495	1.218233	18.31929
4/27/94	70	1676	54	0.9	110.5	45	15.55104	1554192	12.4	157.6875	30727.04	1.215882	1.310019	0.004347	109.8595	1.224576	18.41468
4/28/94	71	1700	24	0.3	110.1	43	14.94821	1575717	12.1	10.76271	30737.8	1.216308	0.51661	0.004368	110.3761	1.225043	18.4217
4/29/94	72	1724	38	0.4	92.3	44	15.24675	1597672	7.6	32.93299	30770.73	1.217611	0.834302	0.004401	111.2104	1.226412	18.44229
5/1/94	74	1774	52	0.8	110.2	45	15.55104	1644325	10.7	256.5921	31027.32	1.227764	2.425962	0.004497	113.6364	1.236758	18.59786
5/2/94	75	1805	56	1	110.3	45	15.55104	1673250	12.6	216.937	31244.26	1.236349	1.619796	0.004561	115.2562	1.24547	18.72887
5/3/94	76	1821	60	0.95	110.1	47	16.17683	1688780	12.4	108.7083	31352.97	1.24065	0.931786	0.004598	116.1879	1.249845	18.79467
5/4/94	77	1845	55	0.8	110.5	48	16.49835	1712538	12.6	130.6669	31483.64	1.245821	1.306669	0.004649	117.4946	1.255119	18.87398
5/5/94	78	1870	50	0.9	110	47	16.17683	1736803	13.4	157.7241	31641.36	1.252062	1.213263	0.004697	118.7079	1.261457	18.96927
5/6/94	79	1894	46	0.8	110.4	48	16.49835	1760561	10.2	130.6669	31772.03	1.257233	1.092851	0.004741	119.8007	1.266714	19.04833
5/7/94	80	1923	50	0.6	110.1	48	16.49835	1789268	12.4	100.4749	31872.5	1.261208	1.435356	0.004797	121.2361	1.270803	19.10982
5/9/94	82	1966	42	0.8	110.1	48	16.49835	1831833	12.6	234.1115	32106.61	1.270472	1.787761	0.004868	123.0238	1.280208	19.25126
5/10/94	83	1990	34	0.8	110	48	16.49835	1855591	12.1	130.6669	32237.28	1.275643	0.807759	0.0049	123.8316	1.285443	19.32997
5/11/94	84	2014	34	0.8	110.1	48	16.49835	1879349	12.2	130.6669	32367.95	1.280813	0.807759	0.004932	124.6394	1.290677	19.40868
5/12/94	85	2038	10	0.3	109.9	43	14.94821	1900874	12.2	10.76271	32378.71	1.281239	0.215254	0.004941	124.8546	1.29112	19.41534
5/13/94	86	2062	0.1	0.26	109.8	45	15.55104	1923268	12.4	2.239349	32380.95	1.281328	0.002239	0.004941	124.8569	1.291209	19.41668
5/16/94	89	2124	12	0.3	109.9	37	13.27759	1972660	9.6	24.69632	32405.65	1.282305	0.592712	0.004964	125.4496	1.292233	19.43208
5/17/94	90	2149	11	0.3	109.6	55	18.90976	2001025	9	14.18232	32419.83	1.282866	0.312011	0.004976	125.7616	1.292819	19.44089
5/18/94	91	2173	13	0.3	110	47	16.17683	2024320	9	11.64732	32431.47	1.283327	0.30283	0.004988	126.0644	1.293304	19.44818

Date	Elapsed Ti	Elapsed Ti	VOC, ppm	CO2, %	Temperat	Flowrate,	Flowrate,	Cumulativ	Moisture,	CO2, cc	Cum CO2	Moles CO	VOC, cc	Cum VOC	Cum VOC	Total mole	% Total C
5/19/94	92	2196	13	0.3	110	45	15.55104	2045780	8.1	10.73022	32442.21	1.283752	0.278986	0.004999	126.3434	1.293751	19.4549
5/20/94	93	2220	24	0.3	110.2	47	16.17683	2069075	8.5	11.64732	32453.85	1.284213	0.559071	0.005022	126.9025	1.294256	19.46249
5/23/94	96	2282	19	0.3	109.7	43	14.94821	2124682	7.2	27.80368	32481.66	1.285313	1.05654	0.005063	127.959	1.29544	19.4803
5/24/94	97	2306	10	0.3	109.9	43	14.94821	2146207	6.4	10.76271	32492.42	1.285739	0.215254	0.005072	128.1743	1.295883	19.48696
5/25/94	98	2331	12	0.3	109.8	68	24.13477	2182410	7.3	18.10108	32510.52	1.286455	0.434426	0.005089	128.6087	1.296633	19.49824

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Date	Elapsed Ti	Elapsed Ti	VOC, ppn	CO2, %	Temperat	Flowrate,	Flowrate,	Cumulativ	Moisture,	CO2, cc	Cum CO2	Moles CO	VOC, cc	Cum VOC	Cum VOC	Total mole	% Total C
2/16/94	0	0	5600	2	72.6	0	0	0	6.8	0	0	0	0	0	0	0	0
2/17/94	1	20	120	3.8	74.5	40	14.08706	16904.47	6.2	600.1086	600.1086	0.023747	2.028536	8.03E-05	2.028536	0.023907	0.359505
2/18/94	2	44	210	6	94.1	42	14.65542	38008.27	6.7	1213.469	1813.577	0.071764	4.431798	2.56E-04	6.460334	0.072275	1.086846
2/19/94	3	68	180	3.9	95	38	13.54167	57508.27	6.2	711.7501	2525.327	0.099928	3.51	3.95E-04	9.970335	0.100717	1.514546
2/20/94	4	96	180	5.8	111.8	45	15.55104	83634.01	6.8	1449.979	3975.306	0.157305	4.702633	5.81E-04	14.67297	0.158466	2.382944
2/21/94	5	118	320	14.2	115.9	40	14.08706	102228.9	6.1	2593.99	6569.296	0.25995	5.950372	8.16E-04	20.62334	0.261582	3.933564
2/22/94	6	142	480	7.2	116	40	14.08706	122514.3	7.4	1409.833	7979.129	0.315738	9.736973	1.20E-03	30.36031	0.31814	4.784064
2/23/94	7	166	220	5.5	114.1	40	14.08706	142799.6	8.9	1064.981	9044.11	0.357879	4.462779	1.38E-03	34.82309	0.360635	5.423086
2/24/94	8	190	160	4.5	113.1	40	14.08706	163085	9.5	862.1278	9906.238	0.391994	3.245658	1.51E-03	38.06875	0.395007	5.939952
2/25/94	9	214	97	4	113.2	40	14.08706	183370.4	9.9	760.701	10666.94	0.422095	1.96768	1.58E-03	40.03643	0.425264	6.394945
2/26/94	10	244	66	3.5	112.6	36	13.01925	206805	9.5	761.6264	11428.57	0.452233	1.546687	1.65E-03	41.58312	0.455524	6.849986
2/27/94	11	266	75	3.2	112.7	15	8.920979	218580.7	9.1	347.3829	11775.95	0.465979	0.883177	1.68E-03	42.46629	0.46934	7.057746
2/28/94	12	287	78	2.8	12.6	40	14.08706	236330.4	8.5	452.6171	12228.57	0.48389	1.384476	1.74E-03	43.85077	0.48736	7.32872
3/1/94	13	311	76	2.2	112.2	40	14.08706	256615.8	8.4	395.5645	12624.13	0.499542	1.541687	1.80E-03	45.39246	0.503135	7.565933
3/2/94	14	336	55	2.3	111.8	42	14.65542	278598.9	8.1	450.6541	13074.78	0.517375	1.209072	1.84E-03	46.60153	0.521063	7.835531
3/3/94	15	360	53	1.5	111.2	40	14.08706	298884.3	8	253.567	13328.35	0.527408	1.075124	1.89E-03	47.67665	0.531182	7.987694
3/4/94	16	384	52	1.2	110.7	47	16.17683	322178.9	7.9	221.2991	13549.65	0.536165	1.211321	1.93E-03	48.88797	0.540034	8.120818
3/5/94	17	406	86	4.5	111.1	40	14.08706	340773.8	8.2	790.2838	14339.93	0.567437	1.599163	2.00E-03	50.48714	0.571433	8.592975
3/7/94	19	454	78	3	10.9	43	14.94821	383824.7	7.9	1183.899	15523.83	0.614285	3.357967	2.13E-03	53.8451	0.618546	9.301443
3/8/94	20	478	68	3.4	111	37	13.27759	402944.4	9.5	602.2715	16126.1	0.638117	1.300142	2.18E-03	55.14525	0.642481	9.661368
3/9/94	21	502	88	3.3	110.8	40	14.08706	423229.7	9.1	618.7035	16744.81	0.662599	1.785112	2.25E-03	56.93036	0.667105	10.03165
3/10/94	22	523	95	3	110.6	42	14.65542	441695.6	9.3	507.8102	17252.62	0.682693	1.754253	2.32E-03	58.68461	0.687338	10.33591
3/11/94	23	548	84	5.3	110.6	33	12.27871	460113.6	13.5	930.1124	18182.73	0.719498	1.547118	2.38E-03	60.23173	0.724265	10.8912
12-Mar	24	578	72	3.5	110.9	40	14.08706	485470.3	12.2	824.0928	19006.82	0.752108	1.825682	2.46E-03	62.05741	0.757019	11.38375
3/13/94	25	599	76	4	110.6	40	14.08706	503220	10.8	665.6134	19672.44	0.778447	1.348976	2.51E-03	63.40639	0.783465	11.78142
3/14/94	26	621	75	3.2	110.3	40	14.08706	521814.9	10.9	548.5499	20220.99	0.800153	1.394619	2.56E-03	64.80101	0.805281	12.10949
3/15/94	27	645	58	3.1	110.3	42	14.65542	542918.7	10.3	601.4583	20822.44	0.823953	1.22402	2.61E-03	66.02503	0.829178	12.46885
3/16/94	28	669	80	2.9	110.9	40	14.08706	563204.1	10.2	537.562	21360.01	0.845224	1.622829	2.68E-03	67.64785	0.850578	12.79065
3/17/94	29	693	68	3	110.7	41	14.36836	583894.6	10	568.9872	21928.99	0.86774	1.40695	2.73E-03	69.05481	0.873205	13.1309
3/18/94	30	717	75	3.2	110.5	40	14.08706	604179.9	10.1	598.4181	22527.41	0.891419	1.521402	2.79E-03	70.57621	0.897005	13.48879
3/19/94	31	744	72	3	110.7	41	14.36836	627456.7	9.9	640.1106	23167.52	0.916749	1.675926	2.86E-03	72.25213	0.922467	13.87168
3/20/94	32	770	72	3	110.8	41	14.36836	649871.3	10.1	616.4028	23783.93	0.94114	1.613855	2.92E-03	73.86599	0.946986	14.24039
3/21/94	33	788	83	3	110.3	41	14.36836	665389.1	10.6	426.7404	24210.67	0.958026	1.28798	2.97E-03	75.15397	0.963974	14.49585
3/22/94	34	812	84	2.9	110.4	42	14.65542	686492.9	9.8	559.2507	24769.92	0.980156	1.772719	3.04E-03	76.92669	0.986244	14.83074
3/23/94	35	836	58	2.8	110.4	41	14.36836	707183.4	9.9	527.6064	25297.52	1.001034	1.200046	3.09E-03	78.12673	1.007217	15.14612
3/24/94	36	860	63	1.4	110.6	67	23.69838	741309.1	9.8	392.4452	25689.97	1.016563	2.149917	3.18E-03	80.27665	1.022916	15.3822
3/25/94	37	884	60	1.7	110.2	63	22.01028	773003.9	9.6	459.5746	26149.54	1.034748	1.901688	3.25E-03	82.17834	1.041252	15.65793
3/27/94	39	934	66	1.9	110.6	44	15.24675	818744.1	9.7	754.7143	26904.26	1.064613	3.018857	3.37E-03	85.1972	1.071355	16.11061
3/28/94	40	956	68	1.8	110.5	41	14.36836	837710.4	9.4	293.9767	27198.23	1.076246	1.289704	3.42E-03	86.4869	1.08309	16.28707
3/29/94	41	981	68	1.9	110.5	38	13.54167	858022.9	9.9	335.1563	27533.39	1.089508	1.38125	3.48E-03	87.86815	1.096462	16.48815
3/30/94	42	1005	80	2.1	111.1	38	13.54167	877522.9	9.2	360.75	27894.14	1.103783	1.56	3.54E-03	89.42815	1.11086	16.70467
3/31/94	43	1029	66	1.8	110.5	41	14.36836	898213.3	9.3	320.7019	28214.84	1.116473	1.365569	3.59E-03	90.79372	1.123659	16.89712
4/1/94	44	1053	74	1.6	110.5	41	14.36836	918903.8	9.6	279.321	28494.16	1.127526	1.531093	3.65E-03	92.32481	1.134833	17.06515

Date	Elapsed Ti	Elapsed Ti	VOC, ppn	CO2, %	Temperat	Flowrate, (	Flowrate, (	Cumulativ	Moisture, 1	CO2, cc	Cum CO2	Moles CO	VOC, cc	Cum VOC	Cum VOC	Total mole	% Total C
5/25/94	98	2331	32	0.6	110.4	61	21.20069	2091557	8.9	111.3036	39102.67	1.547309	1.017633	5.89E-03	148.8613	1.55909	23.44496
5/26/94	99	2355	30	0.7	110.7	30	11.58986	2108246	9.4	75.10229	39177.77	1.550281	0.500682	5.91E-03	149.362	1.562102	23.49025
5/27/94	100	2379	46	0.7	109.4	45	15.55104	2130640	9.1	100.7707	39278.54	1.554268	1.030101	5.95E-03	150.3921	1.566171	23.55144
5/29/94	102	2428	40	0.7	110.4	45	15.55104	2176360	8.9	205.7402	39484.28	1.56241	1.828802	6.02E-03	152.2209	1.574457	23.67604
5/30/94	103	2452	38	0.6	110.2	47	16.17683	2199654	8.7	81.53124	39565.81	1.565636	0.885196	6.06E-03	153.1061	1.577753	23.72561
5/31/94	104	2476	38	0.5	110.4	48	16.49835	2223412	8.6	59.39405	39625.21	1.567986	0.90279	6.09E-03	154.0088	1.580175	23.76202
6/1/94	105	2499	34	0.5	110.4	46	15.86106	2245300	8.5	54.72067	39679.93	1.570151	0.744201	6.12E-03	154.753	1.582399	23.79547
6/2/94	106	2523	30	0.5	110.1	47	16.17683	2268595	8.2	58.2366	39738.16	1.572456	0.698839	6.15E-03	155.4519	1.584759	23.83096
6/3/94	107	2548	22	0.4	110.3	50	17.15861	2294333	8.2	38.60686	39776.77	1.573984	0.566234	6.17E-03	156.0181	1.586331	23.8546
6/5/94	108	2573	26	0.4	110.3	42	14.65542	2316316	8.6	32.97469	39809.74	1.575288	0.571561	6.20E-03	156.5897	1.587681	23.8749
6/6/94	110	2621	16	0.3	103.7	43	14.94821	2359367	6.1	21.52543	39831.27	1.57614	0.688814	6.22E-03	157.2785	1.588587	23.88853
6/7/94	111	2645	25	0.5	110.1	42	14.65542	2380471	10.1	52.7595	39884.03	1.578228	0.527595	6.24E-03	157.8061	1.590717	23.92055
6/8/94	112	2670	26	0.4	110.1	42	14.65542	2402454	9.4	32.97469	39917	1.579533	0.571561	6.27E-03	158.3776	1.592067	23.94086
6/9/94	113	2694	28	0.5	110.3	41	14.36836	2423144	9.2	51.72611	39968.73	1.58158	0.579332	6.29E-03	158.957	1.59416	23.97232
6/10/94	114	2717	24	0.5	110.1	42	14.65542	2443369	8.9	50.56119	40019.29	1.58358	0.485387	6.31E-03	159.4424	1.596199	24.00299
6/11/94	115	2743	26	0.5	110.3	42	14.65542	2466231	9.7	57.15613	40076.45	1.585842	0.594424	6.33E-03	160.0368	1.598507	24.03771
6/12/91	116	2776	26	0.5	110.1	42	14.65542	2495249	9.4	72.54432	40148.99	1.588713	0.754461	6.36E-03	160.7913	1.601438	24.08177
6/13/94	117	2790	26	0.5	110.2	44	15.24675	2508056	9.1	32.01818	40181.01	1.58998	0.332989	6.38E-03	161.1242	1.602731	24.10122
6/14/94	118	2814	12	0.3	77.2	40	14.08706	2528341	6.4	10.14268	40191.15	1.590381	0.243424	6.39E-03	161.3677	1.603152	24.10754
6/15/94	119																
6/16/94	120																

VITA

Donna G. Lautzenhiser

Candidate for the Degree of

Master of Science

Thesis: SUITABILITY OF BENCH SCALE COMPOSTING AS AN INDICATOR OF FULL SCALE BIOREMEDIATION OF OILY SLUDGES

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