Aerobic Stabilizaton of Wastewater Sludge Using Recyclable Material as a Bulking Agent

by

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Thesis submitted to partially comply with
the degree requirements for a

Masters in Science in Chemical Engineering

UNIVERSITY OF PUERTO RICO
MAYAGUEZ

1989

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The nutrient content of the final product was enriched when recycled material was used. Moreover, the heavy metal content of the final product was found to be low and without pathogens, thus it would be appropriate for use as a soil conditioner.

DEDICATION

To my dear parents, Robert and Maruja. To my brothers--Carlos, Fernando, Medalit, and my nephew, Carlos Alberto. For their great support and encouragement during the completion of this work.

ACKNOWLEDGMENTS

My sincere gratitude to the individuals who collaborated with me in this research. In particular, Professors Lueny Morell, Jaime Benitez, and Lorenzo Saliceti for their great support and friendship.

I also wish to thank:

The Department of Chemical Engineering at the University of Puerto Rico.

The Wastewater Treatment Plant of Barceloneta for providing me with the recyclable material under the conditions required for this research.

Dr. Narinder Mehta and the professionals in the quality control laboratory at the University of Puerto Rico, for their help in the chemical testing required for this work.

And, Dr. Caravallo, Professor of the Department of Agriculture, for allowing me to use the atomic absorption equipment.

To Mr. Angel Zapata, for his help in the laboratory.

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1.- INTRODUCTION

Disposal of wastewater is an environmental problem both for the United States and Puerto Rico. The volume of such wastes increases in proportion to the population and industry causing environmental damage. Alternatives for managing these types of wastes should be practical from the technological point of view, low in cost and environmentally sound.

The most common waste disposal practices are: injection into the soil, dumping at sea, and incineration (U.S. Environmental Protection Agency, EPA 625/10-84-003). There are both advantages and disadvantages to these practices. In the case of discharge into the soil, anaerobic decomposition can occur resulting in problems of stench and contamination of ground water due to lixiviation of the waste. Dumping at sea can be harmful to the marine ecosystem, and this practice has also been strictly regulated by the EPA. In the case of incineration, waste is reduced to ashes, completely sterilizing the mixture and destroying toxic organisms; nevertheless, this process is subject to other serious drawbacks--the amount of moisture present, and operational mistakes.

These alternatives serve to illustrate the need to study other waste disposal practices such as the PROCESS OF AEROBIC DECOMPOSITION OF WASTEWATER SLUDGE. This approach transforms the wastewater into an odorless substance which is used for agricultural applications. It has growth-inducing nutrients, which is the reason that it is recognized as a soil conditioner for farm land. The amount of pathogens is insignificant and do not affect the health of living organisms (Haug, 1980).

The process entails a thermophilic biological aerobic decomposition of the organisms found in wastewater sludges. The decomposition produces sufficient carbon dioxide, water, ammonium, and heat to sterilize the waste. These qualities have led to acceptance of the new process by environmental authorities in Puerto Rico.

A bulking agent serves to improve the porosity of the mixture thus facilitating aeration. Use of an organic bulking agent can contribute to the nutrient balance of the final product, which is important for the product's potential use as a soil conditioner in agriculture.

It is evident that in a large scale operation there can be processing constraints because of a lack of a bulking agent. Given limitations, such as financial factors and the availability of material, there is a need to seek alternatives to for bulking material. In this respect, recovered materials and compost without screen represent possible alternatives to test as bulking agents. That is, to test the product of each, both quantitatively and qualitatively. Favorable findings can contribute to cost reduction (in terms of purchasing and transportation costs).

Studies of this process, utilizing diverse bulking agents, have been carried out at the Mayaguez University Campus of the University of Puerto Rico; these include use of the African tulip (Spathodea campanulata), a rapidly-growing, low density wood.

The purpose of this study: "Process of Aerobic Stabilization of Wastewater Sludge Using Recyclable Material as a Bulking Agent" is to assure the availability of a bulking material for this type of process.

2.- LITERATURE REVIEW

2.1.- AEROBIC COMPOSTING OF WASTEWATER SLUDGE

The process of aerobic decomposition of wastewater sludge consists of biological decomposition of all decayed organic matter and composting organic substratum (sustenance for proteins and microorganisms) until it is sterilized.

During the aeration process the organic substrate is decomposed in the presence of oxygen (air), and carbon dioxide, water, ammonia and heat are generated as a result of the organic metabolism (biotic process). On the other hand, in an anaerobic process, biological decomposition of the organic substrate occurs in the absence of oxygen, producing methane, carbon dioxide, hydrosulphide and low molecular weight acids. All these gases emit a strong odor, and the process yields less energy per unit of mass, which is evident in the low temperatures that result. In view of the preceding, generally in engineering the aerated system is used, a system capable of destroying residue from sick plants, insects, AND pathogens and their eggs. But the oxygen transfer sometimes has its limitations, particularly when anaerobic areas are formed in passing (Haug, 1980).

2.2.- OPERATING SYSTEM METHODS

The first studies on the process of biological composting were conducted by Sir Albert Howard while he was in India (1905-1934). He developed the Indore process to compost organic waste, including plant croppings, polluted water, animal manure, wastewater sludge, straw, and garbage. He layered these materials until a 5 or 6 foot pile was formed. After 2, 4, or 8 weeks the piles were turned. The process was completed in a period ranging from 3 to 4 months. This method is a combination of aerobic and anaerobic process. In this manner Howard demonstrated that the composting process for organic waste through biodegradation is a good alternative, thus marking the start of a new era of composting wastewater sludge (Willson et al., 1980 a).

Diverse research has led to the development of three major methods:

1) Naturally-aerated method, 2) Mechanically-aerated static-pile method, and 3) closed system.

1) Naturally-aerated method: So-named because the piles are stirred continuously to aereate them and thus maintain them in aerobic condition. The sludge for composting is mixed with the bulking agent forming parallel lines of rectangular, trapezoidal or triangular piles, depending on the characteristics of the equipment used to mix and turn the piles. Among the bulking agents used is the product of the process, recycled material. The amount of bulking agent is adjusted in accordance with the solid content of the initial mixture, which is from 40 to 50%. Bulking material is used to provide the mixture with structure and porosity in order to facilitate aeration during the process. Moreover the bulking agent is a source of carbon and the carbon-nitrogen ratio (C/N), can increase to approximately 20:1 or 30:1 (basic mass) in the mixture. The primary wastewater sludge generally has a 9:1 to 15:1 C/N ratio. The Water Pollution Control Company of the Los Angeles, California Wastewater District has used this method since 1972 (EPA 625/1-79-011).

2) Mechanically-aerated static pile method: This method has been developed by the Agricultural Research Services (ARS) of the U.S. Department of Agriculture (USDA), at the experimental station in Beltsville, Maryland. It is frequently known as the Beltsville process (Haug, 1980). The aerated static-pile method differs from the preceding in that the compost material is not stirred. The aerobic condition is maintained by injecting air through the piles by perforated pipes located at the pile base. The ratio of sludge to woodchips required for the initial mixture is 1:2 to 1:3 on a volumetric basis. Obviously the size and amount of bulking agent should be controlled to provide porosity to the pile during the

process. The steps for creating a pile are as follows: mix the sludge with the bulking agent; prepare a base of woodchips or other bulking agent, as well as perforated pipes for ventilation; construct the pile on the prepared bed; cover the outside of the pile with either screened or unscreened compost; and start ventilation. At this point the pile is ready for the process to begin. Aeration can be positive or negative; it is positive when air is injected into the mixture, and negative when existing air is suctioned from the mixture. Negative aeration is generally used when the pile needs to be deodorized prior to initiating the process (Haug, 1980).

Usually part of the bulking agent needs to be recycled due to the use of great quantities of bulking agent in each initial mixture, and the high cost of materials like woodchips. With time, the reduced size of the bulking agent due to breakage and degradation, will allow it to pass through a screen along with the sludge. It is necessary to take this loss into account in the final product (Haug, 1980).

3) Closed system method: The aerobic decomposition process is conducted in a completely closed receptacle (reactor), where the operational conditions, such as temperature and air flow, are controlled to minimize the odor and processing time. This method is viable for cold climates and when there is limited space to carry out the process. This method is utilized in Europe, and since 1984, in the United States installations were constructed to process wastewater sludge with this method (EPA 626/10-84-003), (EPA 625/4-85-014). The reactor system has several advantages over the other two systems; these are: odor control; requires less space; control and management of materials used in the process; more appealing for aesthetic reasons; requires less personnel; and greater reliability in the quality of the product (Walker et al., 1986).

2.3.- BENCH SCALE REACTORS FOR RESEARCH ON THE AEROBIC DECOMPOSITION PROCESS

Various laboratory studies have been conducted to find the relationship between the different operational variables that affect the process of aerobic decomposition, such as: the type of bulking agent, moisture, carbon-nitrogen ratio, pH and oxygen concentration (Deschamps et al., 1979).

One of the first research reactors was constructed by Karl Schulze, a civil engineering professor at the University of Michigan. The reactor was a cylinder with a 10" diameter and 19" in length, and a capacity of 0.75 cubic feet. It had three frontal openings: one to introduce the thermocouple; another for air feed; and the third for sampling. Since the capacity was known, the purpose of the research was to calculate oxygen consumption, temperature and moisture content, using a feed material consisting of a garbage and screened sludge mixture. The findings indicated that the ratio of oxygen consumption increases directly with the temperature, at intervals between 27° C and 63° C. A logarithmic regression of the oxygen consumption versus temperature generated the following:

$$W_{02} = 0.1(1.0066)^T$$

where:

W_{02} = ratio of oxygen consumption (mg O_2/g volatile material-hr)

T = temperature of the mixture in (°C)

It also showed that the activity during the process, measured as a function of the speed of oxygen consumption, is directly in proportion to the moisture content. Findings indicated a minimum of zero activity for moisture under 20%, and a maximum for 60% humidity (Schulze, 1962).

In 1977 Suler and Finstein studied the effect of temperature, aeration ratio, humidity content, and formation of carbon dioxide as parameters for composting wastewater sludge. Their findings indicated that the maximum yield of carbon dioxide occurred when the moisture content of the initial mixture was 60%; and, that the optimum temperature for the process was 56° C to 60° C. Moreover, they established that the temperature of the process can vary according to the nature of the wastewater sludge utilized in the initial mixture (Suler and Finstein, 1977).

Studies conducted at Rutgers University determined that speed is a very important factor in the process of aerobic decomposition, and that this is affected negatively when the temperature is over 60° C. This is due to the inactivity of the microbial population. Decomposition is very slow if self-heating occurs in the mass up to temperatures of 80° C. High temperature results from the excessive accumulation of biologically-generated heat. At this stage the thermophilic organisms become inactive, and the kinetics of decomposition lessen. Consequently, the success of the aerobic decomposition process lies in the control of heat generated within the bed of the mixture that is being used in the process. This heat creates temperatures ranging from 40° C to 80° C. To achieve the necessary temperature control excessive heat must be removed through aeration until the temperature falls below 60° C. This is known as the Rutgers technique. When compared to the Beltsville method, the Rutgers strategy quickens the speed of the material's decomposition by a factor of approximately four, cutting processing time in half (Finstein et al., 1985).

In 1986 Frankos, Gouin and Sikora completed a study to determine if woodchips from low density trees were adequate for aerobic decomposition. They used five different species, characterized as having rapid growth, low density, and low lignin content. A Polyvinyl Chloride (PVC) cylinder was used in the study, having an internal diameter of 15.2 cm and 50 cm high. The initial mixture (woodchips and primary sludge) was poured into the cylinder. The cylinder was placed in another aluminum cylinder, having an internal diameter of 20.3 cm and 61 cm high. Thermocouples were placed at various levels in the PVC cylinder, with direct contact to the mixture in order to obtain the necessary temperature readings. Another thermocouple was placed in the empty space between the cylinders. Aeration was conducted at 74 cc/min, using a suction pump connected to the PVC cylinder (reactor). Humidity and temperature content were controlled. In this experiment, the mixture lost 33% of its moist weight, and 9% of its dry weight, 6 to 10% of its nitrogen content; the entire process took 49 days to complete. Material balance was used to calculate that approximately one third of the woodchips that were placed in the reactor could be recycled (Frankos et al., 1986).

2.4.- BULKING AGENTS

The bulking agent is the material that is mixed with the sludge to guarantee a quick decomposition process. The sludge should be mixed with an appropriate material to provide structure, texture and interstitial volume in order to allow for satisfactory automatic aeration. The bulking agent is usually organic, and thus provides carbon to radiate energy among the microorganisms during aerobic decomposition. While the degradable carbon in the bulking agent is useful, it is not essential for the process of composting (Willson et al., 1980b).

The amount of bulking agent required depends on the moisture content of the sludge. For example, liquid sludge having 6 to 8% solid content requires approximately 5 to 7 times the amount of bulking agent. It is preferable to partially drain the sludge until its solid content is in the range of 22 to 24%.

The objective of the bulking agent is to lessen the effects of compacting the sludge by creating porosity and interstitial volume that allow air circulation; and, if necessary, to provide sufficient extra carbon for an effective C/N ratio. The characteristics of an ideal bulking agent are:

a) Insignificant degradation or no degradation during the process of composting, so that the bulking agent can be recycled. Or the other extreme, that degradation is complete throughout the process and thus there is no need to remove the bulking agent by screening. It has to be the right size to be screened and recycled and allow adequate drainage and aeration of the materials.

b) Insignificant or no heavy metal content in the final product (Singley et al., 1982).

The appropriate physical properties of a bulking agent are:

a) Discernible density: Proportion of weight to volume as measured in Kg/m^3 or $lb/ft^{3.}$

b) Interstitial volume and porosity: Refers to the amount of spaces in the initial mixture and is closely linked with the moisture content; measured in percent.

c) Moisture content: Affects microbial activity; optimum humidity for the initial mixture is 55 to 65%.

d) Ratio of mixture: Refers to the proportion of bulking agent to drained sludge. The ratio is determined by the moisture content and the porosity of the bulking agent in addition to the drained sludge.

e) Uniformity of materials: In order for the organic material to be processed effectively it is necessary to begin with a homogenous initial mixture. If the bulking agent is not uniform, it becomes more difficult to manage, and thus each resulting batch will be different; this will require different proportions to obtain the initial mixture.

ABSTRACT

Aerobic stabilization of wastewater sludges is today one of the most attractive alternatives for managing these materials, which are potentially hazardous to the environment. A drawback of this process is that it requires substantial quantities of a bulking agent to improve the aeration characteristics of the mixture undergoing processing.

This research studies the effects of recycling (either recovered woodchips or compost without screen) to reduce bulking agent requirements on the aerobic decomposition (composting) of wastewater sludge. The experiments were conducted in three phases. During the first phase raw material was prepared for subsequent phases. Fresh woodchips from the African "Tulipán" (tulip) tree (Spathodea Campanulata), a rapidly growing tropical tree species, was used as the bulking material. The second phase studied the performance of the recovered and recycled woodchips as bulking material, as well as the number of times these materials could be recycled. The third and final phase was undertaken in order to compare the use of recovered woodchips versus recycling part of the compost without screen in terms of their effectiveness as bulking materials during the process.

Decomposition of the organic matter was accomplished in a short period of time by recycling the woodchips. Temperatures above 55°C were maintained for more than three consecutive days, virtually sterilizing the product. It was determined that the woodchips could be recycled up to five times while maintaining an appropriate carbon content. Likewise, 75% of the woodchips retained a size appropriate to improve the porosity of the mixture.

The results obtained indicated that the recovered woodchips were a more suitable bulking agent than the recycled intermediate product (compost without screen), because less time was required for composting.

f) Easy materials to manage: refers to the apparent density, decay, and other properties that can make it difficult to manipulate the bulking agent (Bolan et al., 1978).

The important chemical properties of the bulking agent are:

a) Source location: Proximity to this source from the place where the composting process is carried out, if it is abundant, or limited in amount. These are very important aspects to consider.

b) Constant or seasonal supply: Is it known whether the bulking agent is available throughout the year, or provisional according to different seasons.

c) Regularity of collections: For example, agricultural waste is collected at the end of the growing season, while fallen trees are only collected occasionally.

d) Recovery: Considers whether or not the bulking agent can be recycled through screening, recycled numerous times, or if a fresh bulking agent must be used for each batch.

e) Cost/volume: The bulking agent should be available at a reasonable cost (Singley et al., 1982).

2.4.1.- Common Bulking Agents

Some materials that are frequently considered to be waste are appropriate, in some manner, for use as bulking agents. A few examples are: wood pulp , woodchips, sawdust, peanut shells, corn husk, vegetable leaves, garbage, bagasse, rice husk, and other cereal crops. Woodchips is the most commonly used bulking agent for sludge composting (Willson et al., 1980a).

Woodchips are widely used as bulking material because they are the most readily available in most areas, moreover, it possesses all the qualities of any excellent bulking agent. After the process and curing phase are completed, the wood can be separated for recycling (Frankos et al, 1986).

The screening process can be difficult when it is carried out in place where the temperature is under freezing or when the moisture of the compost without screen is around 50%. The screening operations represent an additional cost (Colacicco et al., 1977).

2.4.2.- OTHER BULKING AGENT ALTERNATIVES

Using woodchips as a bulking agent has some serious disadvantages. Purchasing, and such activities as storage, shipping, mixing and screening comprise another third of the total cost. Additionally, stored woodchips provide conditions for the development of the Aspergillus fumigatus fungus. This fungus develops in organic material and produces spores that can cause allergies or pulmonary diseases in humans. A viable alternative would be to replace the woodchips with aged wood or a by-product obtained from the production of each processing plant.

Experiments have been conducted to measure the output of the processing process using inert material as a bulking agent (Higgins, 1986). Car tires were used as a bulking agent, shredded into pieces ranging from 2x2-2x3". This size was necessary to maintain the porosity of the mixture and provide effective aeration.

Six related experiments were conducted at Rutgers University. Each trial was conduced with ten tons of material , made-up of:
1) rubber and sludge, 2) rubber, recycled wood and sludge, and
3) rubber, wood shavings and sludge. The first two trials were carried out used a mixture with a 2:1 ratio of rubber:sludge. The first pile, with the highest anaerobic activity, had an initial moisture content of 69%; the final moisture content was 56%. On the other hand, in the second pile the moisture content fell from 66% to 44%. The air flow ratio caused the discrepancies between both piles. In the

first pile, 500 foot^3/hr/dt was used, while in the second, 1000 foot^3/hr/dt. The results indicate that a higher air flow ratio is more efficient for moisture removal.

To reduce the moisture content in the initial mixture the next two experiments used recycled wood. The ratio of the mixture, rubber:recycled wood:sludge, was 2:1:2. In these first four experiments the initial moisture was reduced, the ratio of C/N increased, and the odor decreased significantly.

These experiments demonstrated that you can reach thermophilic temperatures when using inert material for bulking agent, but this depends on the type of sludge used, which should contain 70 to 75% organic material.

Analysis showed an increase in heavy metals when the process used shredded rubber. Iron and zinc in the rubber were also present in the final product. Heavy metal content decreased in proportion to each cycle using the same recycled rubber.

The goal of this study was to seek new alternatives related to the amount of bulking agent that can be recycled. In each cycle 99% of the rubber and 70% of the wood could be recovered. From this point of view the rubber has greater advantages. On the other hand, in terms of other factors, such as moisture, the rubber does not decrease the moisture content of the sludge, it only provides it body and does not have organic carbon, which is an important element to decomposition. For this reason, rubber always requires such additives as chips, cuttings, husk, etc. (Higgins, 1986).

Another bulking agent used is the African tulip (Delgado, 1989). This is a tree native to tropical West Africa that has been cultivated in tropical regions around the world. It is an ornamental plant, with brilliant tulip-shaped orange flowers, and grows to a height of 50-60 feet, with a diameter of 1-1.5 feet. The tree flowers and bears fruit throughout the year and can be propagated through seed or root cuttings. It is fast-growing and requires no care. Occasionally during the development of this tree new seedlings sprout from the roots thus making it an undesirable species. The wood from this tree is not used in Puerto Rico, It is soft wood with low density which accounts for its rapid growth (Little and Wadsworth, 1964).

2.5.- BIOLOGICAL PRINCIPLES

The microbial community (bacteria and fungi) plays an important role in that it causes the decomposition of the decayed organic materials toward more stable moisture levels. The metabolism produces water, carbon dioxide, ammonia, nitrate, methane, and heat. In this manner the microorganisms incorporate some of the organic matter within a daughter cell for growth and reproduction. The physical and chemical environment within the mixture is constantly changing for this microorganisms, primarily as a result of their own metabolism, including the heat that is present. The change in their environment has major effect on their ability to develop, metabolize, and survive (McKinley et al., 1985a).

2.5.1.- MICROBIAL ACTIVITY (METABOLISM).- The metabolism can be aerobic, anaerobic or anoxic. The first, requires oxygen for metabolism of the microbial community. The second, anaerobic, occurs without the presence of oxygen. And in the third, oxygen is obtained from inorganic oxidants.

The aerobic oxidation of wastewater sludge can be expressed as:

$$C_{10}H_{19}O_3N + 12.5\,O_2 \longrightarrow 10\,CO_2 + 8\,H_2 + NH_3 \qquad (2.2)$$

This is an oxidation-reduction reaction. Electrons are transferred from the sludge and accepted by the oxygen. The oxygen is reduced while the carbon oxidizes. For this reason all organisms that require oxygen to accept electrons is called aerobic (Haug, 1980).

The process of aerobic composting is based on the spontaneous phenomena of self heating due to the microbial metabolism which is evident in the temperature increase of the material in the process (Finstein et al., 1987a).

Other components can be used as electron acceptors, such as nitrate and sulphate. Metabolism with these electron acceptors is called anoxic. An example of this is the metabolism of glucose, expressed as:

$$C_6H_{12}O_6 + 3\ SO_2 + 6\,H^+ \longrightarrow 6\,CO_2 + 3\,H_2S \qquad (2.3)$$

The formation of H_2S can be controlled maintaining an aerobic condition. It is also known that the generation of energy is less when compared with aerobic metabolism (Haug, 1980).

Anaerobic metabolism is more complex than the fermentation process. The transformation includes a variety of organisms as intermediates working together. That is, the product of one organism serves as the substrate of a second, and so on. In the long run a great variety of intermediate products are formed, such as organic acids with low molecular weight, methane, and aldehydes, thus resulting in a complexity of final products.

Temperature is a critical element in the sludge composting process. Small changes in temperature during the process can effect microbial activity and biomass more drastically than changes in moisture, pH, organic molecules or C/N ratio (McKinley et al., 1985b).

2.5.2.- BACTERIA.- Are single cell organisms that reproduce through binary fission. Given their small size quick transfer of soluble substrates occurs within the cell allowing for high metabolic activity. In aqueous solutions bacteria are more numerous than larger microbes. Bacterial cells consist of 80% water and 20% dry matter of which 90% is organic.

Bacteria are classified according to range of temperature they can tolerate. Mesophilic bacteria grow at temperature ranges of 25-40° C, and thermophilic bacteria grow at temperatures over 45° C (Haug, 1980). Initially a large number of mesophilic bacteria are found in the biodegradation process. They consume degradable carbohydrates and proteins, multiply, and their biological activity causes the temperature to increase (over 40° C), which in turn causes a decrease in the mesophilic population, and they are in turn replaced by a thermophilic population (McKinley et al., 1985b). The thermophilic population consume non-cellulose carbohydrates, hemicellulose fragments, proteins and lipids. Their metabolism generates heat, initially increasing the temperature to ranges between 40-70° C, and later decreasing (McKinley et al., 1985b).

2.5.3.- FUNGI.- Simillar to organoheterotrophic bacteria. Distinguished by their eucaryotic cells. They are larger and have a more sophisticated reproductive system than bacteria. Both organisms require similar substrates for metabolic activity. The fungus is generally less affected by decreases in moisture, and can develop in drier substrates, requiring a lower nitrogen content (Haug, 1980).

Fungus are cassified similarly to Bacteria--mesophilic and thermophilic. During the composting process mesophilic fungi compete with the remaining microflora for a short time, consuming carbon from the substrate, and being quickly replaced by thermophilic fungi when the temperature increases over 40° C. The rise in temperature causes thermophilic fungi to grow and later die when temperatures rise over 60° C. Both type of fungi require carbon, and thus both breakdown cellulose and hemicellulose (Crawford, 1985). Conditions that limit the development of fungi are: high temperatures, acidity, and anaerobic conditions.

2.5.4.0 PATHOGENS.- There are a wide variety of pathogenic bacteria in wastewater sludge. The type and amount of pathogens present

present varies substantially from community to community. Among the diseases that can be spread by these organisms are the following: cholera, typhoid fever, gastroenteritis, and generally most stomach ailments. The presence of intestinal parasites (in the form of eggs) has been linked to polluted water. Ascaris is among the most common type of parasite. The egg shell from this parasite is very resistant to chemical products, and can survive for weeks in a 10% chlorine solution. This resistance has made it one of the most common parasites (Haug, 1980).

With respect to these pathogens it can be said that the objectives of the aerobic biodegradation process of wastewater sludge are to:

1.- Stops the growth and increase of pathogens.

2.- Destroy any pathogens initially found in the sludge.

3.- Produce a stable material. The product of the aerobic decomposition is not a hospitable medium for the growth of pathogens.

The first objective seeks to prevent the growth of fungi. Some fungi tend to grow on decayed organic matter, and can produce spores that cause allergies or infections in human lungs. Disturbance of the organic matter that produces the spores growing in that environment can affect workers in industrial facilities (Finstein et al., 1987c).

A species of fungus called Aspergillus fumigatus develops on organic matter (including wood) and can produce spore masses that sometimes cause bronchopneumonia or asthma. This fungus requires temperature ranging from 12 to 57° in order to develop, with 35 to 43° C representing the optimum temperature range. A temperature of 62° C is deadly. The fungus uses cellulose as an energy source because of its carbon content. Stored woodchips are very suitable to its development. In order to avoid this problem, woodchips that have already been recycled and composted are used since they do not provide the necessary conditions for the development of the fungus (Finstein et al., 1985), (Miller et al., 1982), (Miller et al., 1985).

There are three operative mechanisms to sterilize wastewater sludges: 1) Microbial attacks resulting from competition between microbial pathogens and non-pathogens in the face of a limited supply of nutrients; 2) the diffusion of products (as a result of the reactions that occur in the process) with sterilizing properties, such as ammonia and heat causing high deactivating temperatures; 3) deactivation of pathogens at high temperatures which represents an important area for the solution of related problems (Finstein et al., 1985).

Finally, a sufficiently stable product is desired to avoid a reappearance of the pathogens. That is, a product without remaining substrate that can potentially metabolize to produce the growth of pathogens. Alternatively, the space occupied by pathogens can be occupied by non-pathogens, that can only be displaced with great difficulty (Finstein et al., 1985). For example, if the pathogenic bacteria Salmonella is injected into a composted product, it will tend to die instead of proliferating. This is due to an inhospitable environment. The product does not offer optimum condition that permit the reappearance of pathogenic bacteria.

2.6.- KINETIC PRINCIPLES.

Microbial growth is described in mathematical terms using the Monod model, which is similar to others that describe the movement of a simple enzyme substrate compound. Microbial immobilization by heat is due to temperature and the exposure time.

2.6.1.- KINETICS OF MICROBIAL GROWTH - The kinetics of microbial growth are described in mathematical terms using the Monod model, which is similar to the movement of an enzyme substrate compound, as expressed by:

$$dS/dt = -(k_m SX)/ (K_5 + S)$$

dS/dt = speed of substrate digestion (mass/vol time)

X = microbial concentration, (mass/vol)

k_m = maximum speed of digestion, (mass substrate/mass microbes-dia)

K_5 = average speed, (mass/vol)

S = amount of substrate, (mass/vol)

The speed of substrate digestion and microbial growth can be described in terms of four kinetic factors: Y_m (growth yield), k_m K_5 y K_e (endogenous respiration). The yield of an organism by unit of digested substrate is a function of the available free energy in the substrate. The maximum speed for substrate digestion is relative to the speed of electron transfer in the cell and is quite constant for a wide variety of microbes (Haug, 1980).

2.6.2.- **KINETICS OF HEAT INACTIVATION**.- The kinetics of thermal immobility relates to temperature and the time of exposure to a given temperature. A high temperature and short exposure time, or low temperature and long exposure, are equally effective in achieving microbial **inactivation**). The speed at which reduced activity occurs falls within the following first derivative equation:

$$- dn/dt = k_d n \qquad (2.5)$$

Here k_d refers to temperature and can be described by the Arrhenius equation. The activation of many spores and vegetative cells is between 50 and 100 kcal/mol. This means that thermal immobilization is strongly influenced by temperature. A change of a few Celsius degrees can cause a significant change in the speed of thermal immobilization (Finstein et al., 1987d). If the value of k_d is known for a specific microbe the resulting thermal immobilization can be estimated by a specific time-temperature profile Haug, 1980).

Based upon our understanding of the time vs temperature ratio, the heat required for sterilization can easily be generated in the conditions common to aerobic biodegradation. A temperature of 55 to 60° for one or two days is enough to eliminate all viral pathogens, bacteria, protozoa and intestinal worms.

Many factors can reduce the ability to inactivate pathogens. Usually such factors are as follows: 1) The collection of solids that impede sterilization by temperature throughout the entire surface; 2) Variation in temperature, leading to cold areas that allow the pathogens to multiply; 3) microbial conflict with a lessening of the nutrient supply; 4) renewed bacterial growth, including fecal coliform, salmonella and streptococcus. To reduce the possibility of microbes escaping from areas exposed to high temperatures, it is necessary to expose all solids to a high temperature for an appropriate length of time (Haug, 1980).

2.7.- PROCESS CONTROL FACTORS

The environment influences the activity of bacteria and fungi during the biodegradation process. Such activity will determine the speed of the process, thus it is necessary to create an environment conducive to the development and reproduction of these microorganisms. The determinant factors in the control of the environment and achieve optimum processing, are: moisture content, evaporating solids, porosity and interstitial volume, amount of oxygen, carbon-nitrogen ratio, pH and temperature (Singley et al., 1982).

2.7.1.- MOISTURE CONTENT.- High moisture content compresses the mixture, reducing the amount of space, making the flow of oxygen throughout the mixture difficult. This in turn can create anaerobic areas within the system. On the other hand, if the moisture content is lower than 40% the composting process will be slow because water is required for microbe development. The sludge to be processed should have a solid content of 22-25%. When mixed with an organic bulking agent with a 30 or 40% moisture contents, the initial mixture will have about 55 or 65% moisture (Willson et al., 1980a), (Crawford, 1985).

2.7.2.- VOLATILE SOLIDS.- These are determined by the amount of volatile dry solids (as measured by percent) when heated to 550°; widely used as an approximate measure of organic material content (Standard Methods for the Examination of Water and Wastewater),1985). Aerobic biological activity reduces volatile solid content because organic carbon becomes carbon dioxide. In this manner measuring volatile solids during the process can be used as a dimension of speed. In any case this measurement is imprecise and its use has limitations. Tests of volatile solids are not successful when distinguishing between: decayed matter that is easily metabolized, matter less easily metabolized, and organic matter that cannot be metabolized (Golueke et al., 1980).

The amount of volatile solids in organic compost is less than in the initial mixture. For example, if the initial content of volatile solids is 80% and half of the volatile material is destroyed, the volatile solid content is decreased to 67% (Finstein et al., 1986).

In composting wastewater sludges, Golueke et al. (1980) found that the speed of evaporating solid decrease was approximately 0.6% per day during a one month period (Stentiford et al., 1985).

One problem related to evaporated solid testing of sludge composting with woodchips or another bulking agent, is that the test does not distinguish between wood and sludge, and the decrease of volatile solids cannot be determined solely from the sludge. Usually to determine volatile solids small samples of material are burnt. This is a technical problem resulting from working with heterogeneous materials (Finstein et al., 1986).

2.7.3.- POROSITY AND INTERSTITIAL VOLUME.- Porosity is determined by the amount of air space present in the mass. This porosity is the result of the ratio between the number of spaces and total volume. Also, the air spaces are the result of the ratio of the volume of transferable gas to total volume. (Haug, 1980).

The concept of interstitial volume is widely used to obtain optimum processing during aerobic biodegradation. The the literature and research indicates that between 30 to 36% of space is required for optimum processing using a broad variety of materials as bulk. (Haug, 1980).

The addition of bulking agents (highly porous materials) to wastewater sludge provides structure, volume, and creates air spaces.

2.7.4.- OXYGEN CONCENTRATION.- The main effect of oxygen is to decompose organic material aerobically. Air as a carrier of oxygen, in addition to oxygenation, removes the water and heat produced by the oxidation. The stoichiometric oxygen requirements can be determined as a function of the chemical composition of organic solids (Haug, 1980). It is probable that the speed of oxygen consumption varies with: (a) species of microbe and density, (b) digestibility of the nutrients, (c) size, (d) moisture content, (e) pH and (f) temperature. For this reason oxygen consumption will vary from one operation to another (Willson et al., 1980b).

During the process of aerobic composting aeration is essential for the development of the thermophilic microrganisms which will guarantee quick decomposition, eliminate odor, and decompose the remaining organic pieces. The forced aeration system used to treat aerated static piles has an oxygen concentration of between 5 and 15% volume, per volume of material. This range produces maximum temperatures to ensure that pathogens are destroyed and quick composting occurs (Willson et al., 1980a). Increasing oxygen concentration over 15% results in a temperature decrease because of excess air flow. Similarly, oxygen concentration below 0.5% causes an anaerobic process, generally at least 5% oxygen is required to maintain aerobic conditions (EPA 625/1-79-011).

2.7.5.- NUTRIENT CONTENT.- Nitrogen is the nutrient most required by microorganism to absorb a carbon substrate. About 20 to 40% of carbon substrate is absorbed by new cells. The remaining carbon is oxidized. These cells contain approximately 50% carbon and 5% nitrogen. As a result, microbial nitrogen requirement is 2 to 4% of the initial carbon, with a C/N ratio of between 25:1 and 50:1. Microbial activity tends to reduce this ratio about 10:1. If the C/N ratio is less than 25:1, nitrogen is lost as ammonia. Such calculations are complicated as much by the availability of carbon as of nitrogen to the microrganisms. Carbon, as cellulose or lignin, is insoluble and thus nitrogen is lost, although the C/N ratio appeared to be very high. Nitrogen, as keratin, is not present and thus calculations become difficult. Some results indicate that the aerobic biodegradation process occurred when the initial C/N ratio was 200:1, while other indicate an initial ratio of less than 10:1. Processing an initial mixture with a high level of nitrogen will produce free ammonia, because all the nitrogen cannot be converted within the microbial cell or to enrich the "lignin-humus" complex. The nitrogen present in the "lignin-humus" complex can also cause the protein content of the product to increase. This increase can be two to three times as much (Crawford, 1985).

Wastewater sludges usually have a C/N ratio of less than 15. Adding woodchips and other bulking agents enriches the C/N ratio, ensuring the conversion of available nitrogen within the cell. Recovering the material from the product for recycling will not enrich the C/N ratio to the same degree as using fresh wood. The microorganisms consume 30 parts of carbon for each part of nitrogen. Thus an initial C/N ratio of 20 to 35 is ideal for rapid conversion of organic wastes (Willson et al., 1980a).

2.7.6.- pH.- The optimum pH range to develop bacteria is between 6.0 and 7.5, and between 5.5 and 8.0 for fungi. The pH is not the same throughout the material but stays within this range (EPA 625/1-79-011).

Wastewater sludge usually has a pH content of between 5.5 to 6.5. The loss of organic acids or the accumulation of ammonia make the pH of the sludge rise during the composting process. McKinley et al (1986) observed that the pH in an initial mixture fluctuated between 6.5 to 7.0, while the compost without screen had a pH between 8.2 and 9.0. During the curing phase pH normally decreased to a neutral range (Crawford, 1985).

2.7.7.- TEMPERATURE.- Temperature substantially affects the growth and activity of the microorganisms and thus determines the speed for composting the organic materials. The majority of microorganisms in wastewater sludges are mesophilic and achieve major growth at a temperature of 20-35° C. In any case, since the temperature increases during the aerobic biodegradation process, another group of microorganism begins to predominate. These are the aerobic thermophilic organisms that only develop at high temperatures, multiplying quickly at 45 to 65° C. They give off enough heat to increase the temperature to a degree that human pathogens are destroyed (Willson et al., 1980a).

Results of research conducted at Rutgers University established a maximum temperature of 60° C. (Rutger's strategy) to reduce processing time. In order to maintain the temperature at this level they found that it was more efficient to reduce excess heat through forced aeration. As a result, the mass is well-oxygenated because air is required more to remove the heat than to provide oxygen to the biodegradation process that is developing aerobically (Finstein et al., 1985).

The optimum temperature can also vary because the substrate and environment have a selective effect on the microbe species; each one can have their own optimum temperature (Willson et al., 1980b).

McKinley, Vestal and Eralp conducted experiments to determine the optimum temperature for achieving major microbe activity during the composting process. They reached the following conclusions:

1) Temperature is a critical factor during the process. Small variations in temperature can affect microbe activity and biomass in the composting of wastewater sludges more dramatically than a change in moisture, pH, organic changes or C/N ratio. It is thus very important to control the temperature for efficient and consistent processing operations. 2) The temperature inside a reactor was raised to about 55°C but the thermophilic bacteria did not play a significant role. 3) When comparing composting during temperatures as high as 85°, the optimum temperature proved to average 58°C in terms of achieving quick microbe activity. However the processing temperature should be sufficiently high to ensure sterilization (generally around 55°C for 3 days, U.S. Environmental Protection Agency 430/9-81-011). It is thus important to control the temperature to reduce pathogens and maintain a healthy amount of microorganisms to compost the organic waste (McKinley et al., 1985b).

2.8.- RESEARCH CONDUCTED IN PUERTO RICO.

Various studies on wastewater sludge treatment have been conducted in Puerto Rico. Alpert, Taffel and Epstein (Alpert et al., 1981) completed a study on composting wastewater sludge in Puerto Rico through aerobic biodegradation. A wide variety of bulking agents were tried with both moist and dry wastewater sludge. The physical properties and metal content of wastewater sludge were determined at various locations, and the final conclusion was that the process is feasible for Puerto Rico.

Saliceti (1983) conducted studies on aereated static composting as a disposal alternative for the sludge produced by the Barceloneta Wastewater Treatment Plant. The studies utilized various bulking agents (bagasse from sugar cane and rice husk) under the following conditions: moisture of the mixture - 75%, 15.51 C/N ratio, processing temperature of over 70° causing the nitrogen to evaporate and the processing time to last between 45 and 60 days. The end product was a nutrient-rich compost and thus it was deduced that the biodegradation process is physically feasible. However, the concern arose that the supply of bulking agent might not satisfy the demand for a large scale production process.

In 1989 Delgado conducted experiments concerning the effects of bulking material and temperature control on the composting process. Woodchips from the African Tulip tree and shredded rubber (car tires) were used as bulking agents. Temperature control maintained the mixture at under 60°C. Four trials were conducted, two with temperature control and two without. The greatest yield was obtained using woodchips and temperature control. Statistical analysis indicated that temperature control was the most important factor. It was recommended that studies be conducted on process yield using a recycled bulking agent, as well as studies on the degree of degradability of wastewater sludge and bulking agents, in order to develop a simulation process for laboratory use. The preceding was the basis for the present study.

3.- EXPERIMENTAL PROCESS

3.1.- GENERAL DESCRIPTION

The purpose of this research was to determine the effect of recycled material as a bulking agent in aerobic stabilization of wastewater sludge. In order to analyze recycled bulking agents two different raw materials were used: 1) recycled wood, and 2) an intermediate product (compost without screen). Strategies to develop the process were based on the experimental studies refered to in chapter II, such as the following: an initial mixture with 60% moisture; 20 to 35 C/N ratio; approximate 30% porosity; pH between 6.5 and 7; oxygen concentration of not less that 15% (for oxygenation and aeration during the process); and temperature not exceeding 60°C. The changes during the process were measured by the decrease in volatile solids, dewatering, and extent of sterilization (as measured by fecal coliform content). Two laboratory scale reactors were used, each with an 11 lb. capacity.

The experiment involved six trials, each one duplicated, divided into three phases. Each phase may be described as follows:

PHASE I: Base mixture prepared for the phase II and III experiments. Fresh African tulip woodchips were used as a bulking agent. Each trial was conducted twice.

PHASE II: Recovered wood was analyzed and recycled various times as a bulking agent, using 1/3 fresh wood and 2/3 recycled wood (wood recovered from screened compost) as the bulking agent. Three consecutive trials were each run twice.

PHASE III: Analysis of intermediate product used as a bulking agent. The bulking agent used was 1/3 fresh wood and 2.3 intermediate product. Two trials were run twice.

The type of bulking agent in each trial of the corresponding phase and objectives are shown in Table I on the following page.

Table I: PHASE DISTRIBUTION AND BULKING AGENT REQUIREMENTS

TRIAL	OBJECTIVE	BULKING AGENT
	PHASE I	
I	Prepare bulking agent for Phase III	Fresh wood
II	Prepare bulking agent for Phase II	Fresh wood
	PHASE II	
I	Analyze the efficiency of recycled material I	1/3 fresh wood & 2/3 recycled material I (recovered wood from Phase I, Trial II)
II	Analyze the efficiency of recycled material II	1/3 fresh wood & 2/3 recycled material II (recovered wood from Phase II, Trial I)
III	Analyze the efficiency of recycled material III	1/3 fresh wood & 2/3 recycled material III (recovered wood from Phase II, Trial II)
	PHASE III	
I	Analyze the intermediate product as a recycled material	1/3 fresh wood & 2/3 intermediate product (from Phase I, Trial I).
II	Compare results with previous trial	1/3 fresh wood and 2/3 recycled material

3.2.- EQUIPMENT

Two reactors were used for these studies the models and dimensions of which are based on the design of Frankos, Gouin and Sikora (Figure 1). Each reactor was a cylinder, 15.2 cm in diameter and 61 cm high, made of polyvinyl chloride (PVC), sealed at both ends with PVC caps. The caps were fitted with stainless steel tubes to connect the aeration system. Also, the top cap had two holes for the thermocouples. The tubes at each end serve to allow air in and out, respectively. The stainless steel tubes for the ventilation system were 0.952 cm. O.D., connected to the cap at the base of the cylinder. Type K thermocoupes were (Omega Engineering) installed on the top cap. Inside the reactor one thermocouple was set at a height of 15.24 cm, and the other at 45.74.

The PVC reactor was placed inside an aluminum cylinder, 91.5 cm high and with a 20.5 cm inside diameter (Figure 2). A Fisher Scientific heating coil was placed around the aluminum cylinder, and connected to a Simpson Model 390-2 wattmeter and a variable autotransformer Staco Energy Product Co., type 3 PN1010 to control the heating coil temperature. This made it possible to control the heating time at the start of the process and decreases in temperature during the process. The aluminum cylinder was covered with sodium carbonate insulation, 5.08 cm thick. A thermocouple was placed on the inside wall of the aluminum cylinder, and another, Type K, was placed in the circular space between the cylinders. The thermocouples were installed on a multiple switch (selector and a digital thermometer Omega 2170A.

The ventilation system was a pressure pump (Fisher Scientific) connected to an Erlenmeyer flask to stabilize the entering air pressure, followed by calibrated rotameter (Cole Palmer) that controlled the air flow upon entry. Subsequently air was forced into the reactor to oxygenate the material being processed.

Figure 1: Dimensions of the Reactor (cm).

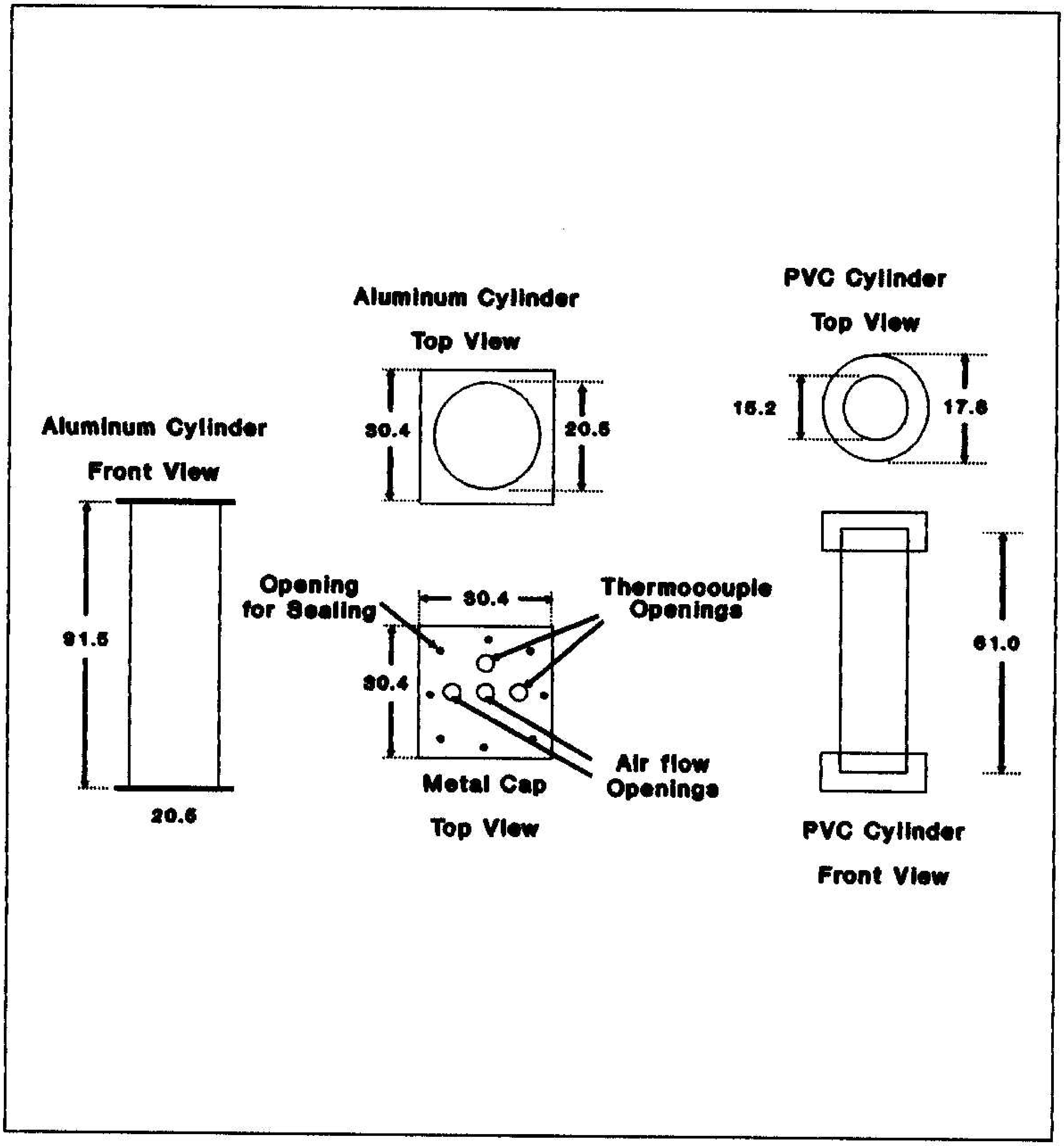
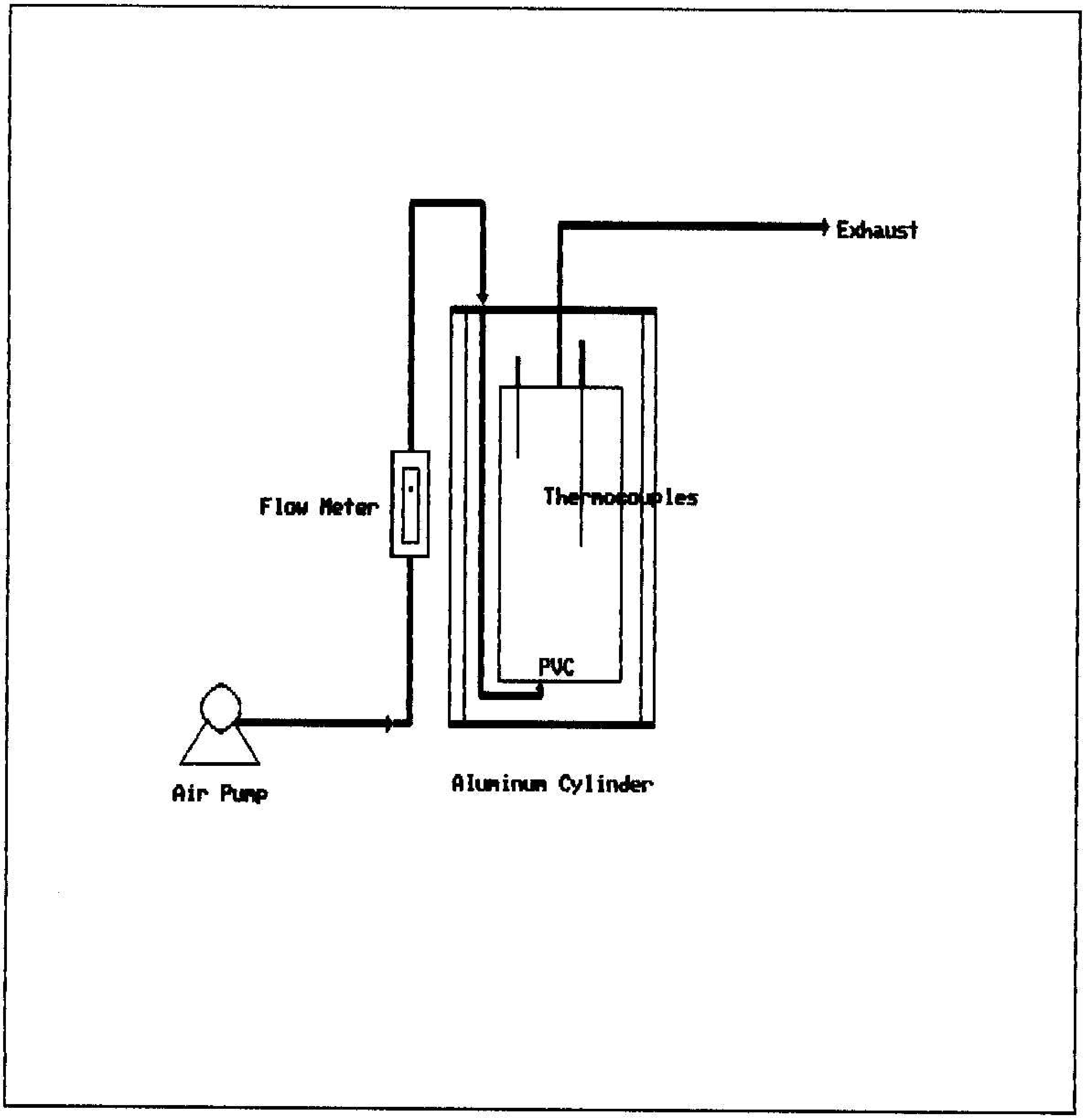


Figure 2: Laboratory scale equipment design.



The outside aeration lines were Tygon tubes with an internal diameter or 0.635 cm, except for those that were made of stainless steel, with an internal diameter of 0.952 cm.

3.3.- DESCRIPTION OF RAW MATERIALS

The major basic material used was the wastewater sludge for composting. Primary sludge, with a pH of 6.8, was obtained from the Barceloneta Wastewater Treatment Plant. It was difficult to obtain this sludge because the plant does not operate in such a way to allow filter presses to dewater the sludge 20 or 25%. The service was requested only once for a total of 12 experiments, thus all the experiments were carried out with the same sludge sample taken on June 16, 1988.

The bulking agent used was: 1) Woodchips from the African tulip (fresh wood); 2) A mixture of fresh wood with recycled wood (one, two, or three times) from continuously screened intermediate product ; and 3) mixture of fresh wood and intermediate product. The wood recovered from the intermediate product during the first processing was labeled Recycled Material I; the wood recovered from the intermediate product of the second processing was labeled Recycled Material II; and the wood recovered from the third processing was labeled Recycled Material III. The wood was obtained from the source and placed in a Grinder (5 hp W.W.), model 5-14-4. The size of the chips varied from 2 to 8 cm. The size distribution of the wood is shown in Table II. The larger pieces (8 mm or more) make up about 40%.

Table II: SIZE DISTRIBUTION AS A PERCENTAGE OF WEIGHT

Mesh #, (width in MM)	%
3, (7.93)	42.4
7, (2.80)	45.6
10, (2.00)	4.6
14, (1.40)	3.0
20, (1.00)	1.4
25, (0.71)	1.0
< 0.71	2.0

3.4.- PREPARATION OF THE MIXTURE.

The mixture was prepared in the following manner: a capful of bulking agent was placed on the bottom of a receptacle, followed by sludge, and another capful of bulking agent. This was stirred until a good mixture was obtained, and then another capful of bulking agent was placed on top, and another of sludge, and so on, until the available material was used-up. The amount of material was based on achieving balanced mass, adjusted to obtain a mixture having approximately 60% moisture. The initial mixture did not have lumps in the sludge.

3.5.- EXPERIMENTAL PROCEDURE

The entire mass of primary sludge, bulking agent and final product was tested for moisture content, volatile solids, total nitrogen and phosphorus. Likewise the wastewater sludge and the product of each experiment was tested for all fecal coliform and heavy metal content (nickel, chromium, lead, cadmium, and potassium). The methods used for these analyses are those found in the manual "Standard Methods for the Examination of Water and Wastewater, 16th Edition, 1985." The methods employed and any changes are discussed in Appendix A.

The volume ratio of sludge to bulking agent varied, depending on the amount of moisture of the primary sludge and that of the bulking agent, this ratio fluctuated between 1:3 and 2:3, taking into account that the moisture of the initial mixture should have been around 60%.

Phase I consisted of preparing bulking agent for subsequent phases. Primary sludge was used with 70 to 75% moisture. The bulking agent used was woodchips from the African tulip tree. The initial mixture was prepared in the manner explained in Section 3.3. The mixture was fed into the reactor until a 3 cm empty space was left . To start the process the heating system was turned on and the aeration system installed and activated at an initial rate of 100 ml/min., until the temperature approached 55°C. The airflow was then doubled and sometimes tripled in order to remove excess heat and maintain a temperature not exceeding 60°C. The temperature was controlled by a digital thermometer and airflow.

When the temperature fell under 45°C the process was considered finished, although the material was kept within the reactor until the temperature approached that of the external environment. The intermediate product was then removed from the cylinder and placed in an ordinary cardboard box for the curing phase to begin.

During the curing phase organic decomposition continues but at a very slow rate. This is considered passive composting, and the phase lasts for 30 days or more if necessary and ventilation occurs automatically. When this phase is concluded the intermediate product obtained from the reactors in Phase I, trial I is used as recycled material for Phase III. The intermediate products obtained from the other reactors in Phase I, trial II, were individually screened in order to separate the wood for recycling. Pieces larger than 2 mm were used as bulking agent in Phase II, and the pieces that were put through a number 10 screen (2 mm wide) created a uniform product with a pleasing appearance.

Figure 4: PHASE I. TRIAL I.
Temperature Curve. Reactor #1.

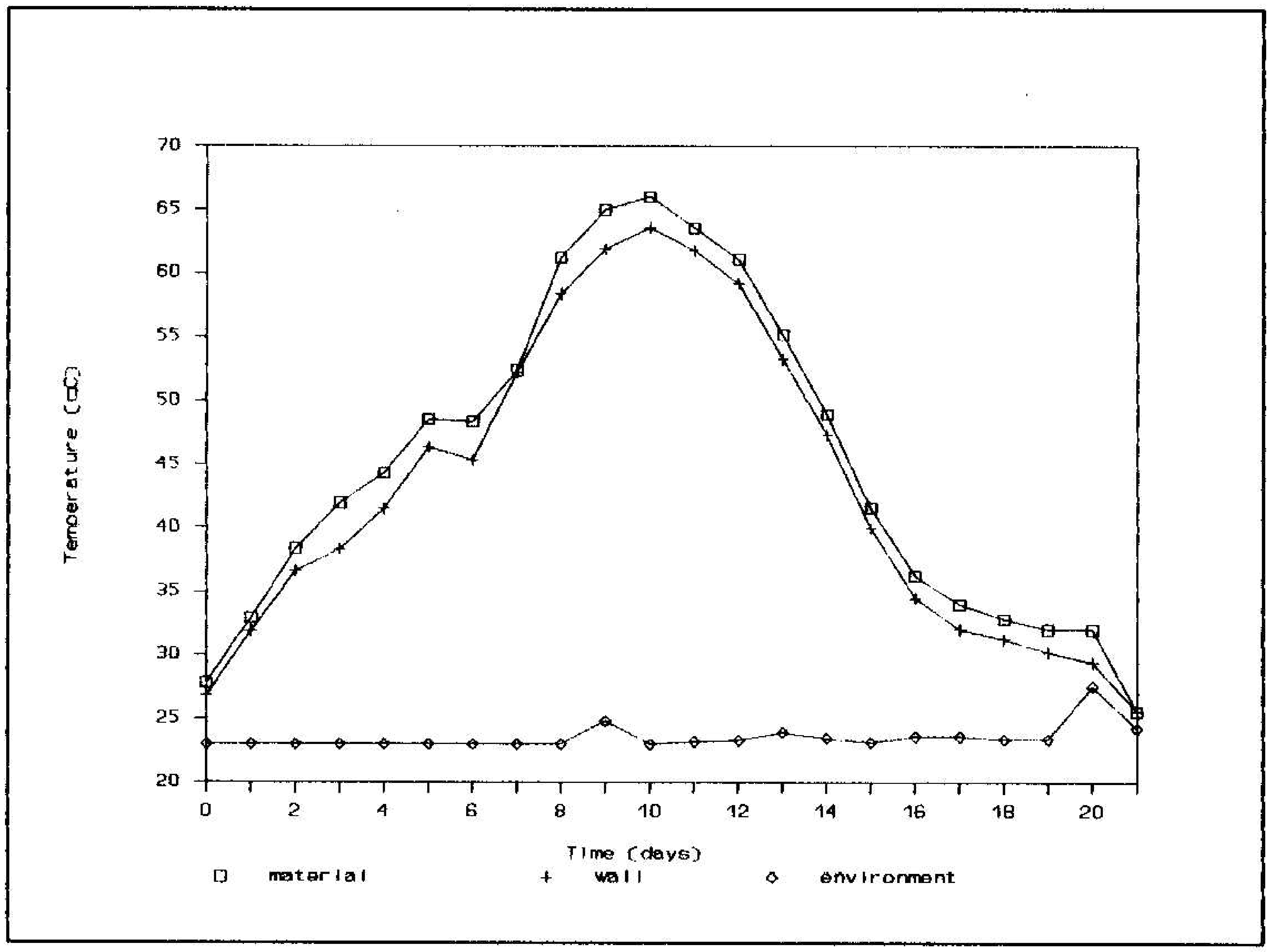


Table III: CHARACTERISTICS OF RAW MATERIAL AND PRODUCT. PHASE I. TRIAL I. REACTOR #1.

	Sludge	Fresh Wood	Initial Mixture	Intermediate Product
Ratio (V/V)	1	3		
Moisture∇ (%)	71.40	37.30	58.50	24.00
Volatile Solids ♦ (%)	62.71	97.47	83.10	79.81
Apparent Density (Kg/L)	0.98	0.17	0.38	0.21
pH	6.80			7.50
Weight ♦ (Kg)	0.74	0.82	1.56	1.12
Weight ∇ (Kg)	2.59	1.30	3.89	1.47
Volume (L)	2.64	7.87	10.30	7.00
Ratio ♦ C/N	10.55	93.36	24.66	25.93
Carbon♦ (%)	34.80	54.15	46.12	44.34
Nitrogen ♦ (%)	3.30	0.58	1.87	1.71
Nitrogen ♦ (g)	24.42	4.76	29.18	19.15
Phosphates ♦ (%)	6.00	0.17	2.90	2.51
Potassium ♦ (%)	0.07			0.31
Coliform (all) ♣	NA			50
Fecal Coliform ♣	NA			<0.20
Cadmium ♦ (mg/Kg)	2.16			2.54
Chromium ♦ (mg/Kg)	117.48			164.93
Lead ♦ (mg/Kg)	44.74			58.96
Nickle ♦ (mg/Kg)	53.03			72.13

♦ Dry base
Δ Moist base
♣ MPN/g.
NA = not analyzed. Report on the total and fecal coliform content of the Barceloneta sludge >24,000 MPN/g (Saliceti, 1983), (Delgado, 1989).

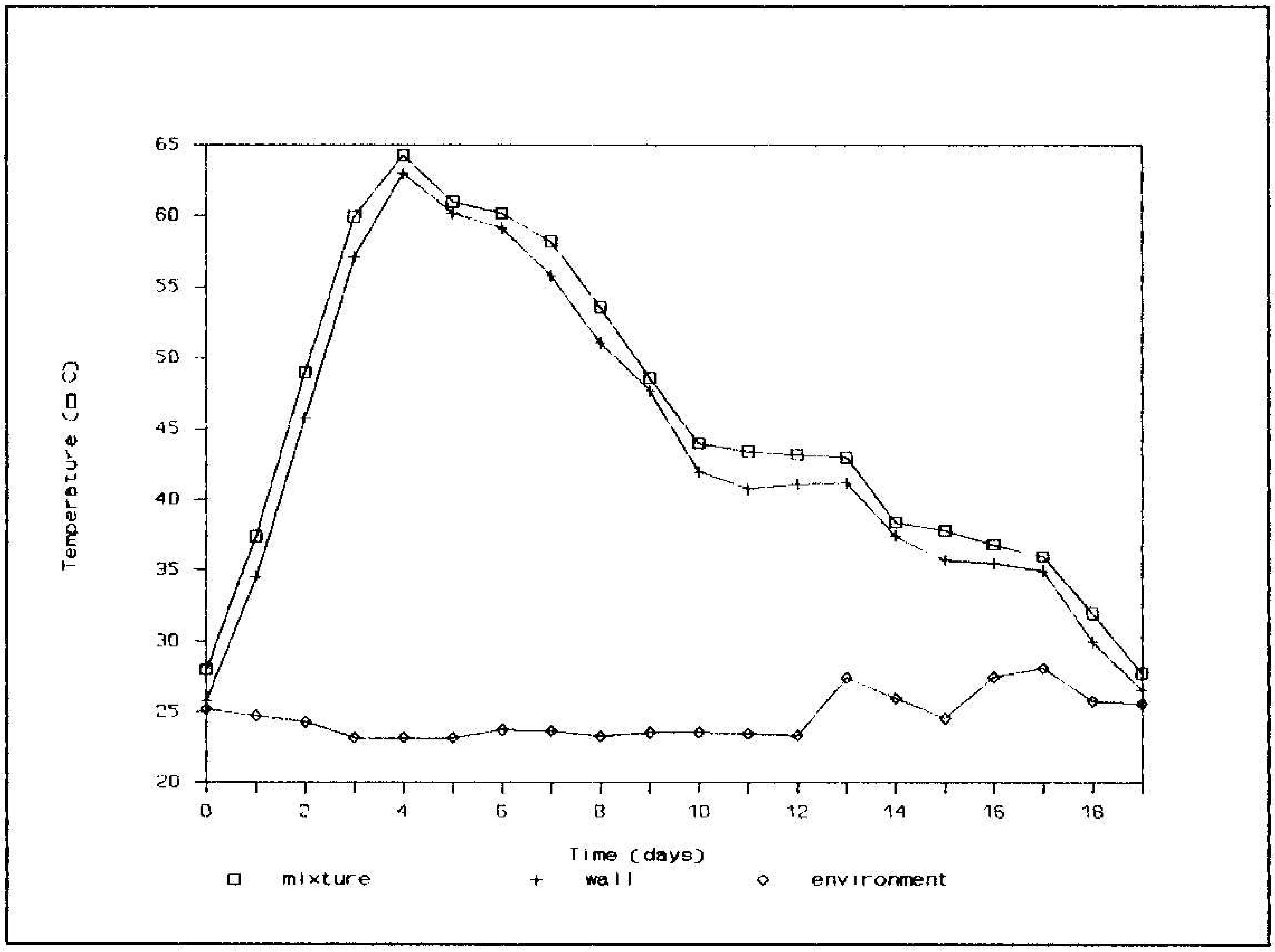

65
60
55
50
45
40
35
30
25
20
Temperature (□ C)
0
2
4
6
8
10
12
14
16
18
Time (days)
□ mixture
+ wall
◇ environment

Table IV: CHARACTERISTICS OF THE RAW MATERIAL AND PRODUCT. PHASE I. TRIAL I. REACTOR #2

	Sludge	Fresh Wood	Initial Mixture	Intermediate Product
Ratio (V/V)	1	3		
Moisture ∇ (%)	71.40	37.30	59.50	14.00
Volatile Solids ♦ (%)	62.71	97.47	80.19	78.03
Apparent Density (Kg/L)	0.98	0.17	0.38	0.21
pH	6.80			7.40
Weight ♦ (Kg)	0.76	0.84	1.60	1.27
Weight ∇ (Kg)	2.66	1.34	4.00	1.47
Volume (L)	2.71	8.12	10.50	7.00
Ratio ♦ C/N	10.56	93.36	23.82	25.05
Carbon ♦ (%)	34.84	54.15	44.55	43.35
Nitrogen ♦ (%)	3.30	0.58	1.87	1.73
Nitrogen ♦ (g)	25.08	4.88	29.96	21.97
Phosphates ♦ (%)	6.00	0.17	2.9	2.57
Potassium ♦ (%)	0.07			0.11
Coliform (total) ♣	NA			50
Fecal Coliform ♣	NA			0.40
Cadmium ♦ (mg/Kg)	2.16			0.93
Chromium ♦ (mg/Kg)	117.48			46.08
Lead ♦ (mg/Kg)	44.74			26.41
Nickle ♦ (mg/Kg)	53.03			29.46

♦ Dry base
Δ Moist base
♣ MPN/g.

NA = not analyzed. Report on the total and fecal coliform content of the Barceloneta sludge >24,000 MPN/g (Saliceti, 1983), (Delgado, 1989).

B.- TRIAL II.- The two experiments began on August 16, 1988. During this trial the same initial mixture was used (sludge and fresh wood) for both reactors, therefore the initial characteristics are the same, but the final conditions were clearly different. The temperature range in reactor #1 is shown in Figure 6. The characteristics of the raw material and product are shown in Table V. The temperature fluctuation during the process in reactor #2 can be seen in Figure 7. Similarly the results of the initial and final analyses are described in Table VI. The thermophilic process for both reactors lasted 21 days given some problems that arose and which are described in the following chapter. The curing time for the two experiments was 22 days. At the end of this period the intermediate product of each reactor was screened separately (this maintained an orderly sequence for each reactor). All pieces that were 2 mm wide and over remained unscreened and were retained for use as bulking agent. Thus for example, the material recovered from reactor #1 served as bulking agent for the next experiment in that reactor, following the same sequence throughout Phase II.

4.2.2.- PHASE II.- During phase II three trials were run in duplicate. During the first trial the mixture used was recycled material #I and fresh wood. After the first trial the intermediate product was divided into final product and recycled material #II. The second trail of Phase II was carried out in a similar manner, using a mixture of recycled material #II and fresh wood. During the third trial the bulking agent was a mixture of recycled material #III and fresh wood.

A.- Trial I.- The experiments for this trial began on October 3, 1988. The mixture processed in reactor #1 was made up of wastewater sludge, fresh wood, and recycled material #I from this reactor. The mixture for reactor #2 consisted of sludge, fresh wood, and recycled material # I from this reactor. The procedure for placing the mixture materials and the conduct of the process was the same as that used for the previous experiments. Figures 8 and 9 show the temperature ranges for reactors #1 and #2, respectively. The thermophilic process in reactor 1 and 2 was 12 to 13 days, respectively. The results of the analyses for each reactor are described in Tables VII and VIII. The product curing time lasted 26 days. At the end of this period the wood was separated from the intermediate product of each reactor. Use the same operations as those described for phase I, Trial II, recycled material #II was removed from each reactor and its respective products, carefully following the same sequence.

Figure 6: PHASE I. TRIAL II
Temperature Curve. Reactor #1.

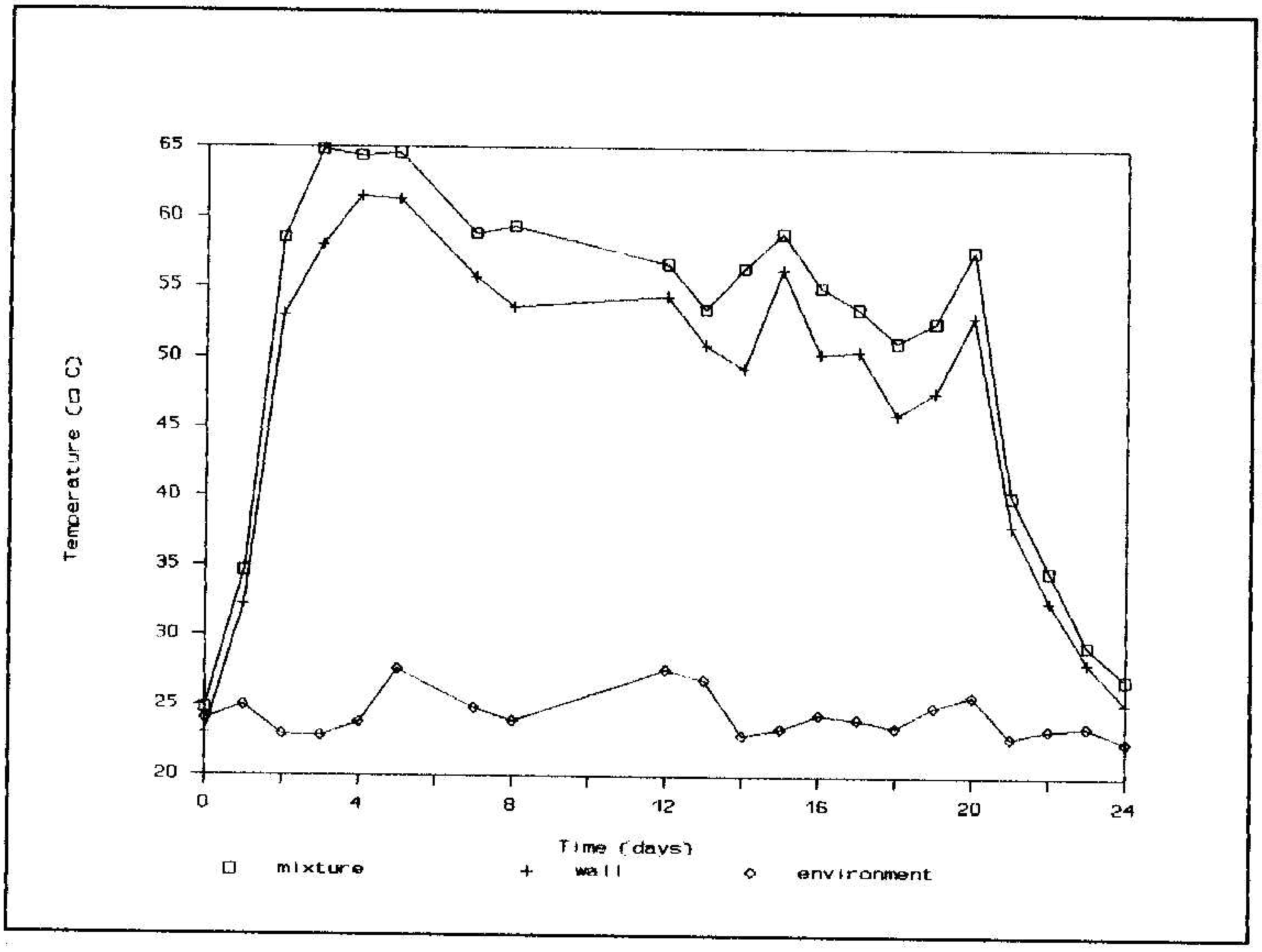


Table V. CHARACTERISTICS OF RAW MATERIAL AND PRODUCT. PHASE I. TRIAL II. REACTOR #1.

	Sludge	Fresh Wood	Initial Mixture	Intermediate Product	Screened Product
Ratio (V/V)	1	3			
Moisture ∇ (%)	72.70	37.30	60.20	51.00	49.00
Volatile Solids ♦ (%)	64.00	97.50	83.00	76.00	58.00
Apparent Density (Kg/L)	0.95	0.17	0.38	0.29	0.35
pH	6.80				7.50
Weight ♦ (Kg)	0.73	0.93	1.66	1.23	0.59
Weight ∇ (Kg)	2.68	1.49	4.17	2.51	1.16
Volume (L)	2.82	8.80	10.97	8.67	3.31
Ratio ♦ C/N	10.77	93.36	26.05	21.32	13.37
Carbon ♦ (%)	35.55	54.15	46.11	42.22	32.22
Nitrogen ♦ (%)	3.30	0.58	1.77	1.98	2.41
Nitrogen ♦ (g)	24.09	5.39	29.48	23.73	14.22
Phosphates ♦ (%)	6.00	0.17	2.70		4.08
Potassium ♦ (%)	0.07				0.16
Coliform (total) ♣	NA				3.40
Fecal Coliform ♣	NA				<0.20
Cadmium ♦ (mg/Kg)	2.16				1.15
Chromium ♦ (mg/Kg)	117.48				83.22
Lead ♦ (mg/Kg)	44.74				27.64
Nickel ♦ (mg/Kg)	53.03				35.03

♦ Dry base

Δ Moist base

♣ MPN/g.

NA = not analyzed. Report on the total and fecal coliform content of the Barceloneta sludge >24,000 MPN/g (Saliceti, 1983), (Delgado, 1989).

Figure 7: PHASE I. TRIAL II
Temperature Curve. Reactor #2

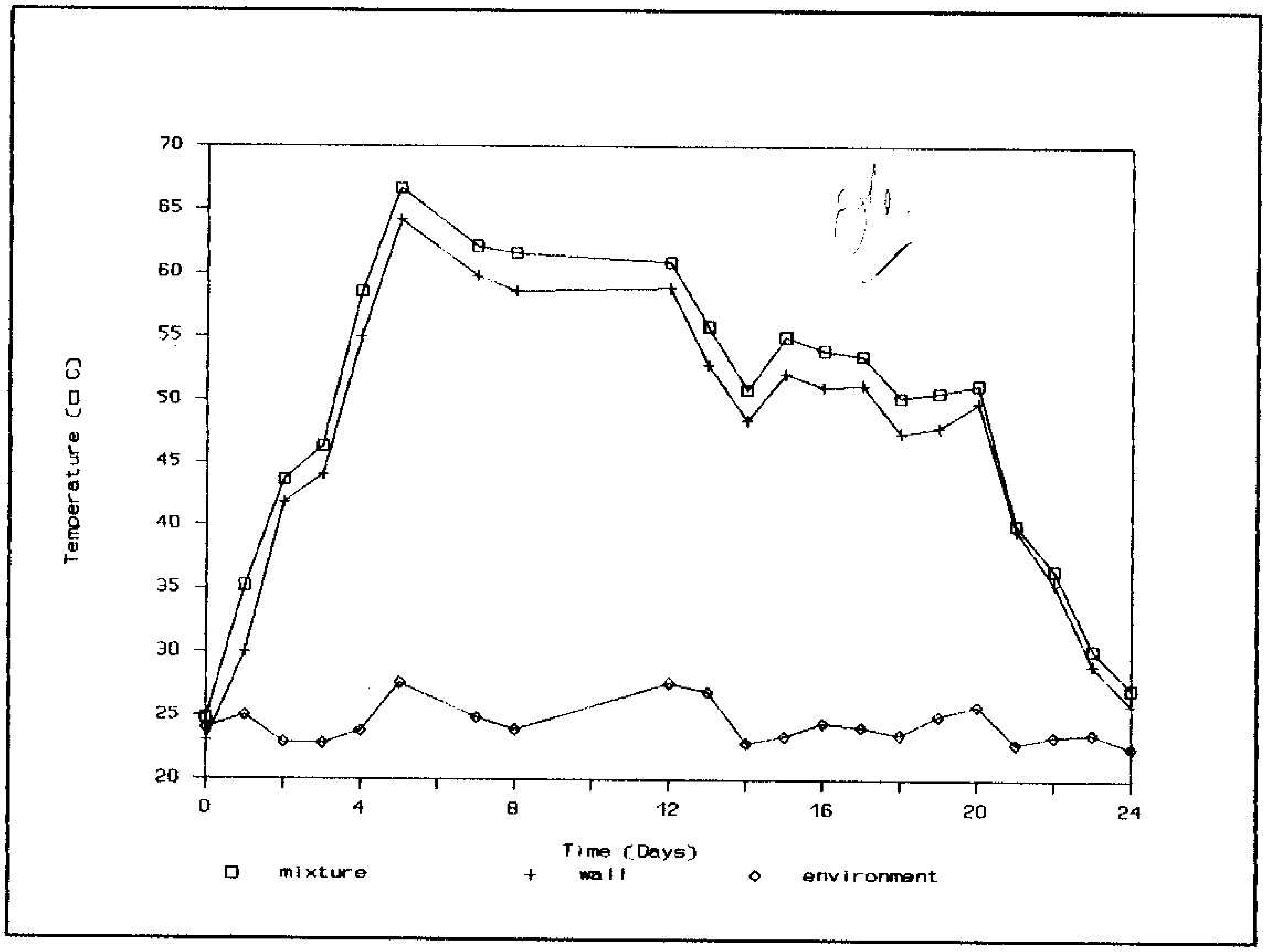


Table VI: CHARACTERISTICS OF RAW MATERIAL AND PRODUCT . PHASE I. TRIAL II. REACTOR 2.

	Sludge	Fresh Wood	Initial Mixture	Intermediate Product	Screened Product
Ratio (V/V)	1	3			
Moisture ∇ (%)	72.70	37.30	60.20	51.50	49.50
Volatile Solids ♦ (%)	64.00	97.47	83.00	74.00	55.00
Apparent Density (Kg/L)	0.95	0.17	0.48	0.29	0.35
pH	6.80				7.30
Weight ♦ (Kg)	0.69	0.87	1.56	1.22	0.56
Weight ∇ (Kg)	2.53	1.39	3.92	2.52	1.11
Volume (L)	2.70	8.20	10.30	8.50	3.17
Ratio ♦ C/N	10.77	93.36	25.90	21.52	12.17
Carbon ♦ (%)	35.55	54.15	46.11	41.11	30.55
Nitrogen ♦ (%)	3.30	0.58	1.78	1.91	2.51
Nitrogen ♦ (g)	22.77	5.05	27.82	23.29	14.05
Phosphates ♦ (%)	6.00	0.17	2.70		3.62
Potassium ♦ (%)	0.07				0.26
Coliform (total) ♣	NA				2.30
Fecal Coliform ♣	NA				<0.20
Cadmium ♦ (mg/Kg)	2.16				1.55
Chromium ♦ (mg/Kg)	117.48				155.03
Lead ♦ (mg/Kg)	44.74				48.22
Nickel ♦ (mg/Kg)	53.03				59.89

♦ Dry base

Δ Moist base

♣ MPN/g.

NA = not analyzed. Report on the total and fecal coliform content of the Barceloneta sludge >24,000 MPN/g (Saliceti, 1983), (Delgado, 1989).

Figure 8: PHASE II. TRIAL I
Temperature Curve. Reactor #1

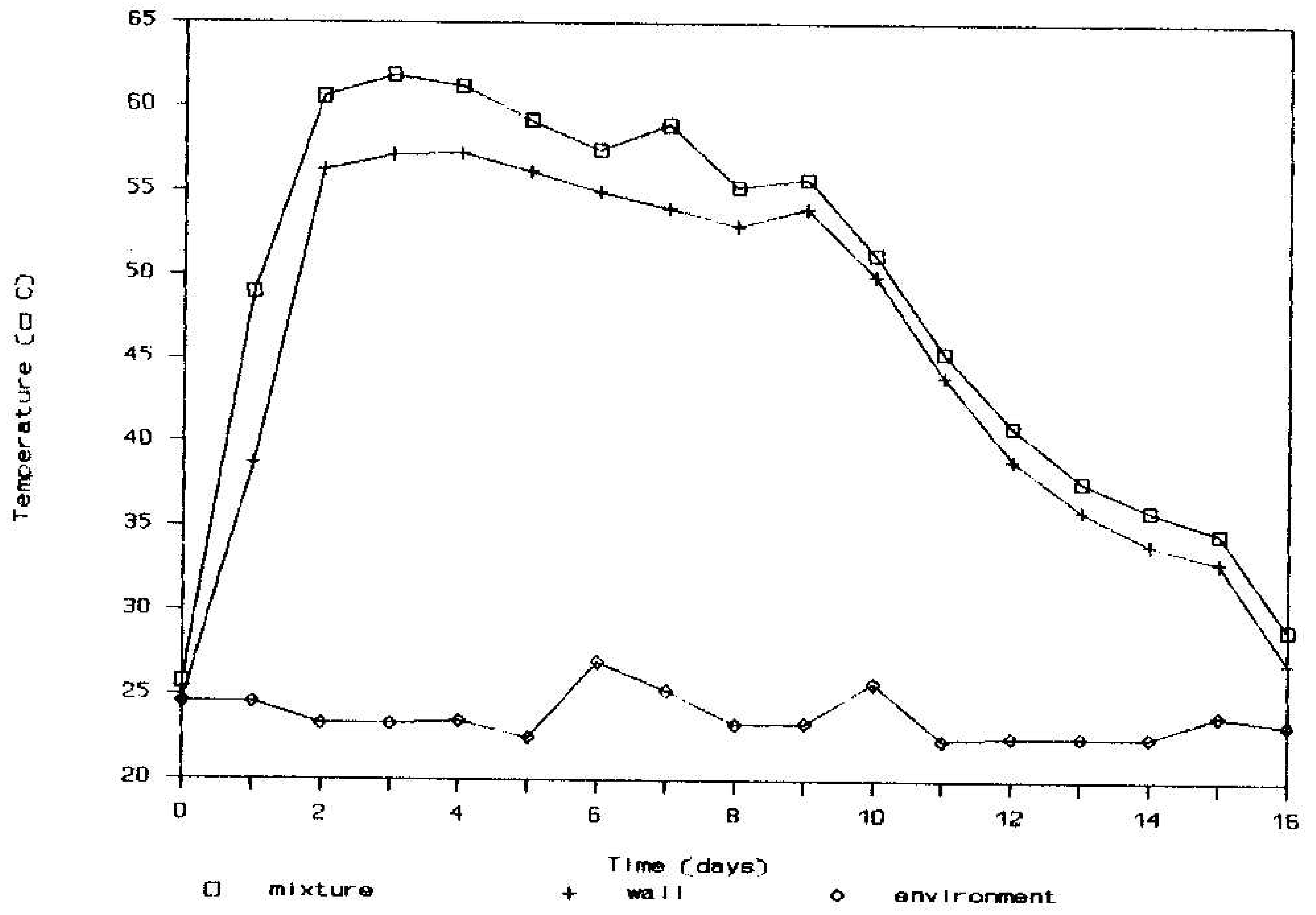


Table VII: CHARACTERISTICS OF RAW MATERIAL AND PRODUCT. PHASE II. TRIAL I. REACTOR #1.

	Sludge	Fresh Wood	Rec. # I	Initial Mixture	Intermed. Product	Screened Product
Ratio (V/V)	1	1	2			
Moisture ∇ (%)	71.00	32.00	53.00	59.90	30.00	25.00
Volatile Solids ♦ (%)	64.50	96.50	85.00	81.00	70.00	50.00
Apparent Density (Kg/L)	0.98	0.19	0.25	0.45	0.25	0.30
pH	6.80					7.30
Weight ♦ (Kg)	0.66	0.40	0.56	1.62	1.41	0.38
Weight ∇ (Kg)	2.27	1.59	1.20	4.05	2.01	0.51
Volume (L)	2.32	3.10	4.80	10.22	8.04	1.70
Ratio ♦ C/N	10.84	92.41	31.48	22.50	19.45	10.41
Carbon ♦ (%)	35.80	53.60	47.20	45.00	38.90	27.80
Nitrogen ♦ (%)	3.30	0.58	1.50	2.00	2.00	2.67
Nitrogen ♦ (g)	21.78	2.32	8.40	32.50	28.20	10.41
Phosphates ♦ (%)	6.00	0.17	1.70	3.07		3.96
Potassium ♦ (%)	0.07					0.37
Coliform (total) ♣	NA					17.00
Fecal Coliform ♣	NA					2.00
Cadmium ♦ (mg/Kg)	2.16					2.36
Chromium ♦ (mg/Kg)	117.48					190.69
Lead ♦ (mg/Kg)	44.74					58.32
Nickel ♦ (mg/Kg)	53.03					87.20

♦ Dry base

Δ Moist base

♣ MPN/g.

NA = not analyzed. Report on the total and fecal coliform content of the Barceloneta sludge >24,000 MPN/g (Saliceti, 1983), (Delgado, 1989).

Figure 9: PHASE II. TRIAL I.
Temperature Curve. Reactor #2.

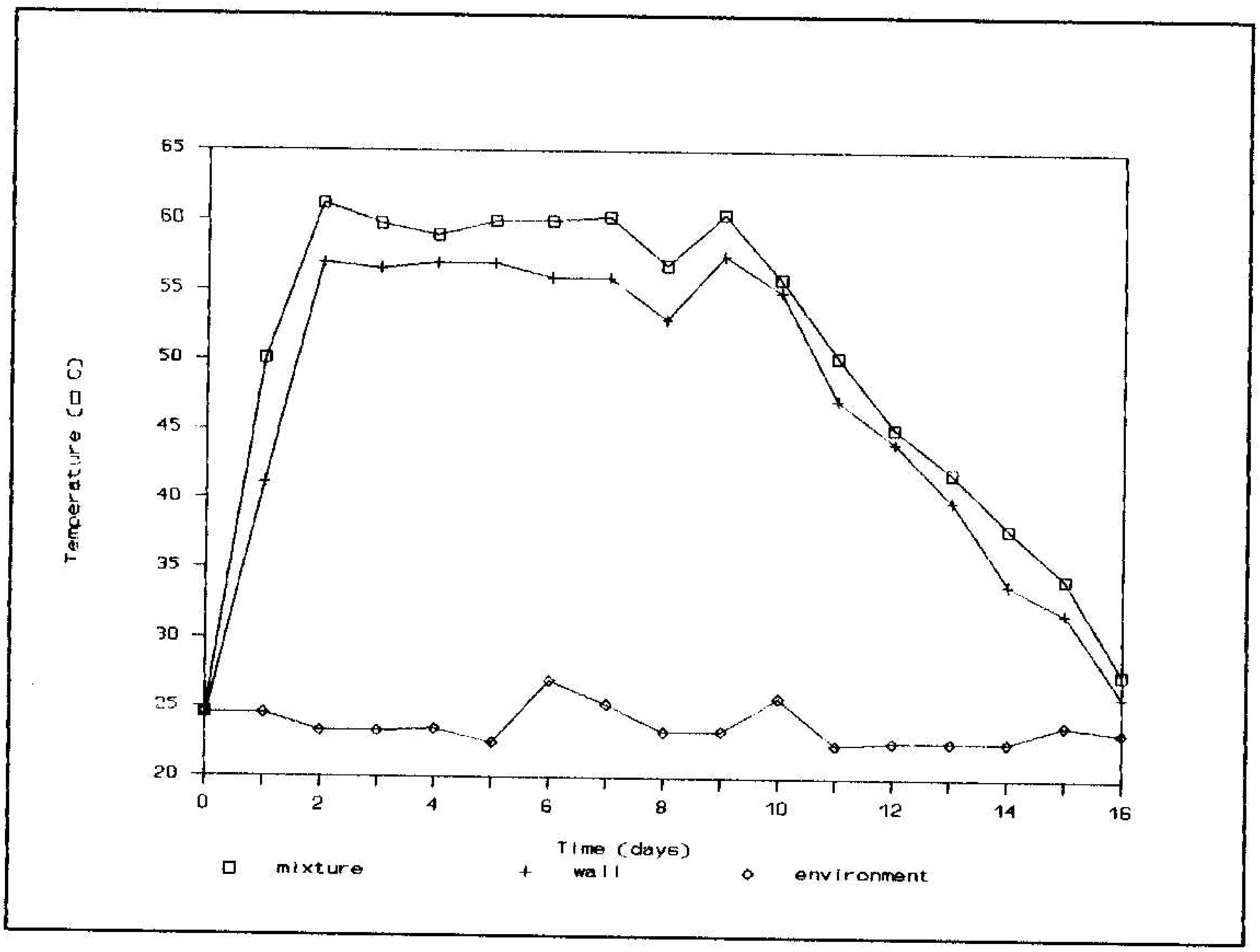


Table VIII: CHARACTERISTICS OF RAW MATERIAL AND PRODUCT. PHASE II. TRIAL I. REACTOR #2.

	Sludge	Fresh Wood	Rec. #1	Initial Mixture	Intermed. Product	Screened Product
Ratio (V/V)	1	1	2			
Moisture ∇ (%)	71.00	32.00	50.00	60.00	31.00	25.00
Volatile Solids ♦ (%)	64.50	96.50	86.00	81.50	72.00	51.00
Apparent Density (Kg/L)	0.98	0.19	0.21	0.44	0.25	0.30
pH	6.80					7.30
Weight ♦ (Kg)	0.69	0.37	0.54	1.61	1.40	0.43
Weight ∇ (Kg)	2.38	0.54	1.08	4.00	2.02	0.57
Volume (L)	2.43	2.84	5.14	9.10	8.04	1.90
Ratio ♦ C/N	10.85	92.43	34.12	22.64	19.32	10.29
Carbon ♦ (%)	35.83	53.61	47.77	45.27	40.00	28.33
Nitrogen ♦ (%)	3.30	0.58	1.40	2.00	2.07	2.60
Nitrogen ♦ (g)	22.77	2.15	7.56	32.48	28.98	11.18
Phosphates ♦ (%)	6.00	0.17	1.72	3.18		4.80
Potassium ♦ (%)	0.07					0.33
Coliform (total) ♣	NA					5.00
Fecal Coliform ♣	NA					<0.20
Cadmium ♦ (mg/Kg)	2.16					2.91
Chromium ♦ (mg/Kg)	117.48					209.72
Lead ♦ (mg/Kg)	44.74					56.19
Nickel ♦ (mg/Kg)	53.03					78.29

♦ Dry base
Δ Moist base
♣ MPN/g.

NA = not analyzed. Report on the total and fecal coliform content of the Barceloneta sludge >24,000 MPN/g (Saliceti, 1983), (Delgado, 1989).

Figure 10: PHASE II. TRIAL II.
Temperature Curve. Reactor 1.

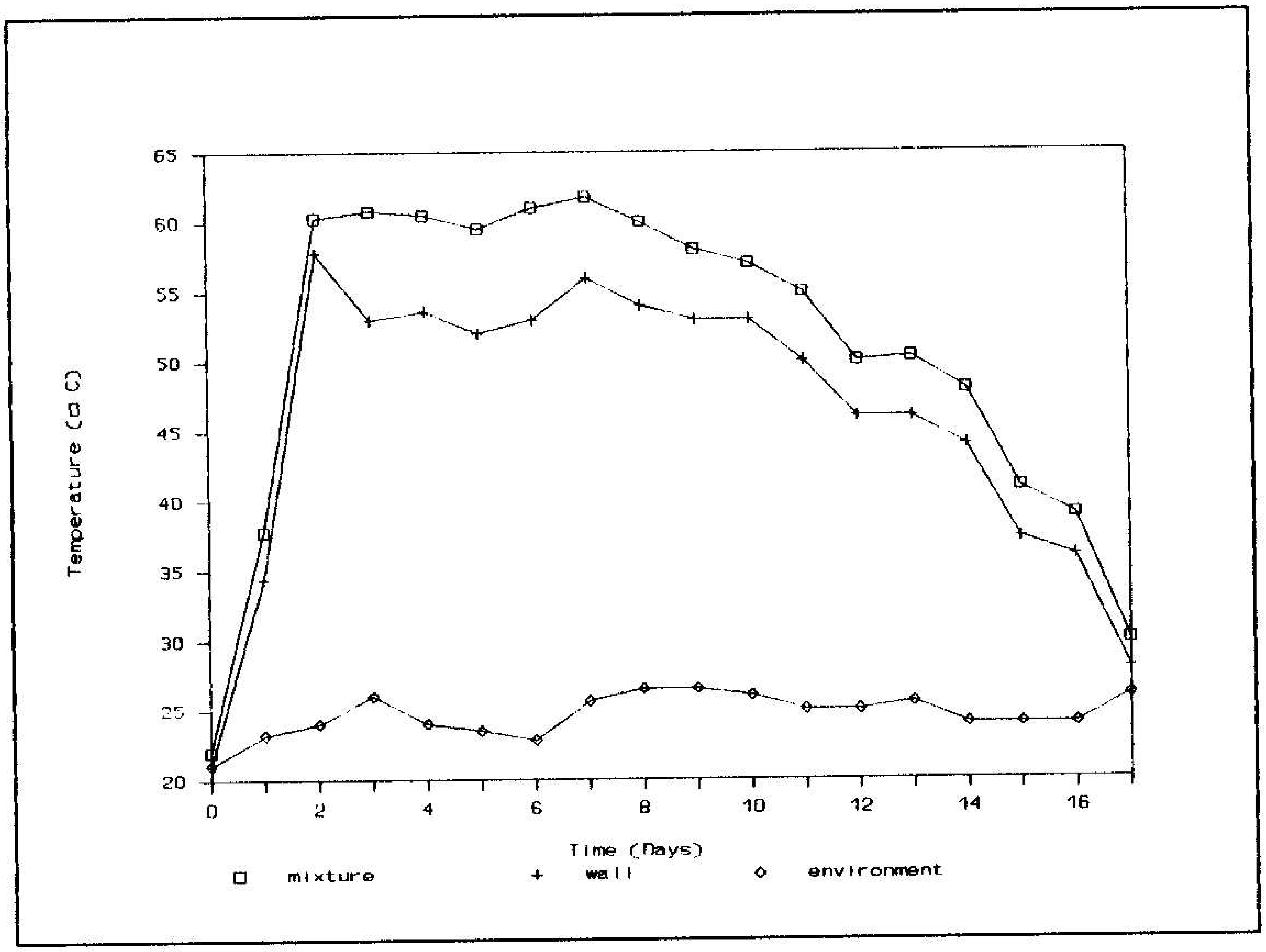


Table IX: CHARACTERISTICS OF BASIC MATERIAL AND PRODUCT. PHASE II. TRIAL II. REACTOR #1.

	Sludge	Fresh Wood	Rec. #1	Initial Mixture	Intermed. Product	Screened Product
Ratio (V/V)	2	1	2			
Moisture v (%)	71.00	15.00	18.00	60.30	13.00	10.00
Volatile Solids ♦ (%)	64.50	95.50	79.00	74.50	67.00	47.00
Apparent Density (Kg/L)	0.98	0.16	0.16	0.50	0.21	0.41
pH	6.80					7.30
Weight ♦ (Kg)	1.09	0.27	0.50	1.86	1.33	0.62
Weight v (Kg)	3.76	0.32	0.61	4.69	1.53	0.70
Volume (L)	3.84	2.00	3.81	9.38	7.51	1.70
Ratio ♦ C/N	10.86	91.46	25.81	16.75	13.94	9.09
Carbon ♦ (%)	35.83	53.05	43.88	41.38	37.22	26.11
Nitrogen ♦ (%)	3.30	0.58	1.70	2.47	2.67	2.87
Nitrogen ♦ (g)	35.97	1.57	8.50	46.04	35.51	17.80
Phosphates ♦ (%)	6.00	0.17	2.52	4.21		5.33
Potassium ♦ (%)	0.07					0.30
Coliform (total) ♣	NA					7.00
Fecal Coliform ♣	NA					<0.20
Cadmium ♦ (mg/Kg)	2.16					1.70
Chromium ♦ (mg/Kg)	117.48					196.70
Lead ♦ (mg/Kg)	44.74					50.70
Nickel ♦ (mg/Kg)	53.03					63.40

♦ Dry base
Λ Moist base
♣ MPN/g.

NA = not analyzed. Report on the total and fecal coliform content of the Barceloneta sludge >24,000 MPN/g (Saliceti, 1983), (Delgado, 1989).

Figure 11: PHASE II. TRIAL II.
Temperature Curve. Reactor #2.

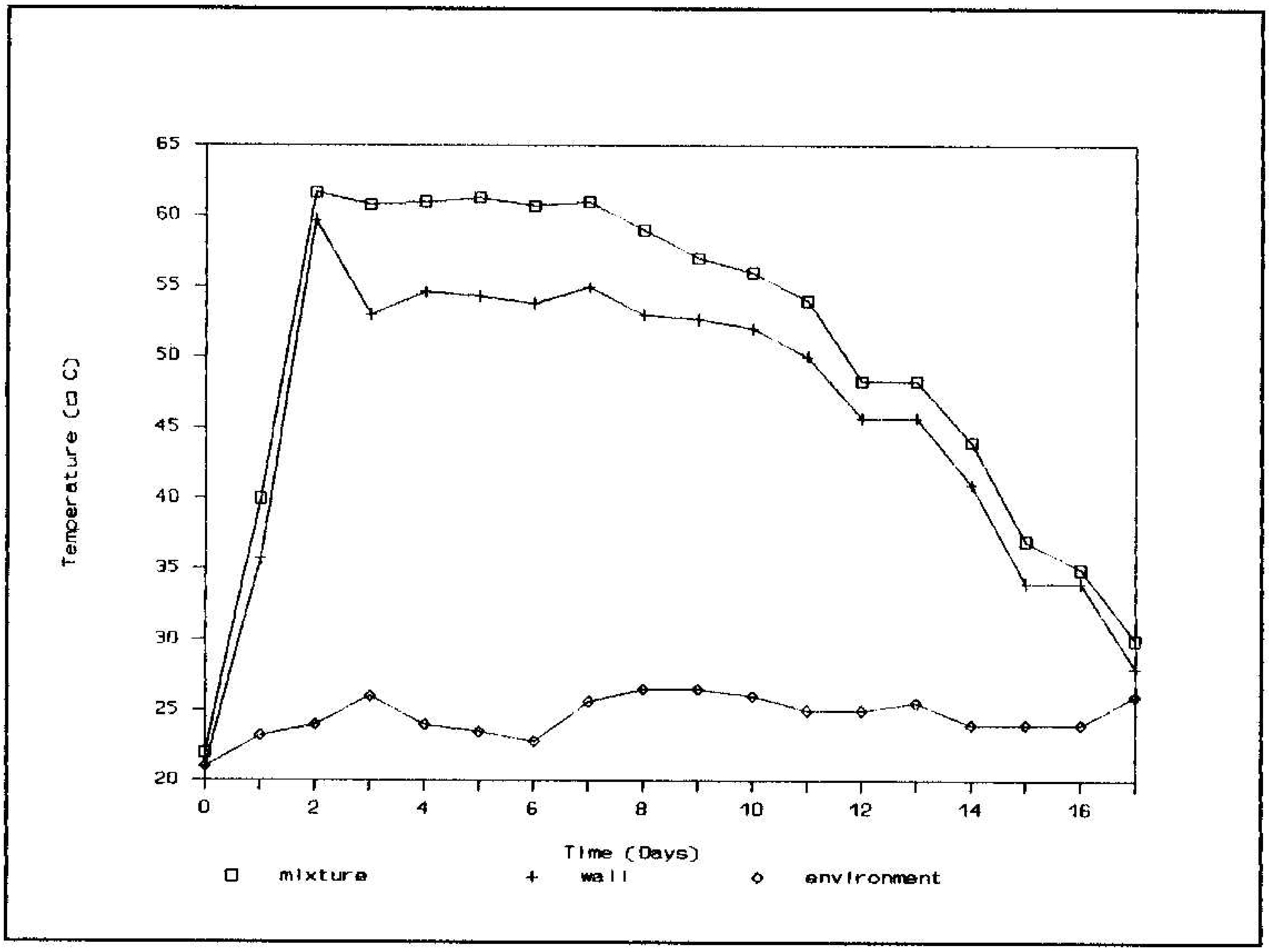


Table X: CHARACTERISTICS OF BASIC MATERIAL AND PRODUCT. PHASE II. TRIAL II. REACTOR #2.

	Sludge	Fresh Wood	Rec. #1	Initial Mixture	Intermed. Product	Screened Product
Ratio (V/V)	2	1	2			
Moisture ∇ (%)	71.00	15.00	20.00	60.50	19.00	14.00
Volatile Solids ♦ (%)	64.50	95.50	80.00	75.00	68.00	47.00
Apparent Density (Kg/L)	0.98	0.16	0.17	0.50	0.21	0.42
pH	6.80					7.30
Weight ♦ (Kg)	1.05	0.26	0.48	1.79	1.34	0.61
Weight ∇ (Kg)	3.62	0.31	0.60	4.53	1.65	0.70
Volume (L)	3.70	1.94	3.65	9.15	7.80	1.64
Ratio ♦ C/N	10.86	91.47	24.69	16.66	14.30	9.33
Carbon ♦ (%)	35.83	53.05	44.44	41.66	37.77	26.11
Nitrogen ♦ (%)	3.30	0.58	1.80	2.50	2.64	2.80
Nitrogen ♦ (g)	34.65	1.51	8.64	44.80	35.37	17.08
Phosphates ♦ (%)	6.00	0.17	2.57	4.23		6.89
Potassium ♦ (%)	0.07					0.32
Coliform (total) ♣	NA					24.00
Fecal Coliform ♣	NA					<0.20
Cadmium ♦ (mg/Kg)	2.16					1.70
Chromium ♦ (mg/Kg)	117.48					177.60
Lead ♦ (mg/Kg)	44.74					54.51
Nickel ♦ (mg/Kg)	53.03					83.70

♦ Dry base
Δ Moist base
♣ MPN/g.

NA = not analyzed. Report on the total and fecal coliform content of the Barceloneta sludge >24,000 MPN/g (Saliceti, 1983), (Delgado, 1989).

Figure 12: PHASE II. TRIAL III.
Temperature Curve. Reactor #1.

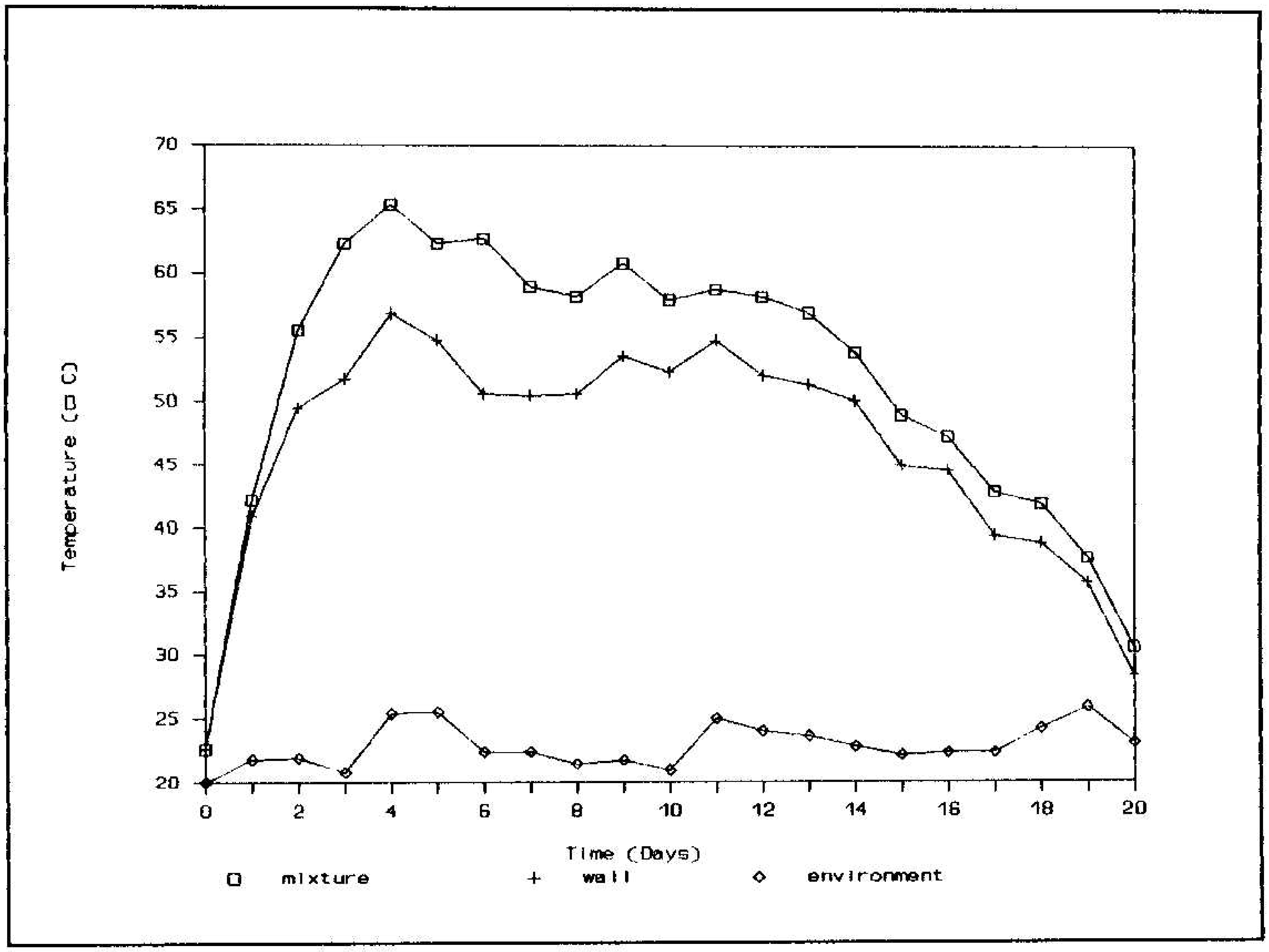


Table XI: CHARACTERISTICS OF BASIC MATERIAL AND PRODUCT. PHASE II. TRIAL III. REACTOR #1.

	Sludge	Fresh Wood	Rec. #1	Initial Mixture	Intermed. Product	Screened Product
Ratio (V/V)	2	1	2			
Moisture ∇ (%)	71.00	13.50	13.00	61.30	17.00	11.00
Volatile Solids ♦ (%)	64.50	97.00	72.50	71.00	62.00	45.00
Apparent Density (Kg/L)	0.95	0.12	0.13	0.46	0.21	0.43
pH	6.80					7.20
Weight ♦ (Kg)	1.08	0.21	0.44	1.73	1.40	0.65
Weight ∇ (Kg)	3.72	0.24	0.51	4.47	1.69	0.70
Volume (L)	3.92	2.00	3.92	9.72	8.05	2.00
Ratio ♦ C/N	10.86	92.89	16.11	14.29	11.87	6.94
Carbon ♦ (%)	35.83	53.88	40.27	39.44	34.44	25.00
Nitrogen ♦ (%)	3.30	0.58	2.50	2.76	2.90	3.60
Nitrogen ♦ (g)	35.64	1.2	11.00	47.84	40.60	23.40
Phosphates ♦ (%)	6.00	0.17	3.50	4.65		8.92
Potassium ♦ (%)	0.07					0.26
Coliform (total) ♣	NA					13.00
Fecal Coliform ♣	NA					0.40
Cadmium ♦ (mg/Kg)	2.16					2.40
Chromium ♦ (mg/Kg)	117.48					170.60
Lead ♦ (mg/Kg)	44.74					49.07
Nickel ♦ (mg/Kg)	53.03					59.80

♦ Dry base
Δ Moist base
♣ MPN/g.

NA = not analyzed. Report on the total and fecal coliform content of the Barceloneta sludge >24,000 MPN/g (Saliceti, 1983), (Delgado, 1989).

FIGURE 13: PHASE II. TRIAL III.
TEMPERATURE CURVE. REACTOR #2.

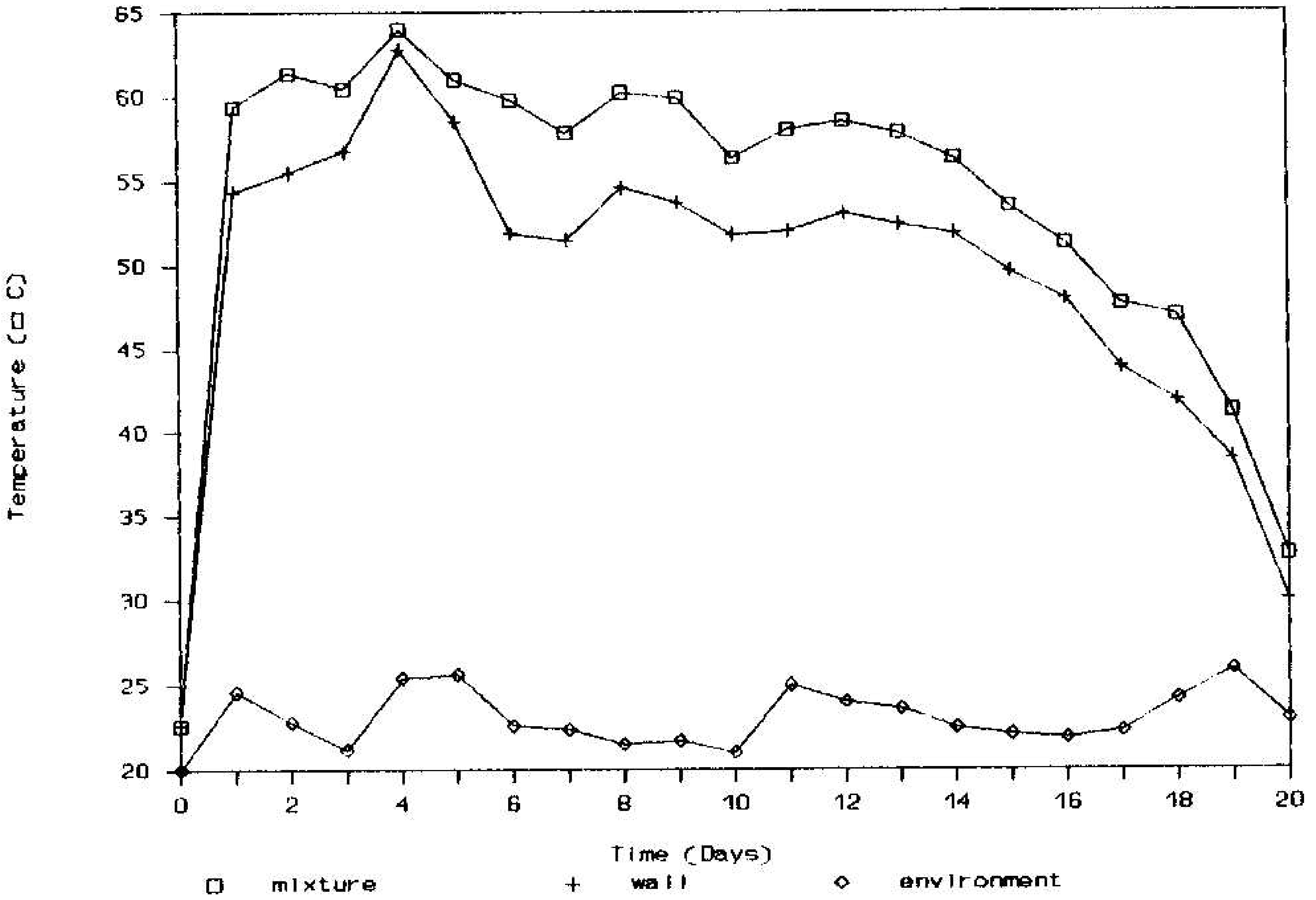


Table XII: CHARACTERISTICS OF BASIC MATERIAL AND PRODUCT. PHASE II. TRIAL III. REACTOR #2.

	Sludge	Fresh Wood	Rec. #1	Initial Mixture	Intermed. Product	Screened Product
Ratio (V/V)	2	1	2			
Moisture ∇ (%)	73.00	13.50	20.00	63.30	15.00	9.00
Volatile Solids ♦ (%)	64.50	97.00	73.00	71.00	62.00	46.00
Apparent Density (Kg/L)	0.95	0.12	0.14	0.49	0.21	0.41
pH	6.80					7.20
Weight ♦ (Kg)	1.18	0.27	0.50	1.95	1.60	0.71
Weight ∇ (Kg)	4.37	0.31	0.63	5.31	1.88	0.78
Volume (L)	4.60	2.50	4.50	10.80	8.90	1.90
Ratio ♦ C/N	10.86	92.90	16.22	14.55	12.00	6.90
Carbon ♦ (%)	35.83	53.88	40.55	39.44	34.44	25.55
Nitrogen ♦ (%)	3.30	0.58	2.50	2.71	2.87	3.70
Nitrogen ♦ (g)	38.94	1.57	12.50	53.01	46.00	26.27
Phosphates ♦ (%)	6.00	0.17	1.70	4.08		10.17
Potassium ♦ (%)	0.07					0.23
Coliform (total) ♣	NA					35.00
Fecal Coliform ♣	NA					0.40
Cadmium ♦ (mg/Kg)	2.16					2.97
Chromium ♦ (mg/Kg)	117.48					145.74
Lead ♦ (mg/Kg)	44.74					41.16
Nickel ♦ (mg/Kg)	53.03					79.06

♦ Dry base
Δ Moist base
♣ MPN/g.

NA = not analyzed. Report on the total and fecal coliform content of the Barceloneta sludge >24,000 MPN/g (Saliceti, 1983), (Delgado, 1989).

Figure 14: PHASE III. TRIAL I.
Temperature Curve. Reactor #1.

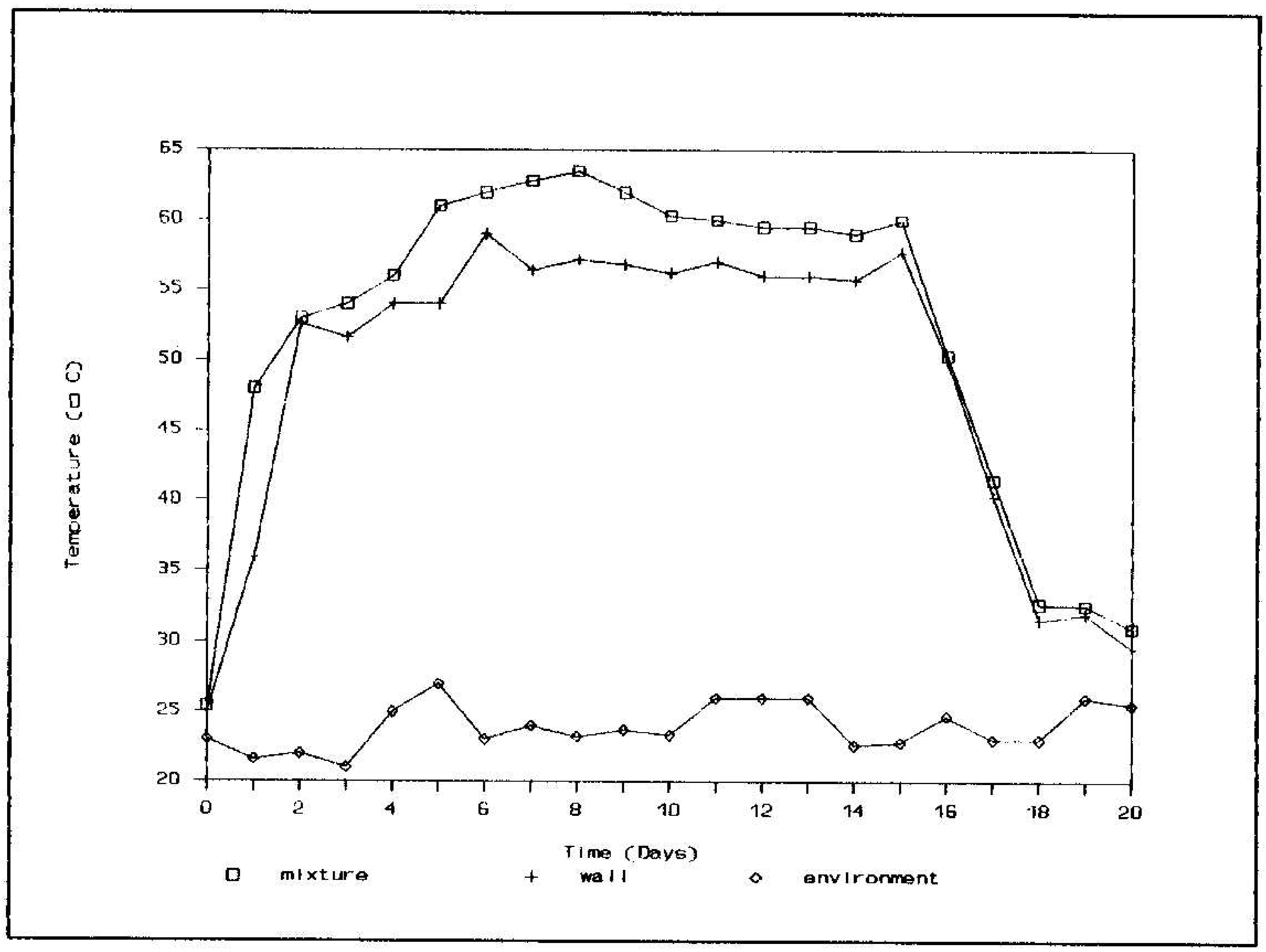


Table XIII: CHARACTERISTICS OF BASIC MATERIAL AND PRODUCT. PHASE III. TRIAL III. REACTOR #1.

	Sludge	Fresh Wood	Recycled Material	Initial Mixture	Intermediate Product
Ratio (V/V)	1	1	2		
Moisture ∇ (%)	72.00	32.40	24.00	59.00	13.00
Volatile Solids ◆ (%)	64.50	96.88	79.00	76.00	63.00
Apparent Density (Kg/L)	0.90	0.19	0.21	0.50	0.23
pH	6.80				7.40
Weight ◆ (Kg)	0.93	0.25	0.60	1.78	1.31
Weight ∇ (Kg)	3.30	0.37	0.79	4.46	1.80
Volume (L)	3.70	1.94	3.76	9.00	7.80
Ratio ◆ C/N	10.86	92.79	25.66	17.74	13.46
Carbon ◆ (%)	35.83	53.82	43.88	42.22	35.00
Nitrogen ◆ (%)	3.30	0.58	1.71	2.38	2.60
Nitrogen ◆ (g)	30.69	1.45	10.26	42.40	34.06
Phosphates ◆ (%)	6.00	0.17	2.51	4.00	5.13
Potassium ◆ (%)	0.07				0.19
Coliform (total) ♣	NA				3.40
Fecal Coliform ♣	NA				0.20
Cadmium ◆ (mg/Kg)	2.16				2.14
Chromium ◆ (mg/Kg)	117.48				108.65
Lead ◆ (mg/Kg)	44.74				30.61
Nickel ◆ (mg/Kg)	53.03				36.47

◆ Dry base
Δ Moist base
♣ MPN/g.

NA = not analyzed. Report on the total and fecal coliform content of the Barceloneta sludge >24,000 MPN/g (Saliceti, 1983), (Delgado, 1989).

Figure 15: PHASE III. TRIAL I.
Temperature Curve. Reactor #2.

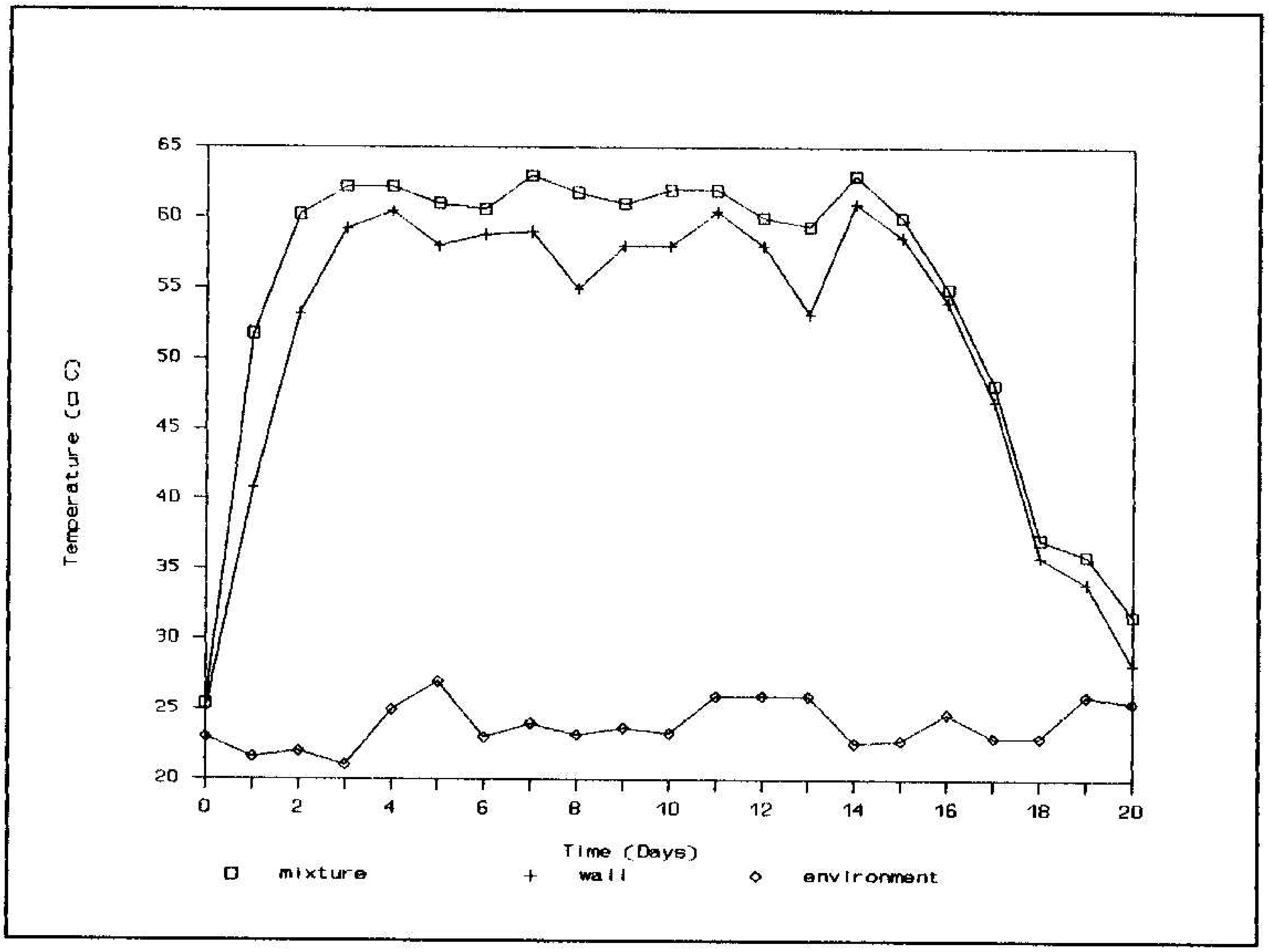


Table XIV: CHARACTERISTICS OF BASIC MATERIAL AND PRODUCT. PHASE III. TRIAL I. REACTOR #2.

	Sludge	Fresh Wood	Recycled Material	Initial Mixture	Intermediate Product
Ratio (V/V)	2	1	2		
Moisture ∇ (%)	72.00	32.40	14.00	59.00	12.00
Volatile Solids ◆ (%)	64.50	96.90	78.00	76.50	65.00
Apparent Density (Kg/L)	0.90	0.19	0.19	0.49	0.21
pH	6.80				7.30
Weight ◆ (Kg)	0.93	0.23	0.60	1.76	1.31
Weight ∇ (Kg)	3.32	0.34	0.70	4.36	1.49
Volume (L)	3.69	1.80	3.68	8.92	7.07
Ratio ◆ C/N	10.86	93.79	25.05	17.71	14.44
Carbon ◆ (%)	35.83	53.82	43.33	42.50	36.11
Nitrogen ◆ (%)	3.30	0.58	1.73	2.40	2.50
Nitrogen ◆ (g)	30.69	1.33	10.38	42.40	32.75
Phosphates ◆ (%)	6.00	0.17	2.57	4.06	5.92
Potassium ◆ (%)	0.07				0.25
Coliform (total) ♣	NA				220.00
Fecal Coliform ♣	NA				0.90
Cadmium ◆ (mg/Kg)	2.16				2.52
Chromium ◆ (mg/Kg)	117.48				133.06
Lead ◆ (mg/Kg)	44.74				38.54
Nickel ◆ (mg/Kg)	53.03				55.97

◆ Dry base
Δ Moist base
♣ MPN/g.

NA = not analyzed. Report on the total and fecal coliform content of the Barceloneta sludge >24,000 MPN/g (Saliceti, 1983), (Delgado, 1989).

5.-DISCUSSION

As stated in section 3, the following variables were used to analyze the performance of the recycled material as a bulking agent:

1) Temperature and reaction time (index of microbial activity), 2) weight loss, and 3) reduction in pathogens. The physical appearance and nutrient content was also evaluated.

Phase I: The material to be processed in reactor #1, trial I, had a 24.66 C/N ratio. Moistened air was used initially for ventilation. During the first two days the temperature was normal, but water had apparently accumulated in the system, reducing oxygenation for the pertinent reactions and for dewatering. The air flow was maintained in this manner for eight days, but upon observing that the temperature began to drop (see Figure 4) because of the excess of moisture, the air entering the system was no longer moistened. Once this was corrected, microbes continued to develop. For five consecutive days the temperature was over 55° C, and the process lasted 15 days. At the end of the curing phase the weight of the dry solid decreased by 28.21%, the total coliform content decreased to 50 MPN/g, and fecal coliform to less than 0.2 MPH/g. In the trial I experiment carried out within reactor #2 the incoming air was not moistened. The initial C/N ratio was 23.82. At the end of the first day of processing the temperature rose over 40° C, and during 4 consecutive days it was kept at more than 55° C (see Figure 5). The process lasted 11 days, which illustrates optimum behavior in terms of microbial activity. The dry solid decreased in weight by 20.63%. The total coliform were reduced to 50 MPN/g, and fecal coliform to 0.4 MPN/g. The weight loss within both reactors and the significant decrease in coliform reflect that a large percentage of material was decomposed.

A problem developed during the trial II experiments carried out in reactors #1 and #2. The electricity was cut off, first for a period of two days, and later for 4 days. However the microbial activity continued despite a heating source (whose main purpose was to avoid loss of heat during the reaction), and a difference in temperature of 35 ° between the material and its surroundings. The ventilation equipment was turned on whenever the electric power was restored even for a few scarce minutes. This attempted to replace the air that had not been injected during the power outage, thus trying to prevent the development of anaerobic conditions. Temperatures over 55° C were maintained in reactor #2 for only three days (see Figures 6 and 7). Notwithstanding these problems, the processing time for both reactors was fifteen days. The initial C/N ratio was 26.05% in reactor #1, and 25.90% in reactor #2. There was a 25.90% weight loss in reactor #1, and 21.79% in reactor #2. The decrease in total coliform content was 3.4 MPN/g and 2.3 in reactor #2. Fecal coliform content in both reactors was decreased to less than 0.2 MPN/g.

Phase II: Wood that was recycled (recovered) from two to three times was used in this phase. The initial conditions were the same as that of phase I except that the C/N content was less each time because recycled material had less organic carbon than fresh wood. The operations were normal.

The experiments carried out in reactors #1 and #2 of trial I were satisfactory (see Figures 8 and 9). The C/N ratio of the initial mixture was 22.5 in reactor #1 and 22.64 in reactor #2. After the first day the temperature was over 40° C. Temperatures over 55 ° C were maintained for a period of seven days in reactor #1, and eight days in reactor #2. In terms of weight loss, the dry solids decreased 13% in each reactor as a result of the organic material decomposing. The decrease in total coliform content was to 17 MPN/g in reactor #1, and 5 MPN/g in reactor #2. The fecal coliform content was reduced to 0.2 MPN/g in reactor #1 and less than 0.2 in reactor #2.

The trial II experiments in reactors #1 and #2 started with a 16.75 C/N ratio in the former, and 16.66 in the latter. After one day the temperature rose over 40° C in both reactors (see Figures 10 and

11). The temperatures remained over 55° C in reactor #1 for more than nine days, and 10 days in reactor #2. The process took fifteen days in reactor #1 and sixteen days in reactor #2. In reactor 1 the dry solid weight loss was 28.49%, and 25.14% in reactor #2. Total coliform were reduced to 7 MPN/g in reactor #1 and to 24 MPN/g in reactor #2. Fecal coliform decreased to less than 0.2 MPN/g in both reactors.

After the first day of trial III, the temperatures also rose to more than 40° C (see Figures 12 and 13). The C/N ratio of the initial mixture was 14.29 and 14.55 for reactors #1 and #2, respectively. Temperatures over 55° C were maintained for eleven days in reactor #1, and for 13 days in reactor #2. The process lasted 18 days in both reactors. In reactor #1 there was a 19.07% decrease in dry solid weight, and 17.95% for reactor #2. Total coliform were reduced to 13 MPN/g in reactor #1 and to 35 MPN/g in reactor #2. Fecal coliform decreased to less than 0.4 MPN/g in both reactors.

Phase III: Recycled material was obtained from the intermediate product. The initial conditions and the operations aspects were carried out in the same way as the other experiments. The C/N ratio of the initial mixture was 17.7 in both reactors.
After the first day the temperatures also rose to more than 40° C. Temperatures over 55° C were maintained for eleven days in reactor #1, and for 13 days in reactor #2 (see Figures 14 and 15). Processing took 16 days in reactor # 1, and 18 days in reactor #2. In reactor #1 dry solid weight loss was 26.40%, and 25.56% in reactor #2. Total coliform were reduced to 3.4 MPN/g in reactor #1 and to 220 MPN/g in reactor #2. Fecal coliform decreased to 0.2 MPN/g in reactor #1, and to 0.9 MPN/g in reactor #2.

Table XV shows the most important results of this research. The results of experiments using recycled wood one, two, or three times indicate favorable development of the thermophilic process (temperatures over 45°C). The average processing time for each trial was 12.5, 15.25, and 18 days, respectively. The time difference is due to a decrease in the C/N ratio of each initial mixture. In each case, temperatures over 55°C were maintained for more than three consecutive days. The process is highly dependent on the moisture content of the mixture, the C/N ratio, and temperature control. It proved beneficial to control the temperature through air flow and a digital thermometer that would maintain the temperature over 60° C. The processing time could thus be reduced even though the initial mixture had a decreased C/N content, additionally this maintained healthy environment for the development of thermophilic microorganisms. Aeration was important in promoting an aerobic condition and to remove water and heat generated. The size of the woodchips was a favorable factor in creating interstititial volume for optimum air flow.

As can be seen in Figures 12-15, the behavior of the process as measured by the temperature curve was similar in trial III (of Phase II), and trial I (of Phase III). Similarly in Table XV one can observe that the processing times was approximately 18 days in both cases, which signifies that the microbial activity was similar, although the average C/N ratio was 14.4 in trial III of Phase II, and 17.7 in trial I of Phase III. The other variables, such as moisture, oxygenation, and operational aspects were similar.

Table XV shows that in Phase III when recovered wood was recycled instead of the intermediate product (unscreened), the processing time is reduced. Thus when an intermediate product was recycled the process took 5 days or more. Additionally, the screened product has a better appearance. The additional cost of investing in a screen will be quickly recuperated.

The nitrogen, phosphate, and potassium analyses yielded data showing that they increased in content whenever the wood was recycled. Consequently the product of the process using fresh wood has an average content of 2.45% nitrogen, 3.85% phosphate, and 0.21% potassium. The product corresponding to recycled material #III has a content of 3.65% nitrogen, 9.55% phosphate (equivalent to

Table XV. SUMMARY OF THE MOST IMPORTANT RESULTS

	INITIAL		TIME (DAYS)		COLIFORM (MPN/G)	
BULKING AGENT	C/N RATIO	WEIGHT LOSS ♦	TEMP. >55°	PROCESS	TOTAL	FECAL
			PHASE II			
Recycled I:	22.50	12.96	7.00	12.00	17.00	2.00
	22.64	13.04	8.00	13.00	5.00	<0.20
Recycled II:	16.75	28.49	9.00	15.00	7.00	<0.20
	16.66	25.14	10.00	15.50	24.00	<0.20
Recycled III:	14.29	19.07	11.00	18.00	13.00	0.40
	14.55	17.95	13.00	18.00	35.00	0.40
			PHASE III			
Intermediate Product:	17.74	26.40	11.00	18.00	3.40	0.20
	17.71	25.56	13.00	18.00	220.00	0.90
Recycled I:	22.50	12.96	7.00	12.00	17.00	2.00
	22.64	13.04	8.00	13.00	5.00	<0.20

♦ Percentage on a dry basis

3% phosphorus) and 025% potassium. The nutrient content of composted sludge is not enough for the product to be considered a fertilizer (see Table XVI), thus it is only considered a soil conditioner.

The analyses showed that the use of recycled material as bulking agent does not considerably increase the heavy metal content. The heavy metal content of the products is within the acceptable range to be used in agriculture without any restrictions; this is shown in table XVII.

As shown in Figures 16 and 17, the volatile solid content of the recycled bulking agent decreased to 30%, in both reactors, at the end of phase II. Initially the wood contained 97% volatile solids, and as in recycle material # IV, this decreased to 68%.

Table XVI: COMPARISON OF NUTRIENT LEVEL BETWEEN COMMERCIAL FERTILIZER AND SLUDGE COMPOST

	NUTRIENTS (%)		
	NITROGEN	PHOSPHORUS	POTASSIUM
Agricultural fertilizer	5.00	10.00	10.00
This research ▶	3.65	3.00	0.25

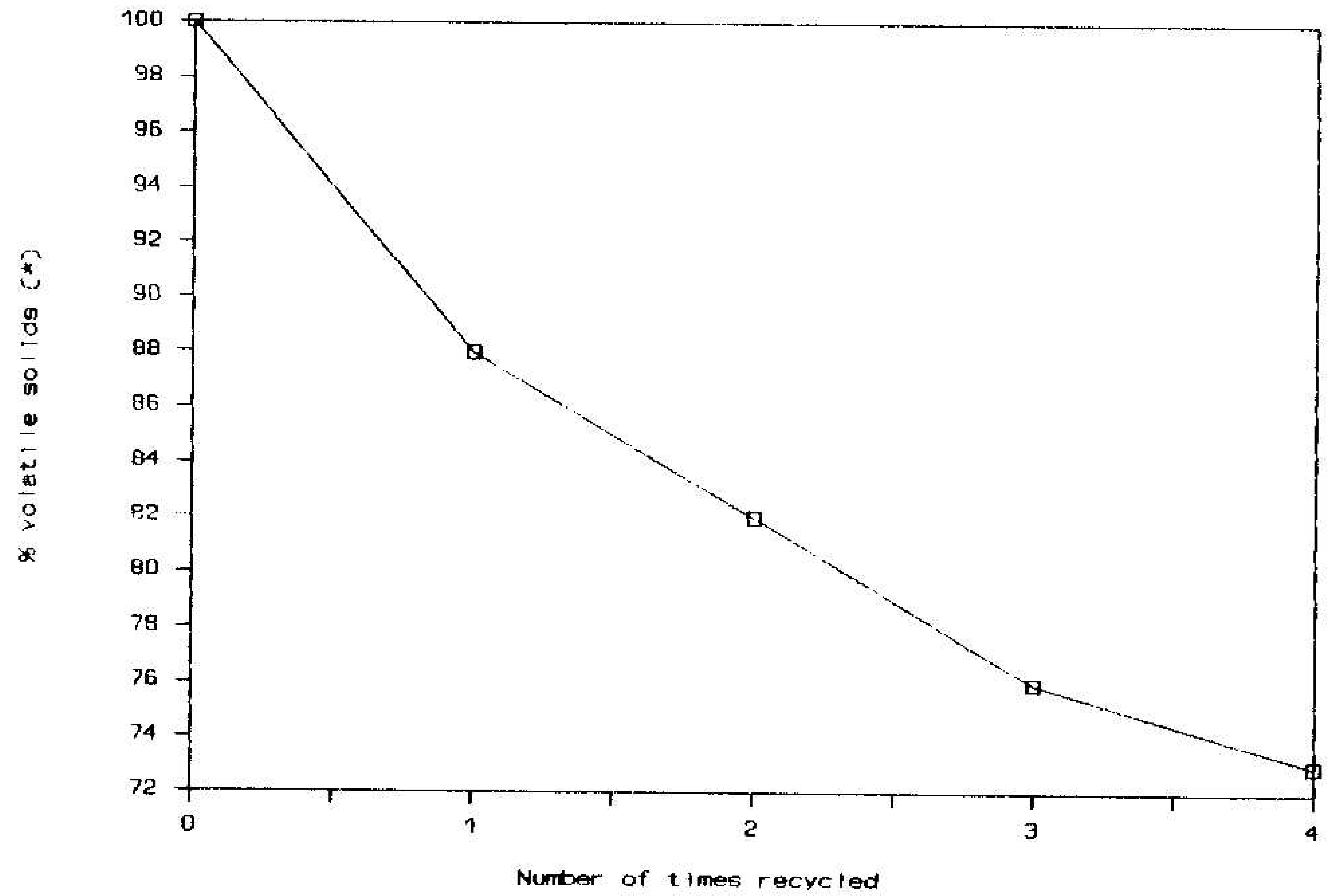
◘ EPA 625/10-84-003

▶ With recycled material #III

Table XVII: HEAVY METAL CONCENTRATION IN SLUDGE COMPOST (MARKETING AND DISTRIBUTION)

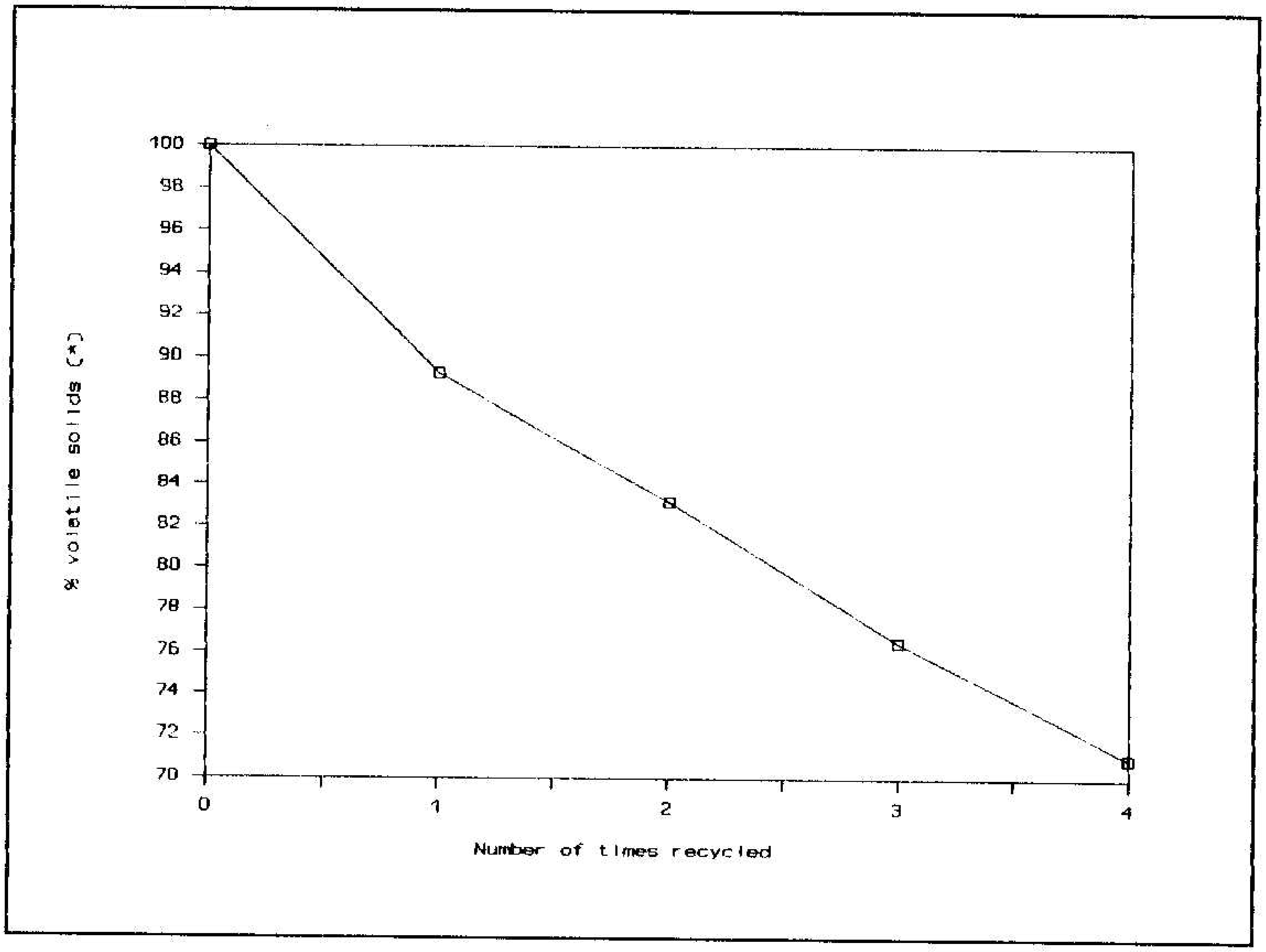
	CADMIUM (mg/Kg)	LEAD (mg/Kg)	NICKEL (mg/Kg)
Allowable range ♠	2-40	300-4800	100-1250
This research	1.35-2.68	37.9-57.2	46.2-82.7

♠ Delagdo, 1989.



* Fresh Woodchips

Figure 17: WOOD DECOMPOSITION.
PHASE II. REACTOR #2.



* Fresh Woodchips

6.- CONCLUSIONS AND RECOMMENDATIONS

6.1.-CONCLUSIONS

The experimental results indicate that wood recovered and recycled repeatedly is a good bulking agent. This technique can dramatically decrease the amount of fresh wood required for a bulking agent, reducing composting cost of aerobic decomposition of wastewater sludge.

Wood recovered and recycled up to three times was used to observe the extent of decrease in volatile solids; it could be recycled up to five times and the thermophilic process might last 25 days.

Evaluation of the intermediate product versus recovered wood as bulking material, showed that the former was less beneficial in terms of processing time because it took five days longer than utilizing the recovered wood.

The use of recycled material as a bulking agent can decrease contamination from the fungus Aspergillus fumigatus, which causes bronchial-pulmonary allergies known as aspergillitis.

6.2.- RECOMMENDATIONS

On the basis of this research the following are recommended: 1)Install a thermocouple at the base of the reactor to verify compliance with the minimum amount of sterilization required in this area; 2) Modify the reactor design to facilitate sample removal during the process; 3) Add carbon substances such as cereal husk, sawdust, or wood shavings, etc. to balance the organic carbon content in the initial mixture when recycled material is used in order to increase the C/N ratio to levels close to 25; and 4) Use larger pieces of wood (8-9 cm) in order to increase the percentage of intersititial volume for better and more effective ventilation.

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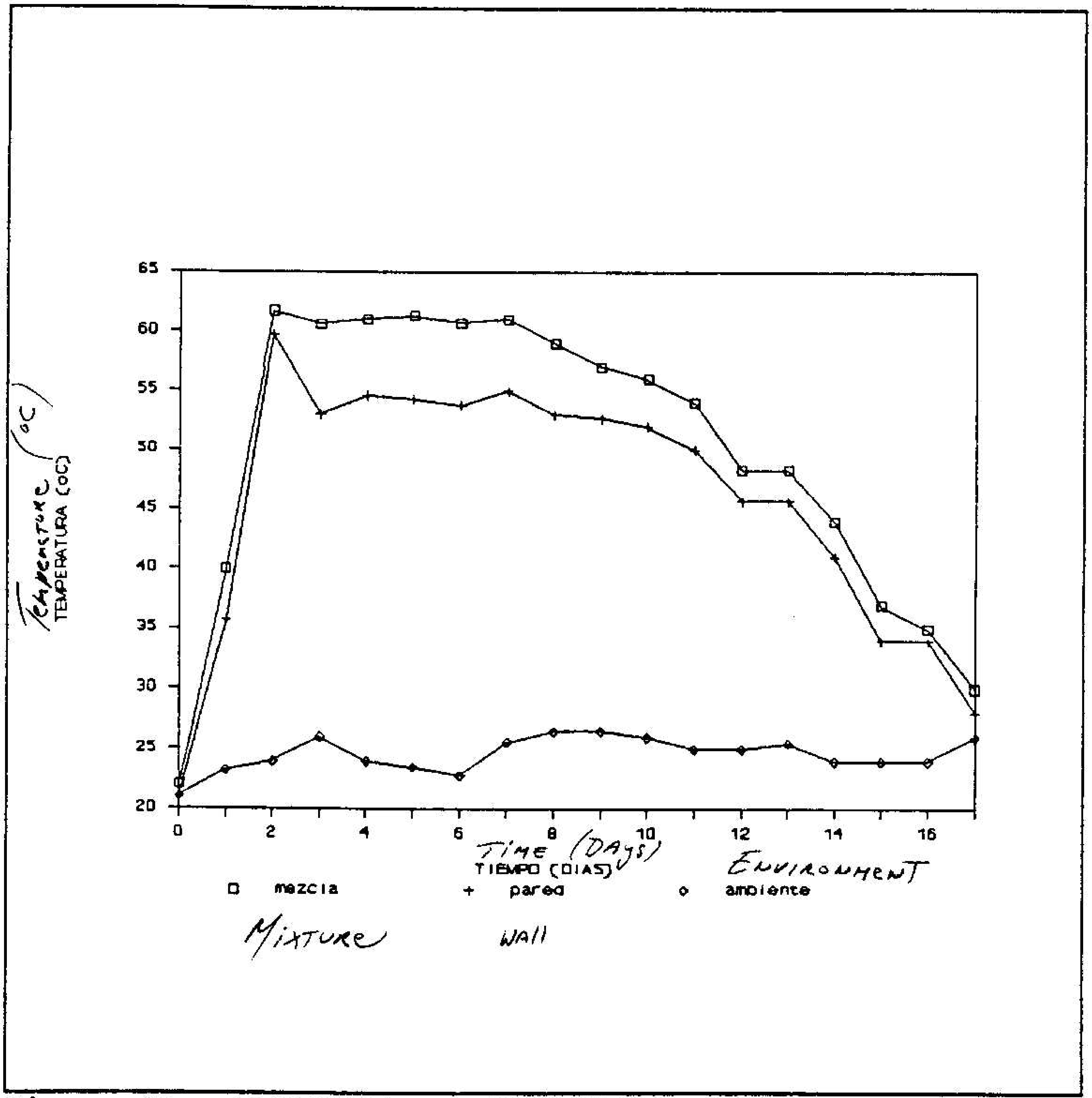


Figura 11: ETAPA II. CORRIDA II.
Figure 11 PHASE II. TRIAL II.
Perfil de temperatura. Reactor 2.
Temperature Curve. Reactor 2

APPENDICES

APPENDIX A

Chemical analyses of the raw materials and products were carried out by modifying standard analysis from the water quality control manual and soil methods, as described in the following sections.

A.- GENERAL ANALYSIS OF RAW MATERIAL AND PRODUCT.

The results were calculated on the basis of material dried at 110° C for twenty-four hours.

1.- Determination of volatile material and settled material of solid and semisolid samples (Standard Methods, 1985). In the calcination of a dry sample for heavy metals the temperature was 450° C (with air circulation) for five hours.

2.- For nitrogen analyses using the Kjeldahl method in accordance with EPA Manual-600 4-79-020, a .2 g moist sample was used instead of 5g.

3.- For total phosphorus the samples were converted in accordance with EPA Manual-600 4-79-020. Starting with 0.50 g of moist sample to obtain 50 mL, rather than 50 mL from an aliquot sample.

4.- For the potassium and heavy metal analyses, 0.5 g of dry sample was calcinated. To samples already calcinated 3 mL of concentrated HNO_3 were added; heated until almost totally evaporated, and cooled to add 10 ml of HCl (1:1), and reheated for 30 minutes. At the end of this time it was cooled for filtering, and 10% HCl was added until reaching a total volume of 100 ml. (EPA-600 4-79-020). Heavy metal readings were carried out in Perkin Elmer atomic absorption equipment.

B. DETERMINATION OF COLIFORMS

1.- Total and fecal coliform were determined in accordance with the manual "Standard Methods for the Examination of Water and Wastewater". Both methods were modified using 1 g. of solid sample instead of 10 ml of liquid sample.

2.- The manual "Standard Methods for the Examination of Water and Wastewater" was also used for estimating the density of the microorganism population.

APPENDIX B

DETERMINING THE PROPORTION OF SLUDGE AND BULKING AGENT FOR THE INITIAL MIXTURE.

The proportion of sludge and bulking agent in the initial mixture was determined on the basis of having a balance of moisture in the initial mixture. The optimum moisture was determined to be 60% for the initial mixture. Expressed as:

$$Mm = S + B \qquad \text{(B.1)}$$

While

$$B = 1/3\ W + 2/3\ R \qquad \text{(B.2)}$$

Where:

Mm = Amount of initial mixture at 60% moisture

S = Amount of wastewater sludge

B = Amount of bulking material

W = Amount of fresh woodchips

R = Amount of recycled material (recovered wood)

In this manner the volumetric ratio of sludge to bulking agent was 1:3 or 2:3, depending on the moisture content of the bulking agent.

DETERMINING OXYGEN CONSUMPTION

The following equations were used to determine oxygen consumption:

$$C_{10}H_{19}O_3N + 12.5\ O_2 \rightarrow 10\ CO_2 + 8\ H_2O + NH_3 \qquad \text{(B.3)}$$

$$C_6H_{11}O_3 + 7.25\ O_2 \rightarrow 6\ CO_2 + 8\ H_2O \qquad \text{(B.4)}$$

The first equation (B.3) corresponds to the oxidation of the sludge. The oxygen required for its decomposition was estimated by unit weight of dry sludge:

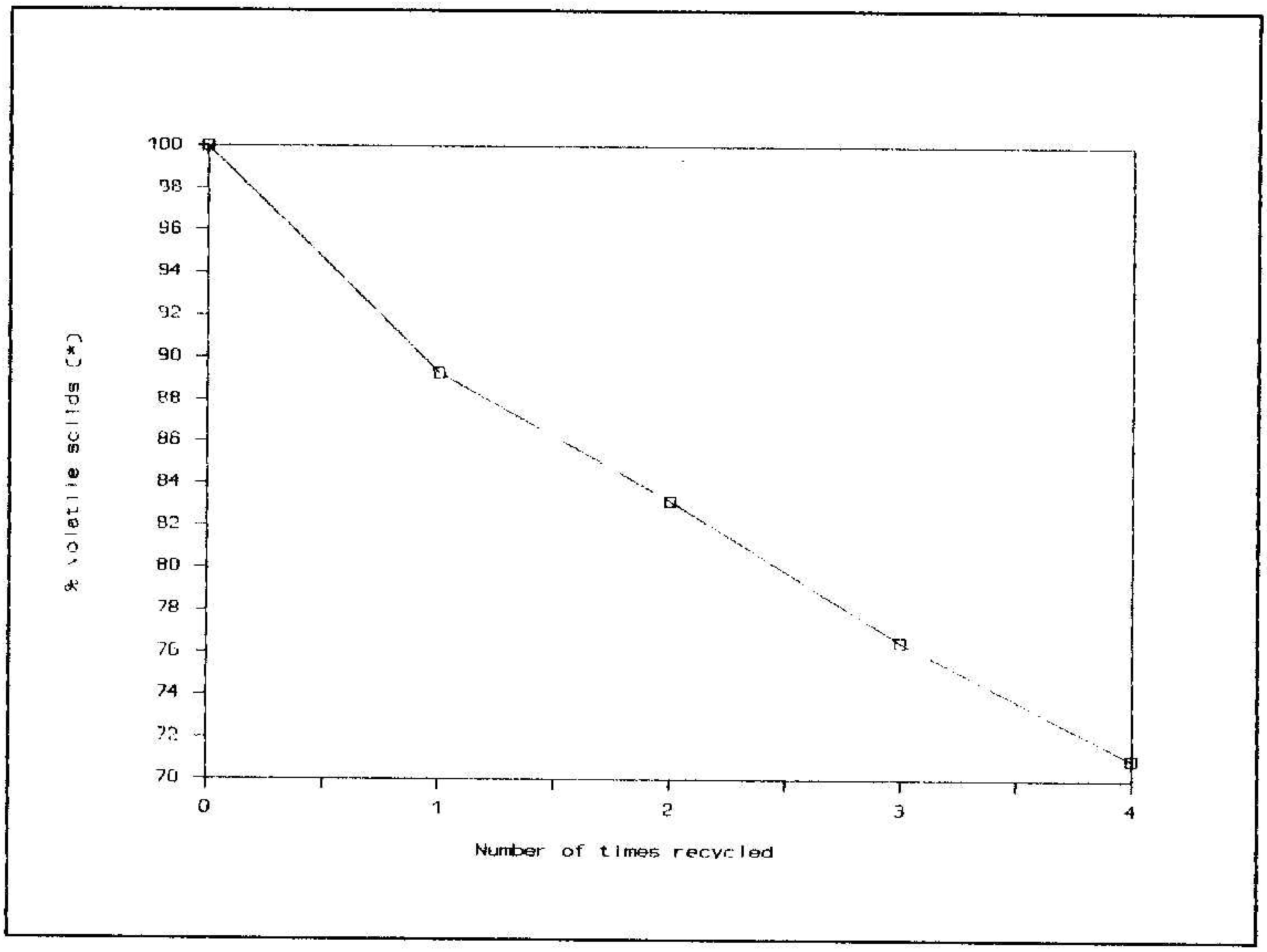
$$O_2 = (32)\ (12.5)/(12)\ (10) + (1)\ (19) + (16)\ (3) + (14)\ (1)$$

$$O_2 = 1.99 \text{ g.}$$

The equation (B.4) corresponds to the reaction of the wood. The oxygen requirement per unit weight of dry wood for composting was:

$$O_2 = (32)\ (7.25)/\ (12)\ (6) + (1)\ (11) + (16)\ (3) = 1.77 \text{ g.}$$

A 0.4 degradability coefficient was used for the sludge (Haug, 1980), (Singley et al., 1982); for the wood it was 0.10 (Haug, 1980), (Singley et al., 1982). Degradation of the material required 685 g. of dry oxygen. Air from the immediate environment was used (with 81.1% relative humidity) at 1 atm pressure. The basic requirement was from 82 mL/min., however more air flow was added to a ratio of 100 mL/min.



* Fresh Woodchips

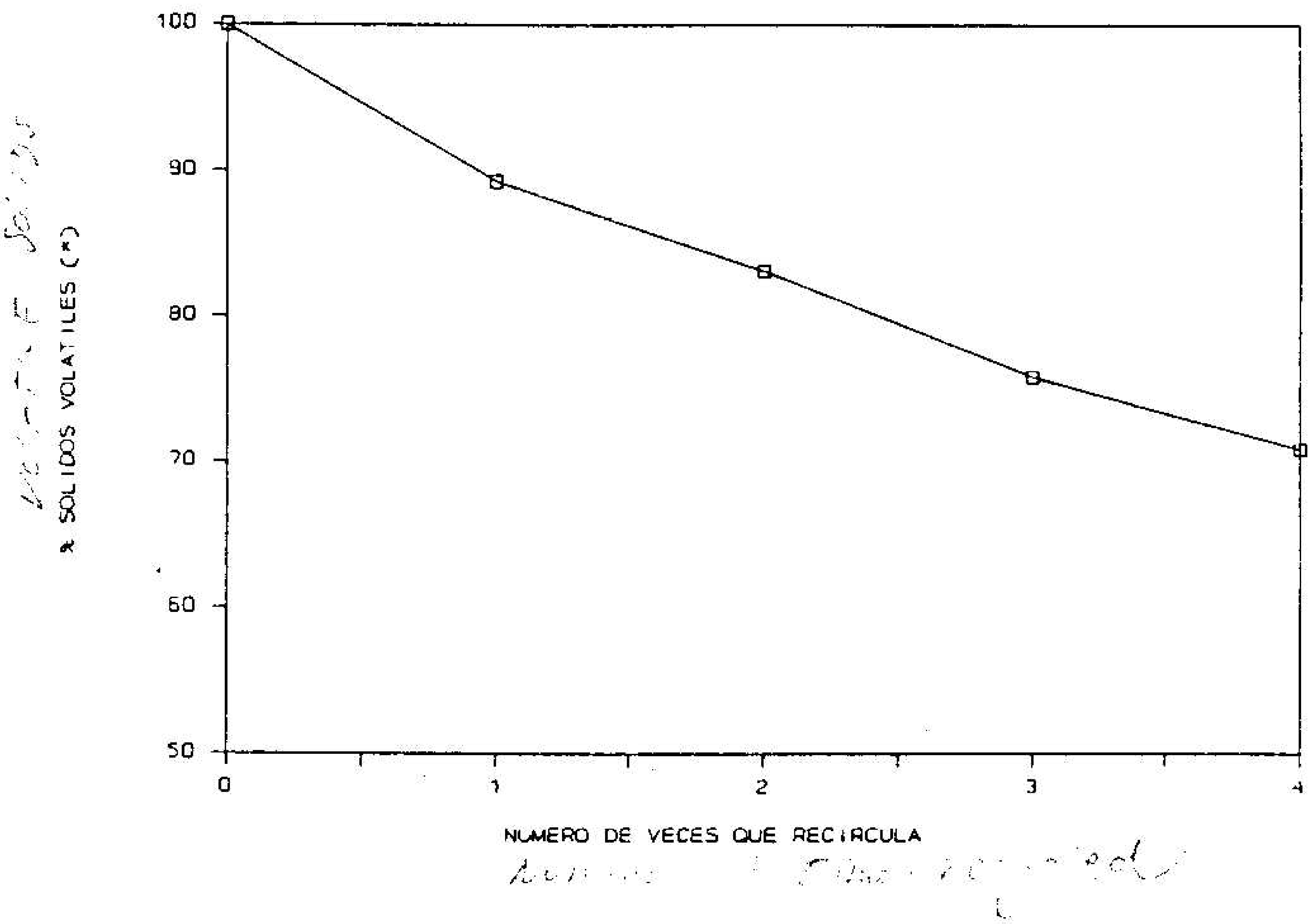


Figura 17: DEGRADACION DE LA MADERA.

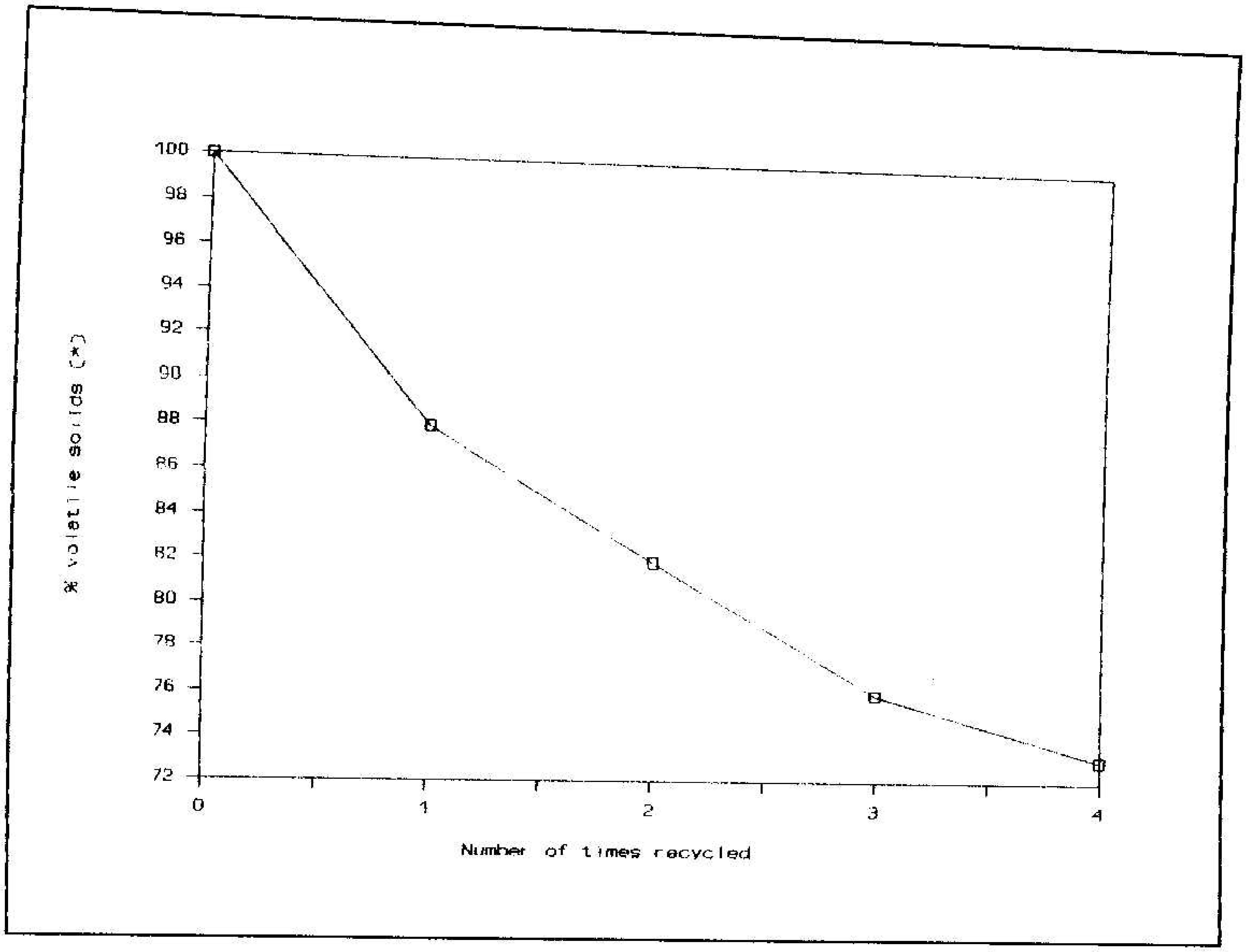
[illegible]

ETAPA II. REACTOR 2.

[illegible]

* Relativo a madera fresca.

Relative to fresh [illegible]



* Fresh Woodchips

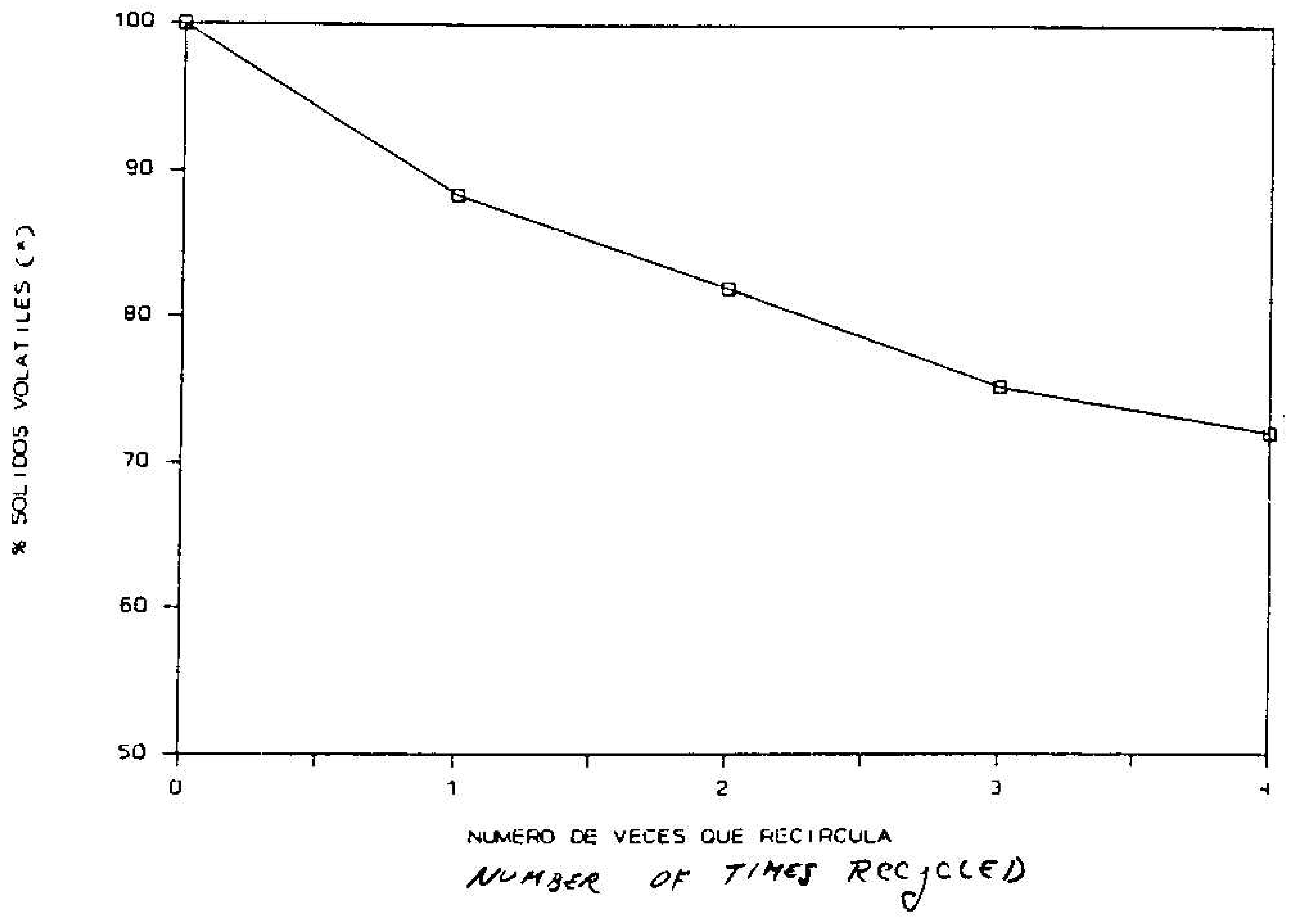


Figura 16: DEGRADACION DE LA MADERA.
Figure 16. DECOMPOSITION OF THE WOOD.
ETAPA II. REACTOR 1.
PHASE II. REACTOR 1.
* Relativo a madera fresca.
FRESH WOOD

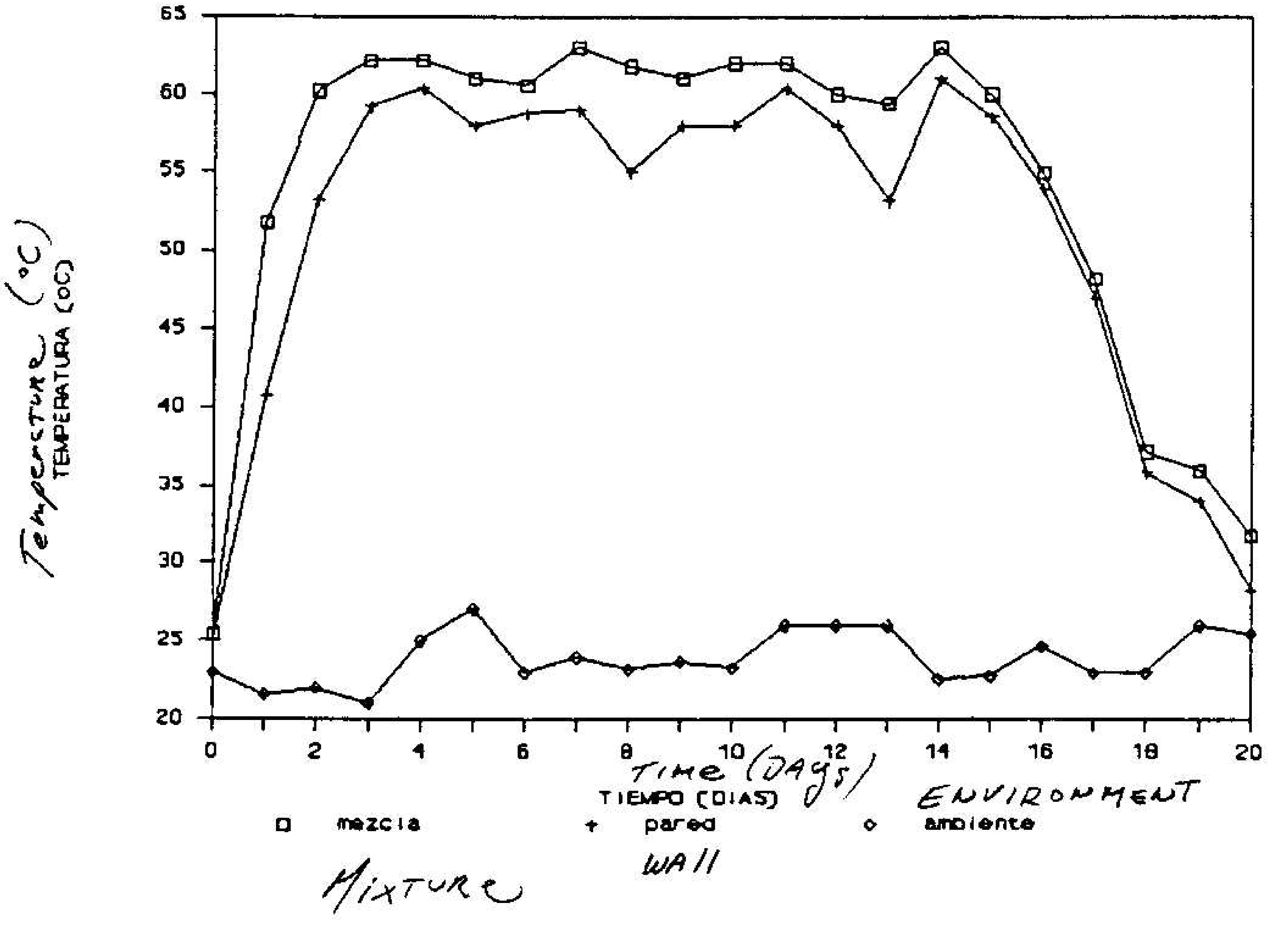


Figura 15: ETAPA III. CORRIDA I.
Figure 15. Phase III. Trial I.
Perfil de temperatura. Reactor 2.
Temperature Curve. Reactor 2.

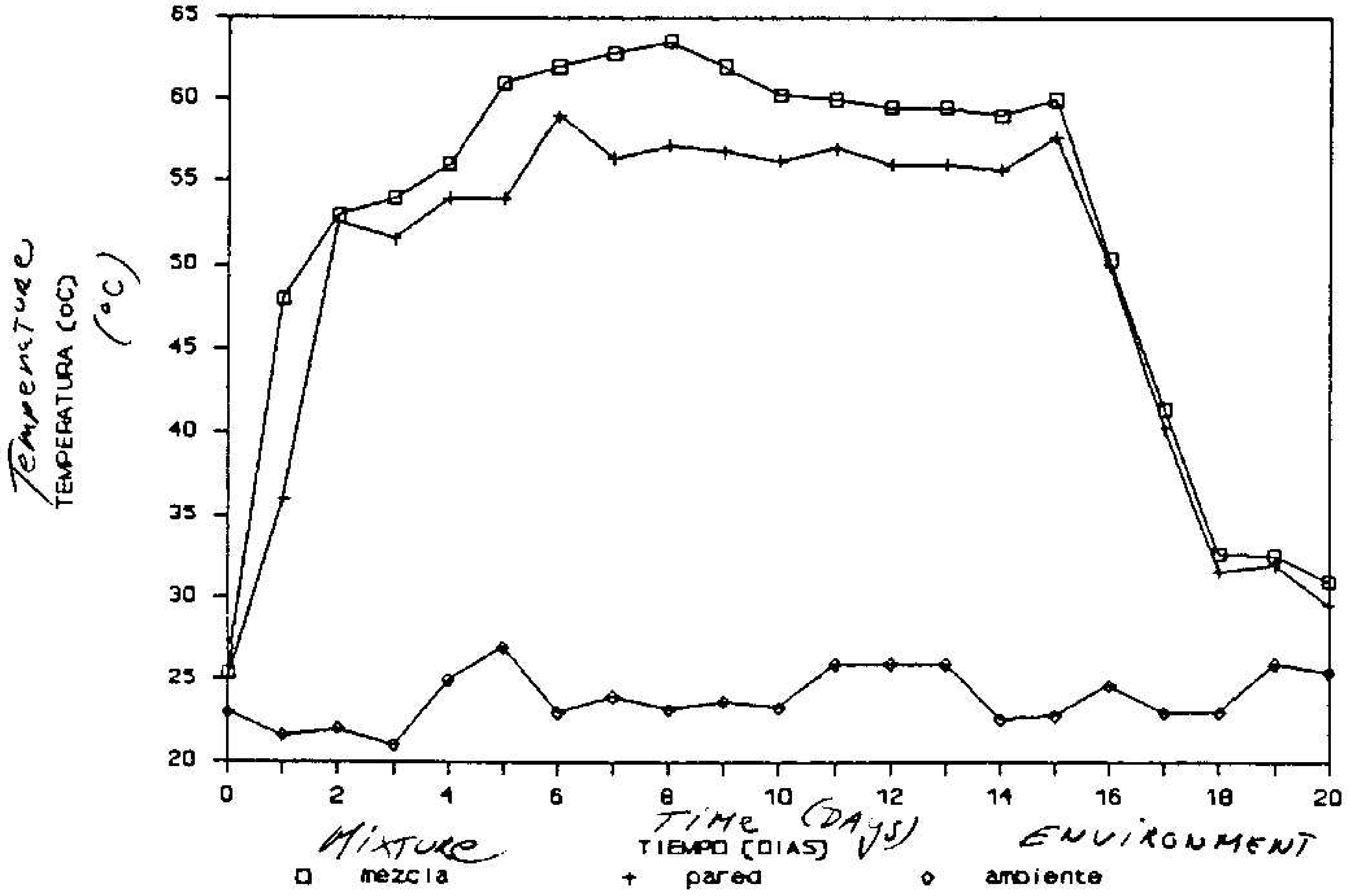


Figura 14: ETAPA III. CORRIDA I.
Figure 14. Phase III · Trial I.
Perfil de temperatura. Reactor 1.
Temperature Curve. Reactor 1.

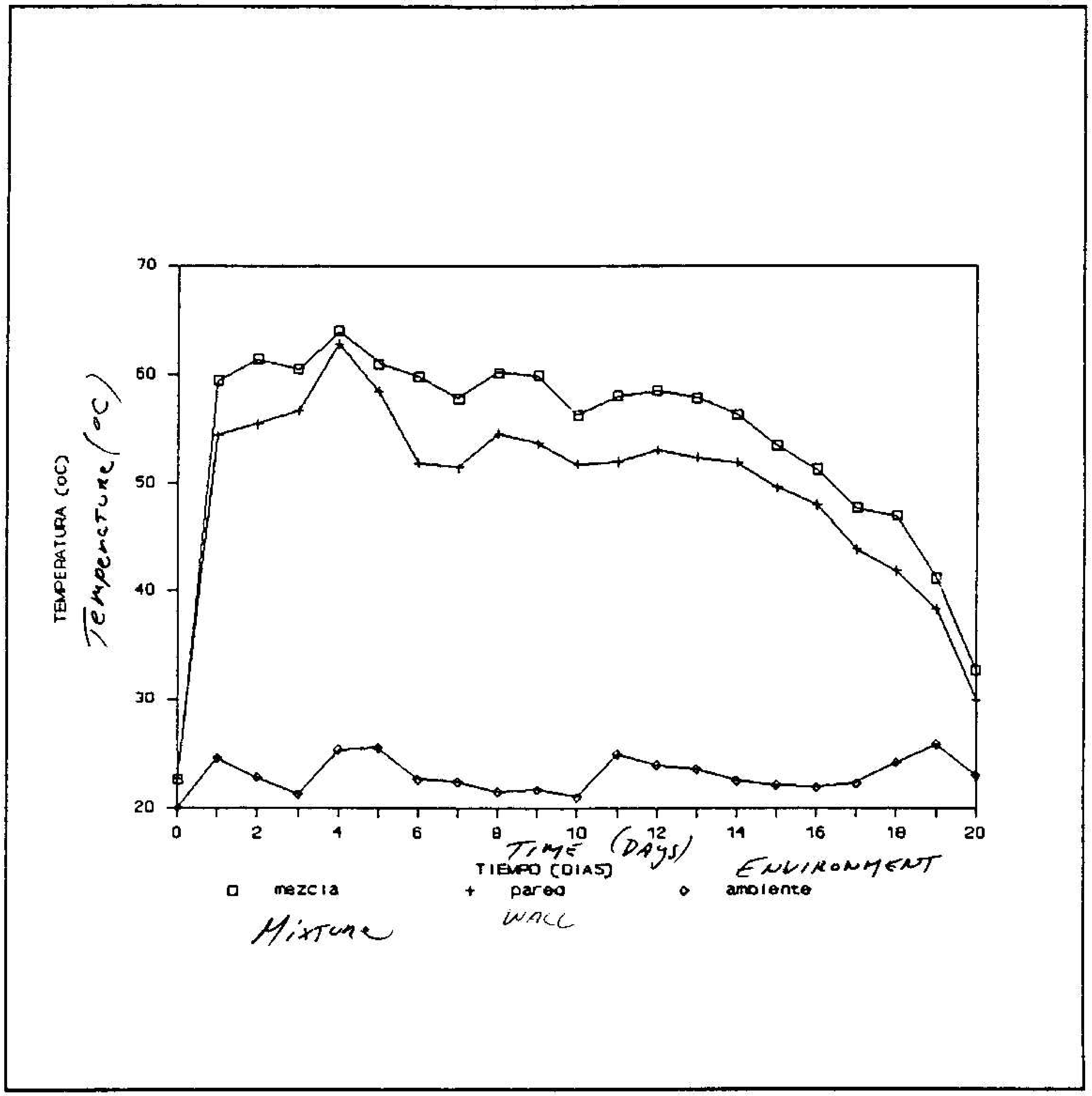


Figura 13: ETAPA II. CORRIDA III.

Figure 13: PHASE II. TRIAL III. Reactor 2.

Perfil de temperatura. Reactor 2.

Temperature Curve.

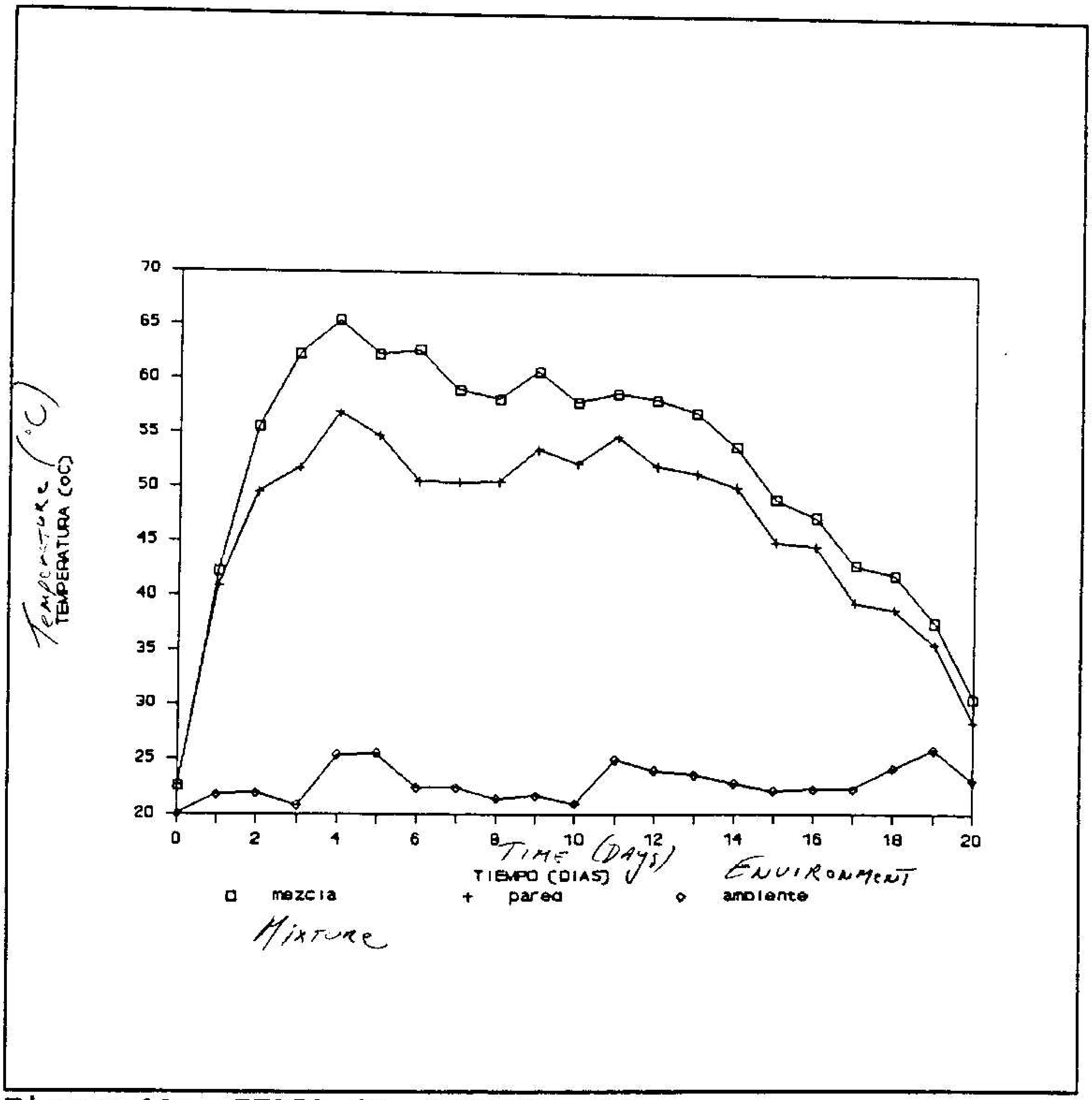


Figura 12: ETAPA II. CORRIDA III.
Figure 12: PHASE II. TRIAL III.
Perfil de temperatura. Reactor 1.
Temperature Curve. Reactor 1.

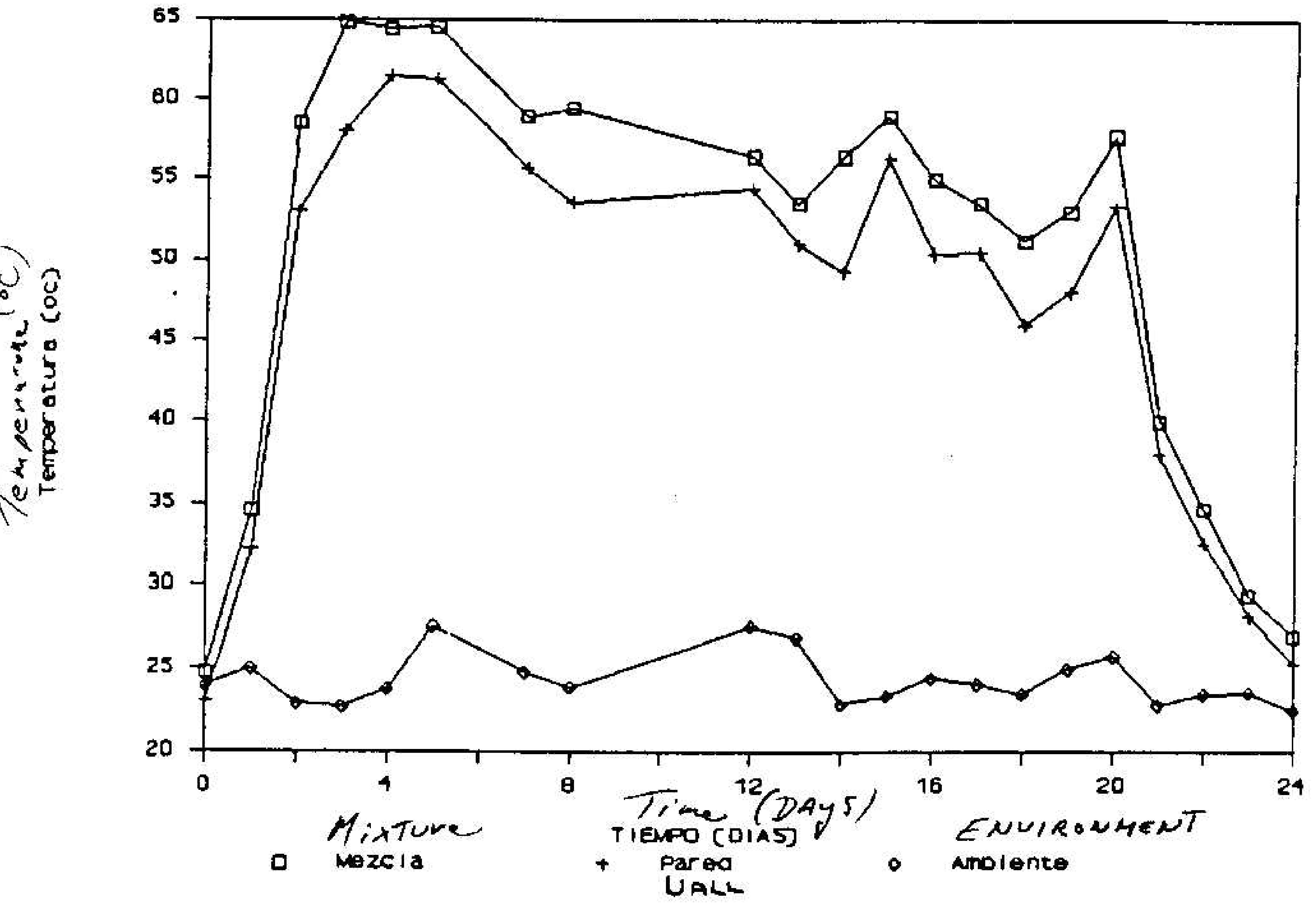
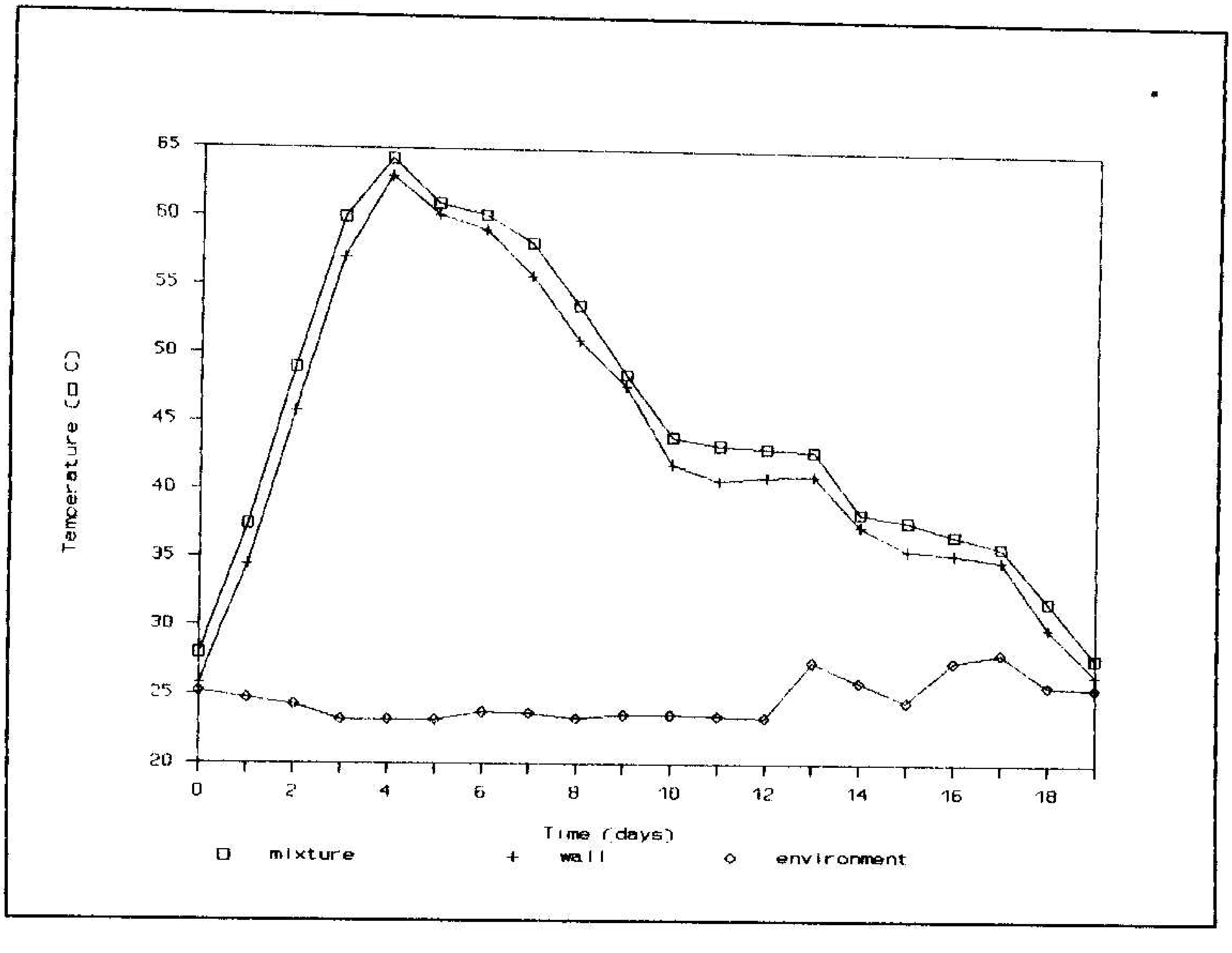


Figura 6: ETAPA I. CORRIDA II.
Figure 6 PHASE I. TRIAL II

Perfil de temperatura. Reactor 1.

Temperature Curve. Reactor 1.


65
60
55
50
45
40
35
30
25
20
Temperature (□ C)
0
2
4
6
8
10
12
14
16
18
Time (days)
□ mixture
+ wall
◇ environment

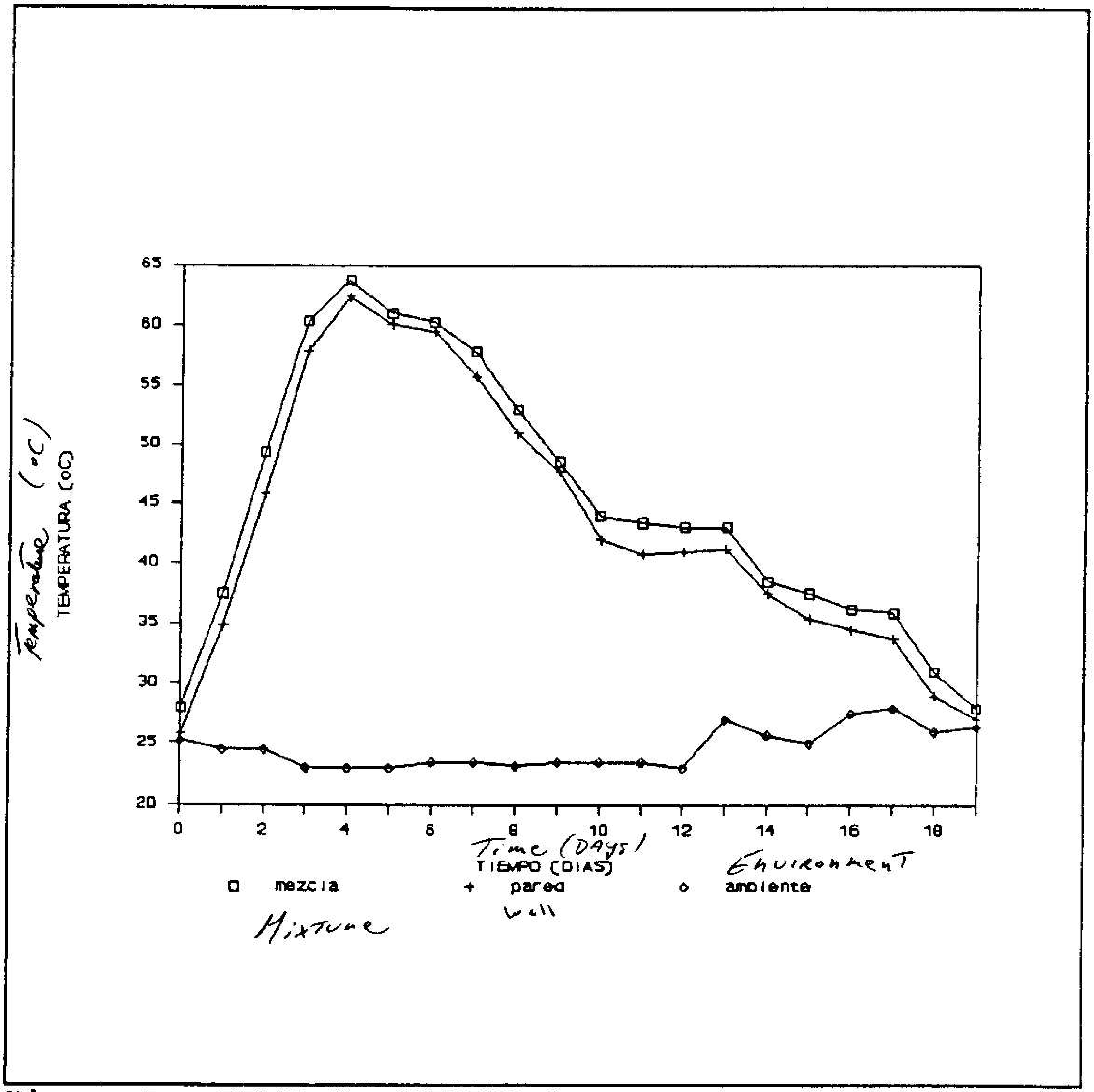


Figura 5: ETAPA I. CORRIDA I.

Figure 5: PHASE I. TRIAL I

Perfil de temperatura. Reactor 2.

Temperature Curve. Reactor 2

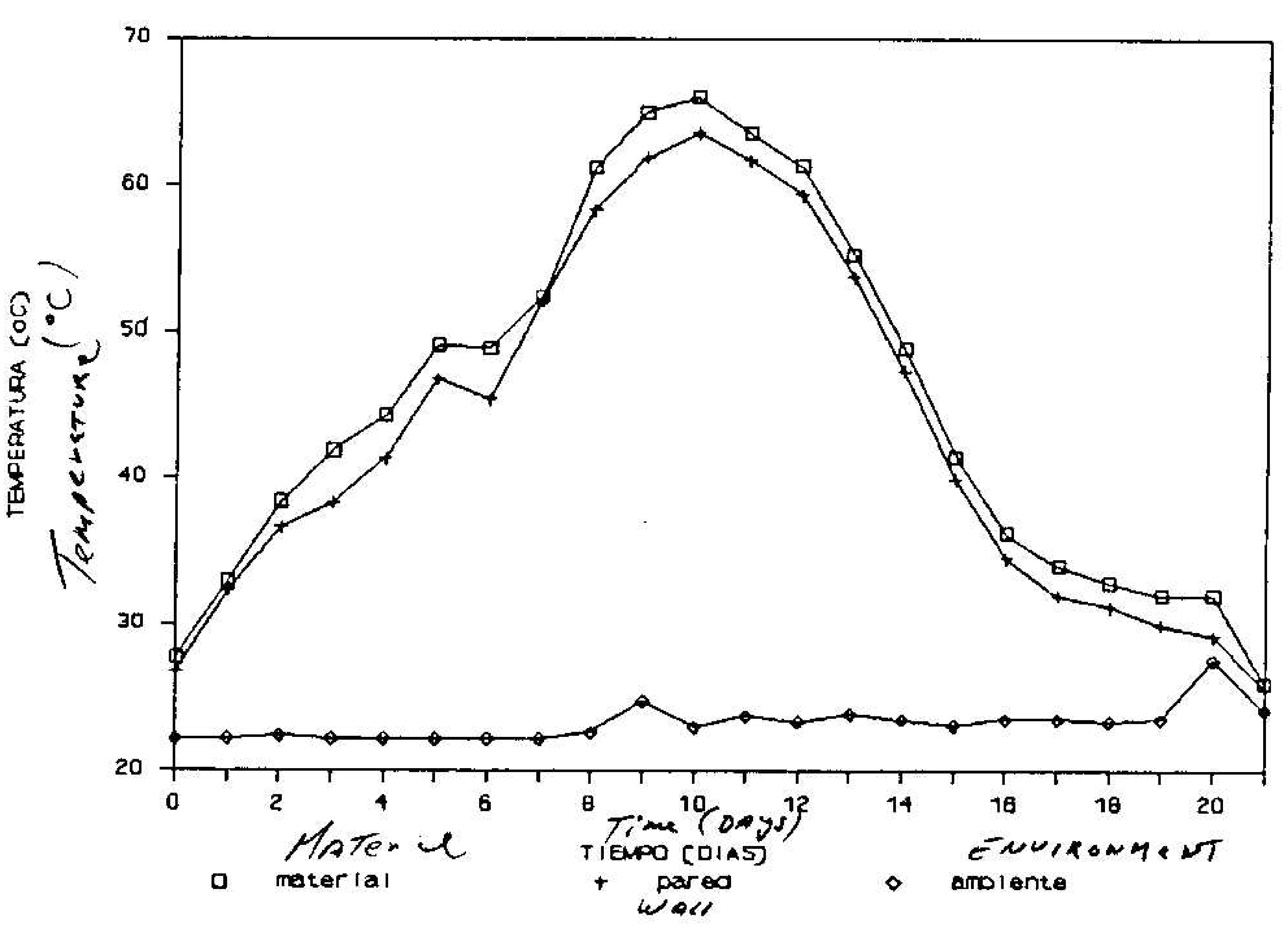


Figura 4: ETAPA I. CORRIDA I.
Figure 4 Phase I. Trial I.
Perfil de temperatura. Reactor 1.
Temperature Curve Reactor 1.

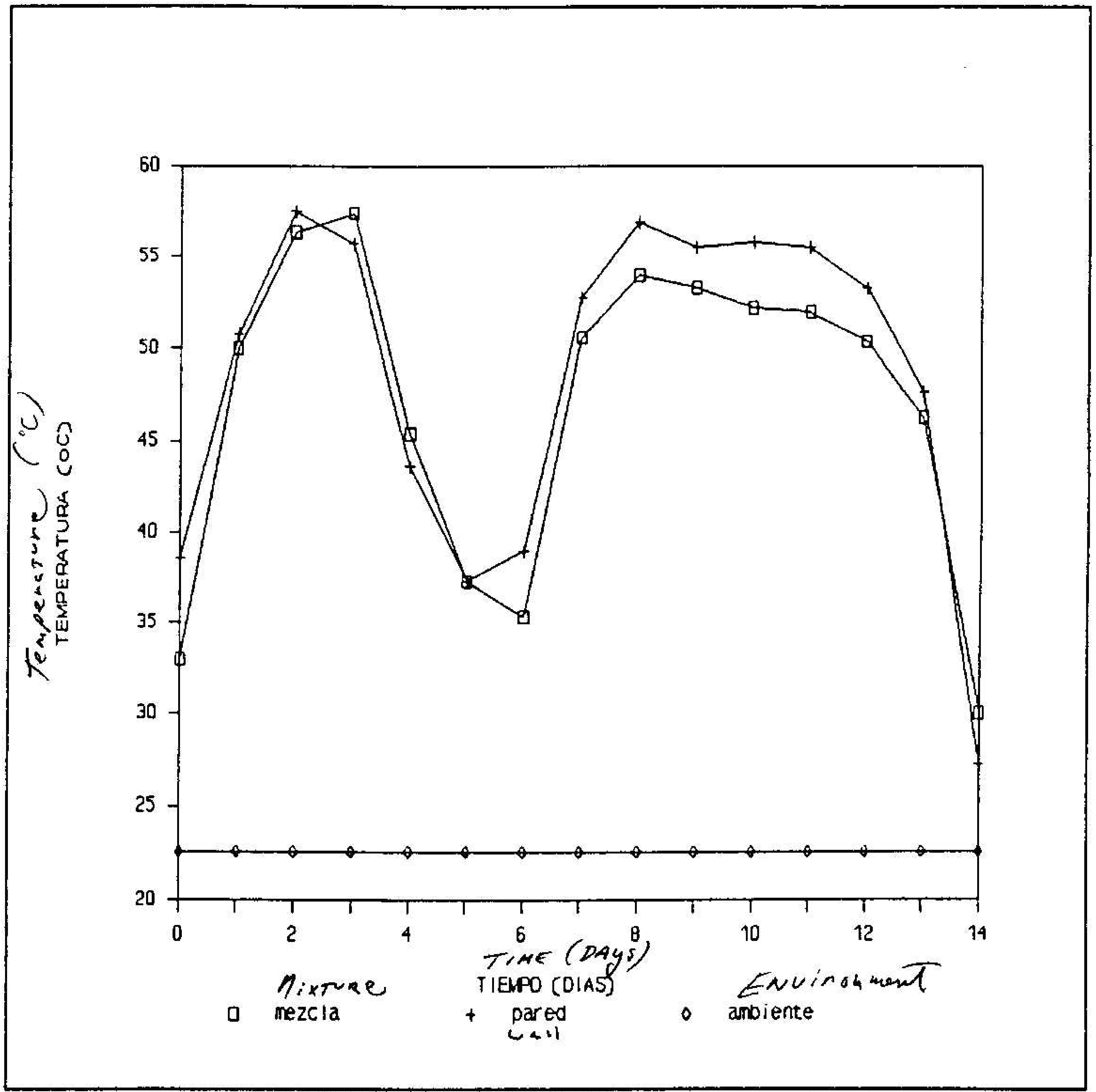


Figura 3: EXPERIMENTO PRELIMINAR. PRELIMINARY EXPERIMENT

Perfil de temperatura.
Temperature Curve

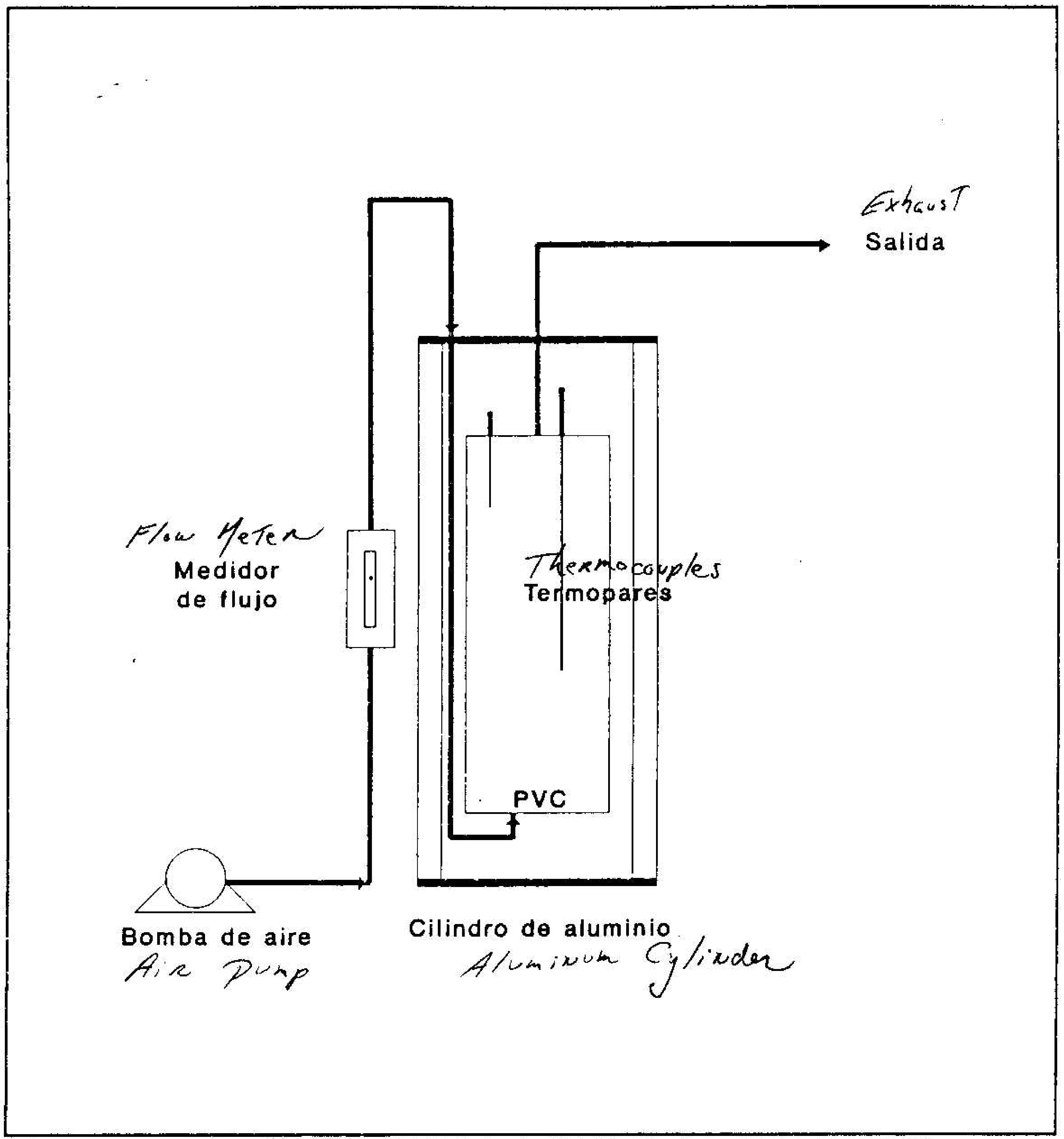


Figura 2: DISEÑO DEL EQUIPO A ESCALA DE LABORATORIO.

Figure 2: Design of Laboratory-Scale Equipment

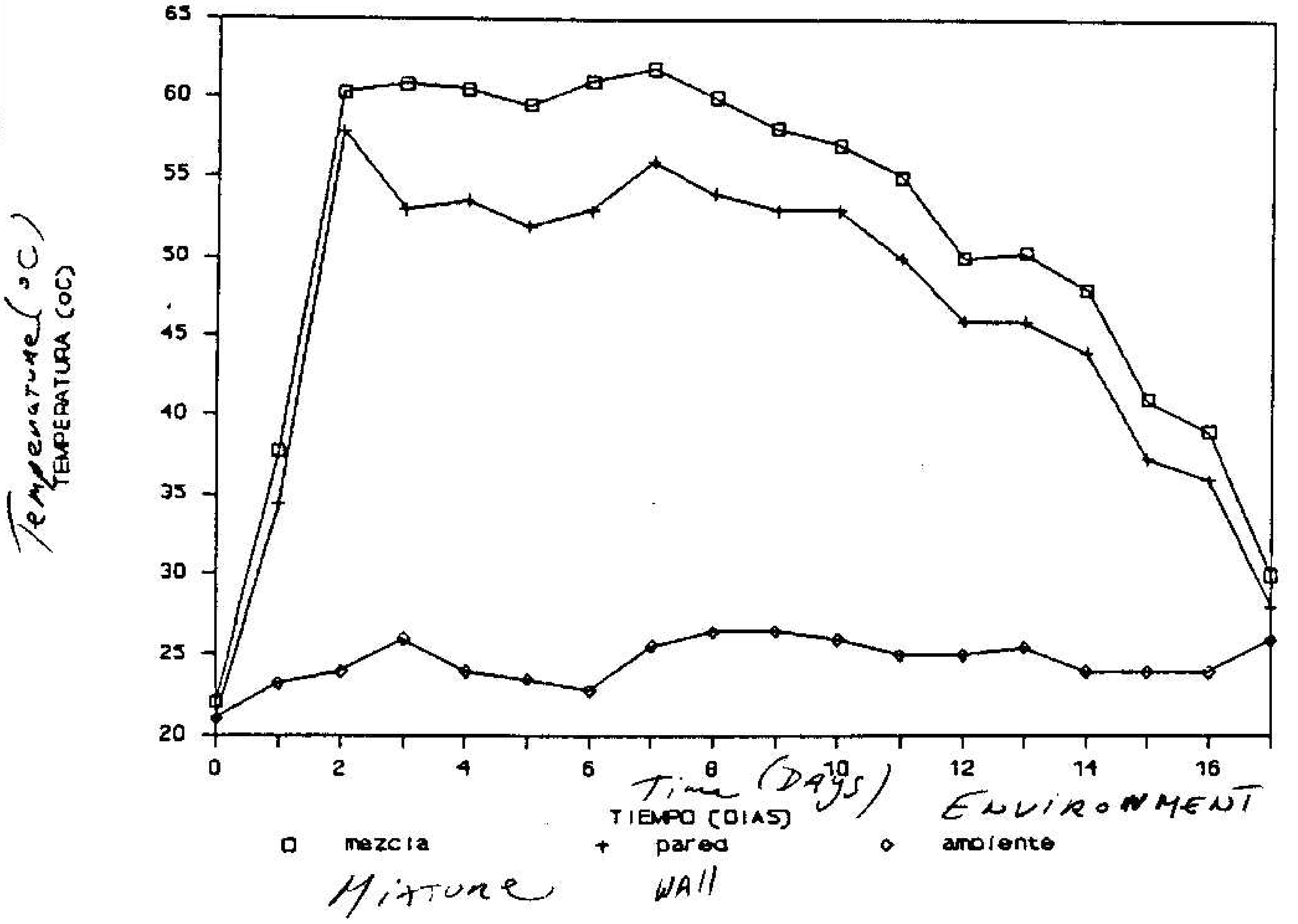


Figura 10: ETAPA II. CORRIDA II.
Figure 10: PHASE II. TRIAL II. Reactor 1.
Perfil de temperatura. Reactor 1.

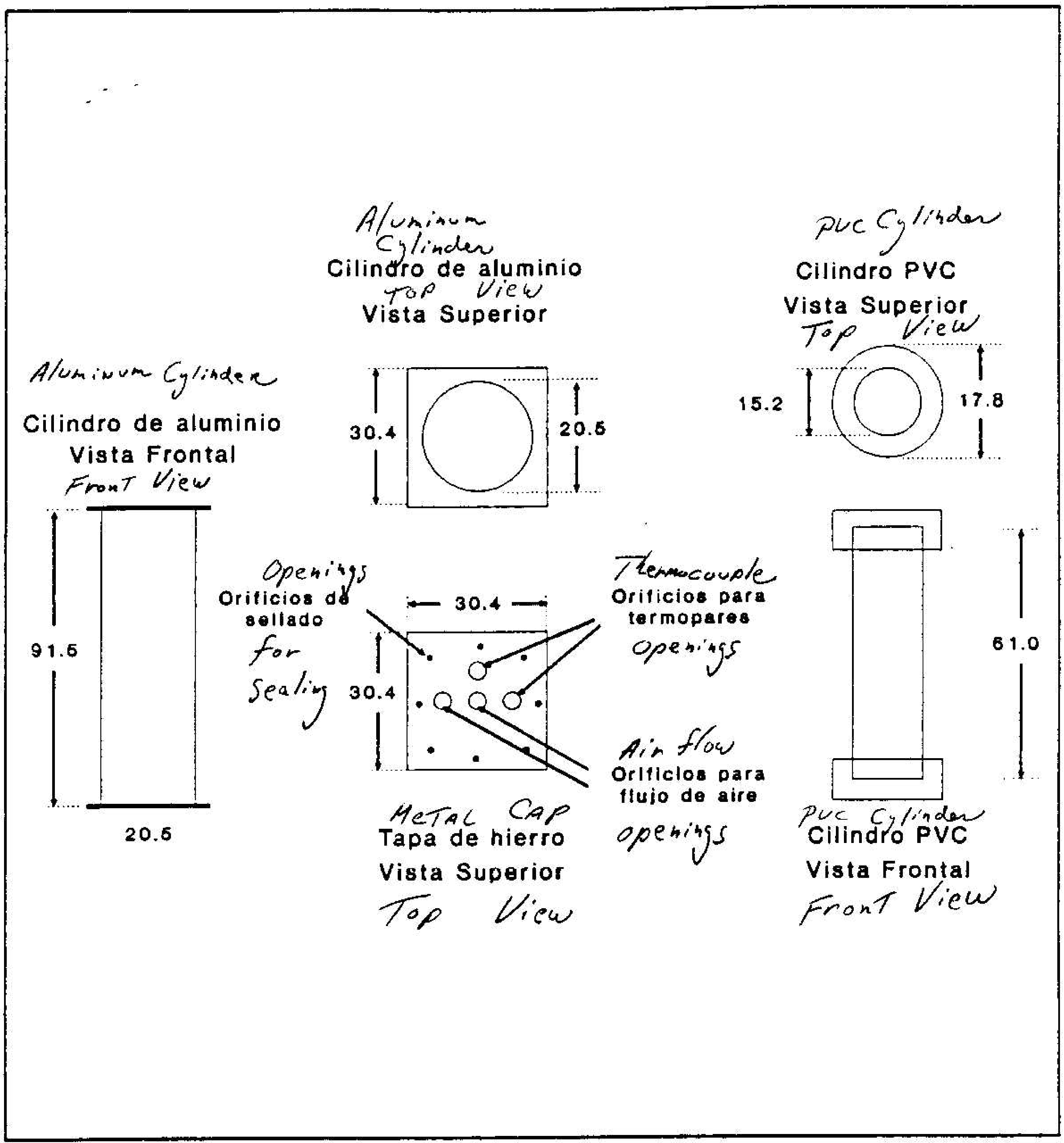


Figura 1: DIMENSIONES DEL REACTOR (cm).

Figure 1: Reactor Size (cm).

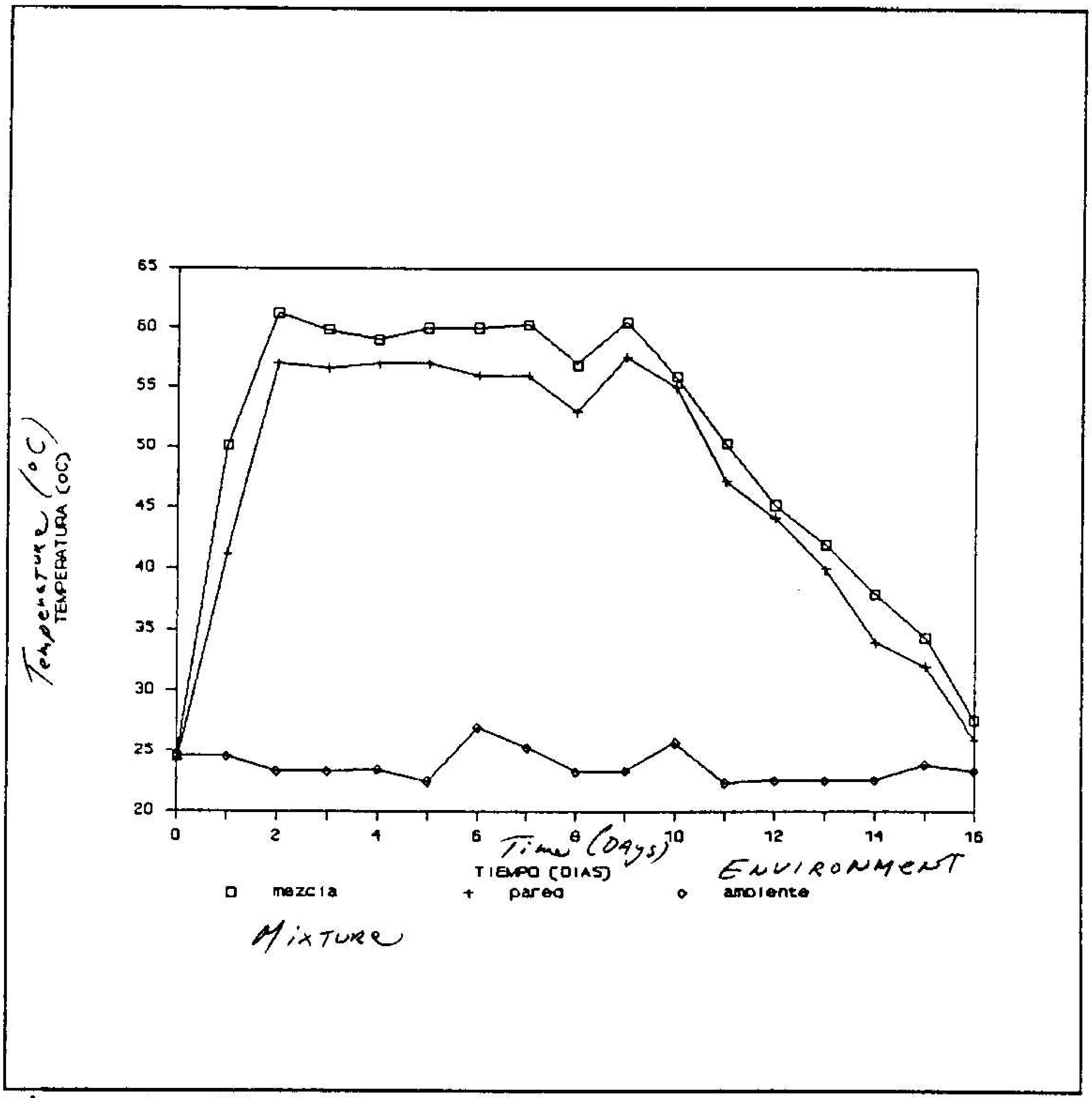


Figura 9: ETAPA II. CORRIDA I.
Figure 9: PHASE II · TRIAL I
Perfil de temperatura. Reactor 2.
Temperature Curve. Reactor 2.

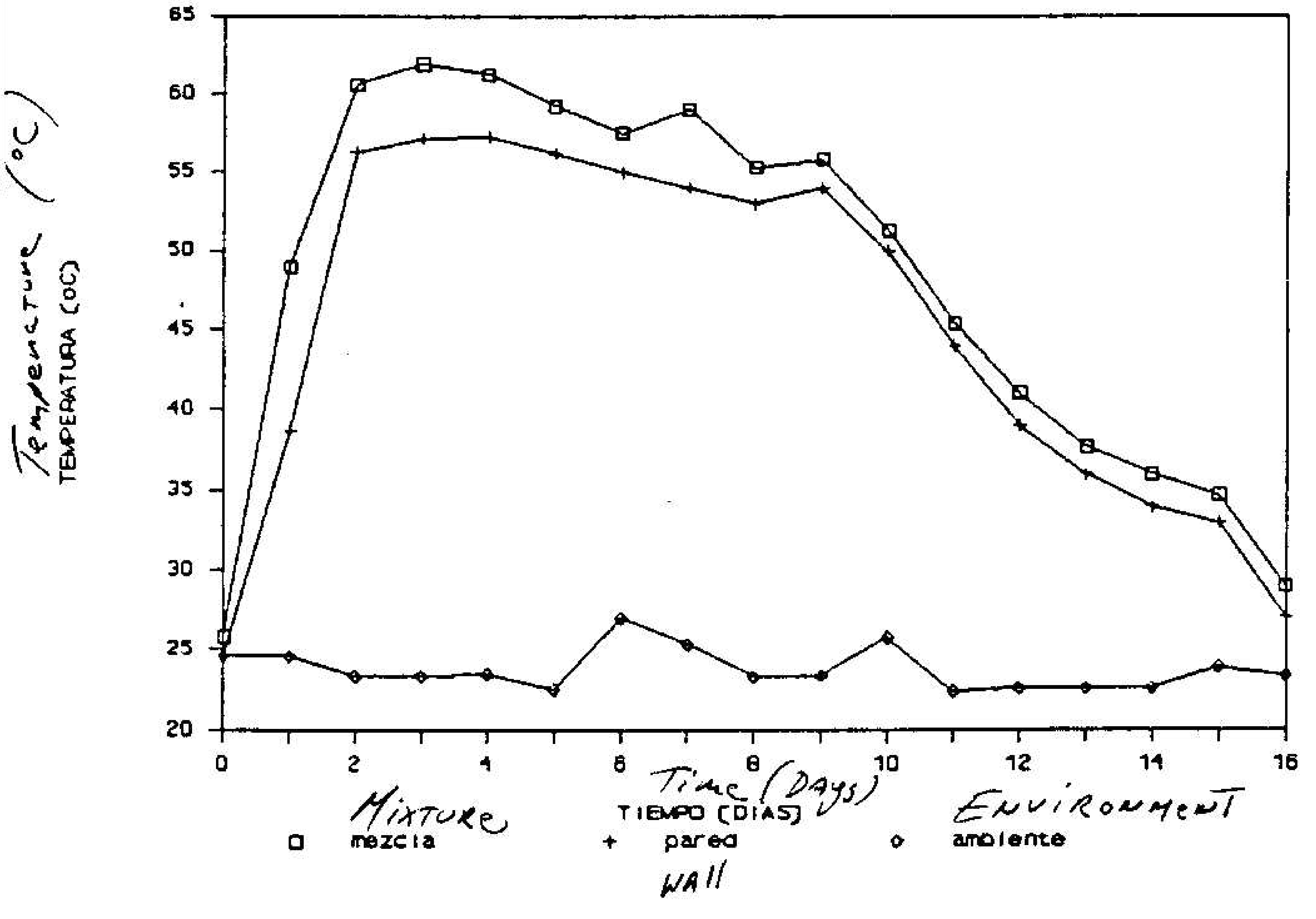


Figura 8: ETAPA II. CORRIDA I.

Figure 8. PHASE II. TRIAL I.

Perfil de temperatura. Reactor 1.

Temperature Curve. Reactor 1.