

HARDWOOD WHOLE TREE CHIPS--
A FUEL STORAGE MODEL ANALYSIS

by

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(ABSTRACT)

A pile of mixed hardwood whole tree chips was monitored for one year to identify the effects outside storage would have on the fuel potential of the exposed pile. A 20 foot conical pile was built by gravity feed from an overhead conveyor.

Moisture content, fiber loss, ash, specific gravity, higher heating value (HHV), temperature, packing density and pH were the variables examined and from these changes, Total Net Heating Value was estimated.

Moisture content and packing density showed a significant increase with time. Pile temperature remained below freezing for the first ten weeks of the study then rapidly rose above the ambient air temperature to a maximum of 82 degrees C before falling to near ambient where it remained.

After six months, moisture content within the pile stratified into layers reflecting steep moisture content gradients. The outermost layer became saturated, primarily due to rainfall while spontaneous drying reduced the innermost layer's moisture content.

The Total Net Heating Value (TNHV) was found to decrease 1.14 percent per month or 13.7 percent a year. Increased moisture content accounts for 88.5 percent of the loss. Lower HHV accounts for 11.5 percent of the loss in TNHV.

Storage suggestions and recommendations are included.

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LITERATURE REVIEW

The oil embargo of the mid seventies coupled with the growing discontent with nuclear power in the eighties has led to a renewed interest in the use of wood as an industrial fuel. It is necessary that wood, a renewable, domestic and safe fuel be processed before it can be used in industrial plants. The wood is usually converted to some particulate form such as chips or pellets before use. The wood particulates can be stored as received or after some processing such as drying or treatment with chemicals. The method of storage and its duration can have an effect on the fuel potential and handling properties of the wood particulates. Before any sound decision can be made on the economics of storing wood particulates for future use as a fuel these factors must be studied.

Storage and fuel characteristics which affect the utility of industrial wood fuels are: Moisture content, loss of biomass due to chemical and biological activity, heat of combustion, temperature, particle size and density, bulk density, pH of water solubles, pile size, pile shape, and climatic conditions. The interaction between these factors makes description of their effects on chips during storage difficult.

An empirical model for predicting the change of total available energy during outside storage of

hardwood whole tree chips in a pile has been developed (Curtis 1980). The model is based on changes in a) higher heating value; b) specific gravity; c) packing density; and d) moisture content, and is sensitive to storage time. The existing model provides estimates of Total Available Energy (TAE). The form of the TAE versus time relationship is:

$$\text{TAE} = a + b/t$$

where "t" is time and "a" and "b" are empirical constants which depend on changes in a) through d) mentioned above.

The effects of some of these factors have been examined by studies primarily stemming from the research and industrial experience of storage of pulp wood and "clean" pulp chips, those free of bark and dirt, for use in paper manufacturing. With the advent of whole tree chipping, studies of storage effects have expanded to include chips other than clean chips traditionally used for paper making.

Moisture Content

The initial moisture content of a storage pile is determined by the moisture content of the material used in its construction. Respiration of living wood cells and microorganisms, precipitation, drainage, runoff and leaching cause the moisture content of the fuel to change during outside storage.

In three experimental chip piles, two made of

spruce chips and one made of pine pulpwood chips between 8.9 and 10 meters tall, observed by Bergman and Nilsson (1971) in southern Sweden, moisture content changes over 9 months were insignificant but the chips were slightly drier at the outer edge in two of the piles.

White and DeLuca (1978) reported spontaneous drying occurring over a 6 month period in the interior zones of a cone shaped pine bark pile and a similarly shaped mixed pine and hardwood sawdust pile. Curtis (1980) also reported internal drying of cone shaped piles over a one year period. Lindgren and Eslyn (1961) also detected a slight difference in the moisture content in experimental pulpwood chip piles, the interior and bottom parts being slightly drier than the exterior which increased by 10 to 15 percent during 6 to 12 months of storage. Bjorkman and Haeger (1963) noted both internal drying and external wetting during a 15 month period in cone shaped piles of clean chips.

Cassens and Choong (1976 B) reported that piles in Louisiana increased from 107 percent dry weight moisture content in the fresh hardwood residues of six area mills to an average of 184 percent over three years. The moisture content increase was attributed to the high yearly average Baton Rouge rainfall of 62.3 inches. The moisture content of Douglas fir sawdust and hemlock stored near the coastal region of British

Columbia (Jenkins and Guernsey 1932) also showed a large increase in moisture content, once again probably due to a high amount of precipitation.

Wood Substance Loss During Storage

Feist et. al. (1972) compared two methods used to determine substance loss. Method one is based on changes in specific gravity over a period of time where specific gravity is measured in the laboratory at the beginning of the study and compared to the laboratory specific gravity at the end of the study. The second method is based on measuring the weight change of specimens contained in net bags placed in the pile which are weighed initially and again at the end of the study. Both methods showed an average loss of wood substance of about 4.5 percent over six months storage time. Feist concludes that both methods are capable of giving equivalent results.

Rothrock et. al. (1961), Shields and Unligil (1968), and Bergam (1973) reported wood fiber losses to be about one percent per month over a 5 month period. Hatton (1970), using the direct method of loss determination on a large pile of spruce and lodgepole pine in British Columbia, measured a substance loss of 2.2 percent after three months and 4.5 percent after six months. Pulpwood chip samples stored for six months in the northeastern United States by Eslyn (1967) averaged losses ranging from 5.6 to 7.4 percent.

Somsen (1962) measured an 8 percent decrease in specific gravity in a pile of southern pine pulpwood over a period of one year. Whole tree chips stored in nylon net bags in Norway exhibited a 2.9 percent loss in weight after one and a half months. In laboratory tests conducted by Zoch et. al. (1976) the weight of unscreened aspen whole tree chips decreased by 18.8 percent and that of clean screened aspen wood chips by 3 percent after six months storage. Percent ash content has been used to determine wood substance losses. Curtis (1980) obtained ash values for wood of below one percent and found the ash content of bark to be 10.92 percent over a one year study period. Jenson et. al (1963) stated that the ash content of bark can be more than ten times greater than it is in corresponding wood.

Higher Heating Value

Changes in the higher heating value (HHV), calories per gram of stored, wood have been reported by Jenkins and Guernsey to vary from a 2.2 percent decrease in 12 months in piles of Douglas fir bark and sawdust (1932). White and DeLuca (1978) noted a 7 percent increase in 5 months in piles of pine bark, mixed hardwood bark and mixed pine and hardwood sawdust. A study by Springer et. al. (1978 A) showed HHV did not change significantly during storage in southern pine whole tree chips. Cassens and Choong

(1976 A) found no difference in HHV in fresh and stored hardwood sawmill residues in Louisiana. Curtis (1980) reported finding no change to a slight loss of higher heating values over a one year period in six outside storage piles.

Working with laboratory cultures, Blankenhorn et. al. (1980) did calorimetric analyses on Populus spp. wood specimens decayed by Lenzites trabea (brown-rot) and Polyporus versicolor. The results were not statistically significant.

Changes in the chemical composition of wood will occur during storage. This will be a function of the type of fungi present. White rot attacks all components of the wood whereas brown rot attacks mainly cellulose and associated pentosans while lignin is left mostly untouched (Cartwright and Findlay, 1958). Studies done by Murphey and Masters (1978) indicated that for oak, lignin has a higher heating value than cellulose. Therefore, an increase in higher heating value should be noted for wood attacked by brown rot where the ratio of cellulose and hemicellulose to lignin is significantly decreased. It is thought, however, that wood substance loss occurs uniformly by lignin and carbohydrates (Henningsson, 1967, Hung and Kuechler, 1971). This is confirmed by Blankenhorn et. al. (1980). Curtis (1980) reported finding no change to a slight loss of higher heating values over a one

year period in six outside storage piles.

Thermogenesis

Initial temperature buildup in stored wood that is reasonably green may be ascribed to the respiration of the still living parenchyma cells. Above temperatures of 40 degrees C, the major buildup in heat is due to the metabolism of the fungi present. The thermopiles multiply rapidly and raise the temperature to 70 degrees C or slightly higher, the peak that can be reached by microbial activity (Cooney and Emerson, 1964).

Some studies indicate that the respiration of living tissue in green chips may be more rapid than in the living tree (Springer and Hajny 1970, Springer et. al. 1971 A, 1971 B, Assarsson et. al. 1970). Heat caused by respiration is lost from the pile relatively slowly. Cell respiration is believed to cease at about 40 degrees C due to the death of the living parenchyma cells. Fungi will continue to respire above this temperature.

Fungi of the Basidiomycetae, Ascomycetae and fungi imperfecti grow within the pile. It is believed that fungal activity is the cause of the majority of the wood substance loss which occurs (Rothrock et. al. 1961, Springer and Hajny 1970).

The extent of wood degradation is highly dependent on pile temperature, moisture content, air flow and

availability (Hulme and Stranks 1976, Smith 1973, Bergman and Nillsson 1971). Bergman (1973) indicated that most fungal degradation occurs in pile zones at temperatures between 20 and 50 degrees C. Hulme and Stranks (1976), however, have isolated two Ascomycetes which survived temperatures over 70 degrees C; the supposition being that at temperatures greater than 50 degrees C that was found in such piles, degradation by fungi may still occur.

It has been found that bacteria could produce a significant amount of the heat generated in a storage pile of chips (Feist et. al., 1973 A). It is generally believed that direct chemical oxidation is responsible for self heating above 80 degrees C (Tsuchiya and Sumi, 1977). Kubler (1982 B) suggests that because self heating is much greater in the center of a pile than near the surface, that possibly thermal disintegration generates heat. He indicates that slow pyrolysis is an exothermic process and not an endothermic one as generally believed. Pyrolytic self heating of wood takes place when temperatures are raised above 80 degrees C. Such conditions exist in piles of sawdust, chips and bark. Heat release that is not dissipated can cause temperatures that reach levels of rapid oxidation and combustion.

Thermocouples are commonly used to record temperatures as they develop within a pile. In

Virginia, White and DeLuca (1978) monitored temperatures in residue piles for 5 months. After two weeks the temperature in a pine bark pile reached 77 to 88 degrees C and, in a hardwood pile the temperature rose to 65 to 70 degrees C within a month. Both piles remained at the elevated temperature for the remainder of the study. Somsen (1962) compared two southern pine chip piles. The first pile reached an internal temperature of 63 degrees C while the second, which had been wetted during construction, attained 55 degrees C. Schmidt* (1969) found that in piles of redwood chips in California the temperature reached 82 degrees C.

Bergman and Nillsson (1971) reported that chips piled frozen may remain that way in spite of ambient temperatures above freezing. Isotherms obtained by plotting temperature gradients found within a pile of spruce pulp chips piled in February remained at temperatures below 0 degrees C until July although the ambient temperature was near 15 degrees C at that time.

Spontaneous Combustion

Exactly what causes spontaneous combustion is unknown. Walker and Manssen (1979) stated that relative humidities higher than 98 percent inhibit spontaneous combustion. The possibility of the wood igniting is dependent upon factors such as the availability of combustible gasses and oxygen as well as temperature.

It is felt that layers of fine particles enhance the probability of internal heat reaching a critical level initiating spontaneous combustion. (Schmidt, 1967, Bergman, 1974). Smaller particles pack to a higher density than do larger ones and if small particles are mixed with larger ones the bulk density is greater than is possible for larger particles alone so that layering and packing is enhanced increasing internal temperatures.

Kubler (1982 A) states that excessive self heating results from compaction of chips, from layers of fines, and from small particles which block air channels between chips, thus preventing air convection and the so called chimney effect. His calculations show that strong convection works against self heating.

Bulk Density

Bulk density of storage piles is important to the pulp and paper industry because inventories can be based directly on measurements of pile volume if bulk density is known. Surveying methods and tape measurements were commonly used to determine volume. The advent of aerial photography has provided quicker and more accurate volume determinations. However, external volume does not accurately reflect fiber content because of bulk density variations due to particle size and packing of chips.

DeMiller (1980) provided some new chip density

factors based upon pile height using a testing apparatus derived from a TAPPI testing procedure T21-05-74. An experiment done by Walsh (1981) using a nuclear probe to determine bulk density proved promising but more testing is needed.

Edberg et. al. (1973) and Hatton (1976 B) indicate that bulk density is indirectly proportional to particle size. Both Springer (1978 A) and Kubler (1982 A) believe that fine particles in a pile increase the danger of spontaneous ignition. If this is true a measure of bulk density could be a useful management tool which may result in fewer fires.

pH

Hatton et. al. (1968) and Feist et. al. (1973 B) indicated that both pulp yield and strength were reported to decrease due to acid formation. Heating, they go on to say, in itself will not cause acid to form; it is rather a symptom.

White and Curtis (1980) noted that wood and bark became slightly more acidic during storage and that hardwood bark, sawdust, and whole tree chips seemed to be less acidic and changed less during storage than did pine. White and Curtis (1980) also noted that low pH may cause corrosion in conversion and processing facilities which will likely cause wood fueling costs to rise compared to storage of fossil fuels.

Storage Suggestions

Substance loss and increase in moisture content appear to be the major factors contributing to the loss of fuel value of stored wood particulates. Extensive losses of wood material may also be brought about by spontaneous combustion or pyrolysis of stored materials.

Research seeking chemical treatments to alleviate the heat buildup and prevent substance loss has been undertaken by the U.S. Forest Service, Forest Products Laboratory in Madison, Wisconsin (Springer et. al. 1969, 1971 A, 1974, 1975 A, 1975 B, 1975 C, 1977 A, 1977 B, Eslyn 1973 A, Feist et. al. 1974, Smith and Hatton, 1971). Chemical treatments have been found to be reasonably effective in slowing heat generation in chips used for tall oil or pulp yield. It is not economically feasible when used on lower value fuel chips.

In general, shorter storage times are preferred. Hatton (1972) recommends that storage time should not exceed three to six months. Zoch et. al. (1976), dealing with unscreened whole tree chips, claims the shorter the storage time the better. A recommendation that softwood chips should be utilized within eight months and hardwood chips by three was put forth by Shields (1967). Bergman (1973 B) also concluded that storage time for fresh chips should be at most three

months in summer and not more than nine months when the majority of storage takes place during the winter months. Springer (1975 A, 1979 B), however, is a strong proponent of the standby storage method of inventory, claiming that in the long run it is better to use fresh chips immediately and leave an old pile aside for emergencies. These studies, however, deal with pulp yield and not fuel potential.

Covering a pile with plastic was found to reduce oxygen levels and hold fungal degrade to a minimum (Feist et. al., 1971). Other factors such as moisture content and internal heating were generally ignored. Kubler (1982) states that plastic covers on chip piles reduce self heating only if properly used preventing oxygen from flowing and defusing into the pile and that imperfect covers do more harm than good by letting nearly as much oxygen pass as would be consumed by open piles while restricting convective cooling.

Water immersion under anaerobic conditions was found by Eslyn and Landrie (1973 B) to prevent losses in specific gravity of Douglas fir wood chips. Watering chips to provide a buffer against heating was suggested by Schmidt (1969) and Somsen (1962). This approach seems impractical for fuel storage because of the adverse effects of moisture on recoverable energy. Springer (1978 B) indicates that the large scale anaerobic storage of fuel chips is impractical. He

suggested drying the woody fuel before storage and to protect from rewetting by covering.

Pile height is also thought to be a pertinent factor in the storage of wood fuel. Hatton (1972) suggested a maximum height of 59 feet, Schmidt (1969), 50 feet, and White (1979) no greater than 16 feet for long periods of storage.

SUMMARY AND JUSTIFICATION

The literature reviewed covered a wide range of factors affecting wood chip storage presenting an overview of current research in the field. Unfortunately, lack of uniformity in research approaches makes the results of any one study hard to compare with those of others. Results are often conflicting.

Most of the studies conducted were upon chips stored for future use in paper manufacturing and the application of these studies to fuel storage is limited. Certain properties such as chemical treatment which improve the quality of wood for paper are detrimental to use of wood as a fuel. Hogged wood fuel, whole tree chips, bark, sawdust and forest residues will vary in particle size, moisture content and species composition. They also contain significant amounts of decayed wood, foliage, and soil contaminants all of which are detrimental to pulp for paper. Residues for fuel will be more valuable the drier they are. Hence, any operation causing an increase in moisture content, such as immersion in water to prevent decay is undesirable. Also biological and many chemical treatments suggested for pulpwood would be unfeasible if applied to the lower value whole tree chip fuel wood.

The interaction of the factors affecting wood fuel storage still needs to be more fully explored, and more accurate measurements of storage effects on available energy should be made to determine optimum storage time and methods. To make such estimates requires a closer look at factors affecting wood fuel and their gradients within the pile for shorter storage cycles than has been explored in past studies.

Objectives

It is the hypothesis that if more accurate measurements of fiber loss, packing, and moisture gradients for short storage cycles are obtained they will improve the ability to estimate the effects of storage on the properties of wood fuel. To verify this hypothesis these study objectives were set:

- 1) Measure the packing density within a 20-foot storage pile of green hardwood whole tree chips;
- 2) Measure material losses within a 20-foot storage pile;
- 3) Measure moisture content gradients near the pile surface;
- 4) Measure these changes for short storage times using a procedure similar to that developed by Curtis (1980) to predict available energy changes in a pile of wood particulate fuels.

METHODS AND PROCEDURES

Design and Construction of the Experimental Chip Storage Pile

A twenty foot storage pile of hardwood whole tree chips was constructed and observed for fuel value changes and settling for a period of one year.

The pile was divided into 25 zones for sampling and monitoring purposes. Figure 1 shows a schematic diagram with each numbered zone and its relative size and position.

Movable aluminum chips attached to metal poles were used to measure vertical movement within the pile; these chips were positioned at sixteen points within the pile as shown in Figures 1 and 2. Table 1 shows the height above ground for each of these chips.

A concrete pad was poured to form an anchoring base for the steel poles to which movable "chips" were attached. The poles were raised and on December 1, 1980 the first shipment of chips arrived. By December 5, four more loads arrived. The 10-inch, 56-foot belt conveyor and front end loader used for construction of the pile arrived on December 9 and construction of the pile was started immediately. The site chosen for construction was directly behind the Brooks Forest Products Center on the campus of Virginia Polytechnic Institute and State University, Blacksburg, Virginia, U.S.A.

A load cell was placed in the center of the pile

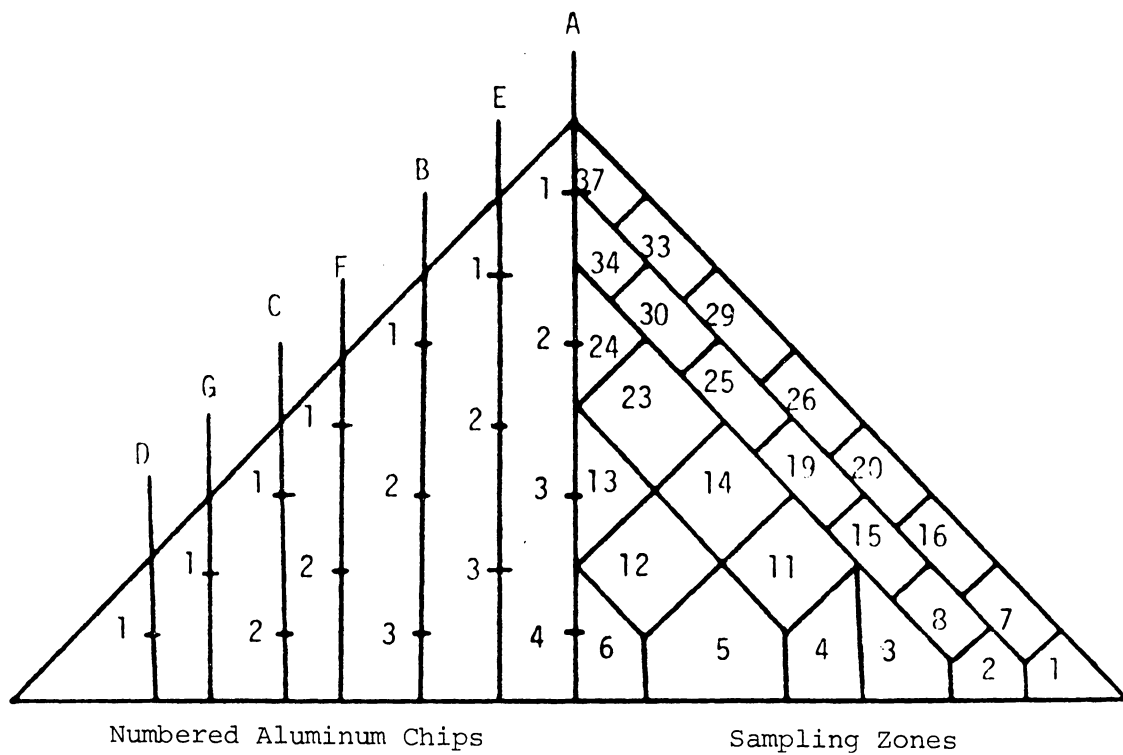


FIGURE 1. Schematic Profile of the Exposed Experimental Hardwood Whole Tree Chip Storage Pile Showing Numbered Sampling Zones and Placement of Poles and Numbered Aluminum Chips

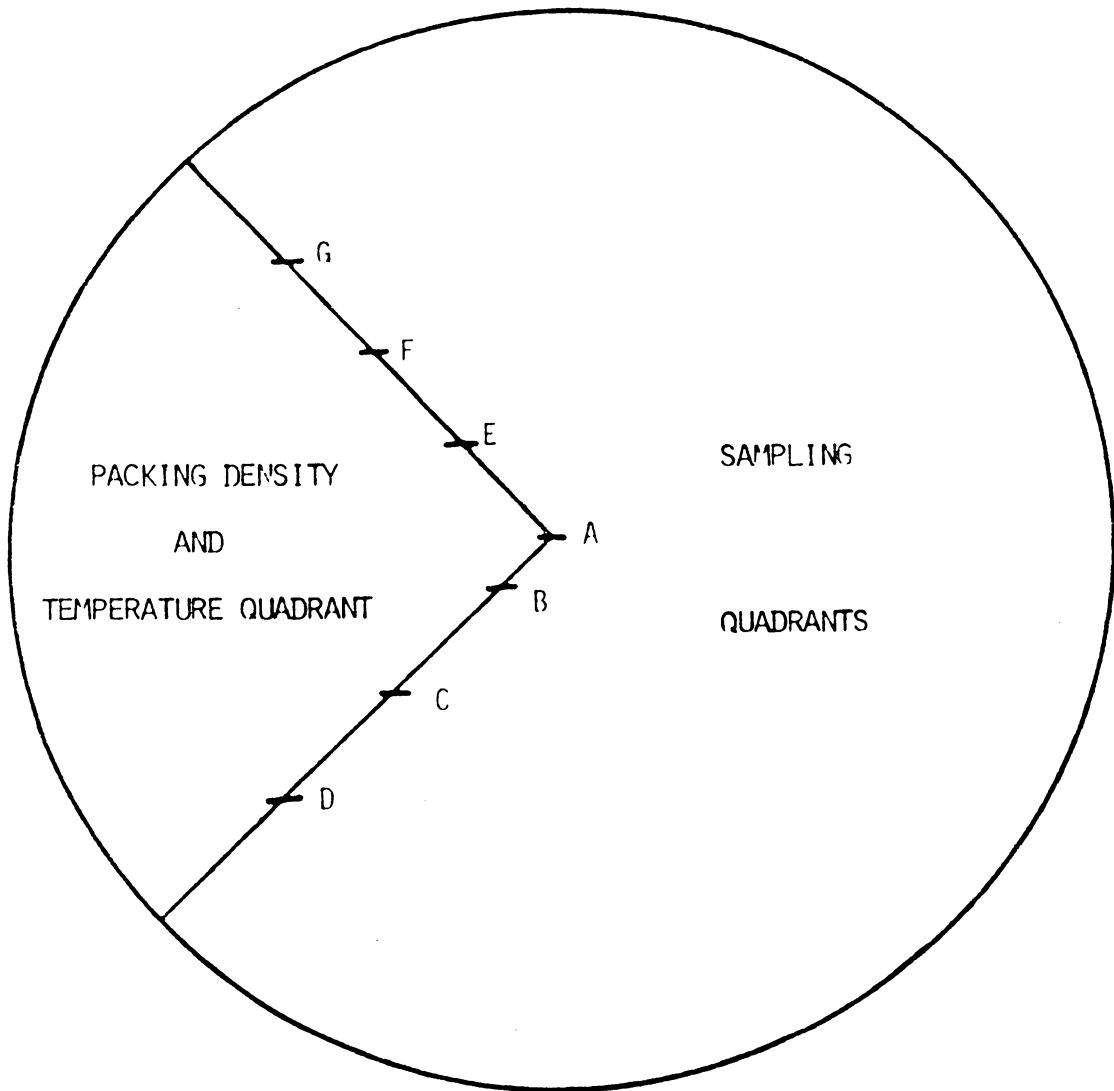


FIGURE 2. Schematic Overhead of the Exposed Experimental Hardwood Whole Tree Chip Storage Pile Showing Numbered Sampling, Packing and Temperature Quadrants and Pole Position

TABLE 1
Aluminum Chip Position Within Pile*

Pole	Chip Number			
	1	2	3	4
A	2.5	7.5	12.5	17.5
B	3	7	11	
C	3	6		
D	2			
E	4.5	9	13.5	
F	4.5	9		
G	4			

* Height in feet above ground (original chip position).

at the base. This was connected by wire to a instrument which provided a digital readout of the pile weight. As the construction of the pile progressed control samples were taken from each zone and nylon mesh bags to study fiber loss were placed within the pile. Thermocouples used to monitor temperature within the pile were placed in zones 4, 5, 6, 12, and 13 during pile construction. Two more chip shipments arrived on December 17 and 18 bringing the total weight of the chips delivered to 150.7 tons. Pile construction was completed on December 19. The resulting pile was 20 feet high with a base radius of 17 feet.

Five samples of approximately 250 g each were taken from each zone as the pile was being constructed. All samples taken in this study were immediately sealed in plastic bags and frozen to prevent moisture loss. Additional samples were obtained from the piles on a bi-weekly schedule for the first part of the study and bi-monthly thereafter. The sampling dates are included in Table 2. The pile was divided into 25 sampling zones. The zone placement and numbering are shown in Figure 1.

To sample deep within the pile a special auger designed by White et. al (1980) was used. A special attachment was constructed enabling a high powered drill to be used when gathering samples from deep

TABLE 2
Sampling Dates

Sampling Number	Week Number	Date
Control	0	12/19/80
1	3	1/09/81
2	5	1/22/81
3	7	2/04/81
4	9	2/18/81
5	11	3/04/81
6	17	4/16/81
7	19	5/01/81
8	21	5/15/81
9	23	5/29/81
10	25	6/11/81
11	27	6/25/81
12	36	8/25/81
13	45	10/28/81
14	52	12/16/81

within the pile.

Temperature, weight and height measurements were taken at the time of each sampling as were visual observations as to the location and extent of decay within the pile. Figure 2, an overhead schematic view of the pile, shows sampling quadrants and pile placement. A transmission model 1060 PPS Minitemp temperature instrument was used to take temperatures and a custom designed load cell on loan from Weyerhaeuser Corporation was used to obtain weight measurements within the pile.

Laboratory Analysis

Experimental Variables

Seven variables were monitored for changes during the storage period. These were:

1. Moisture Content
2. Ash Content
3. Specific Gravity
4. Higher Heating Value
5. Temperature
6. Packing Density
7. pH

Analysis of all samples was conducted at the Brooks Forest Products Center on the Virginia Tech Campus. After moisture content was determined the samples were separated into their wood and bark components. Unless noted, subsequent testing was done

on both the wood and bark components separately.

Moisture Content

Dry basis moisture content, + or - .05 percent moisture content, was determined for each sample. The entire contents of each sample was weighed to 00.1 of a gram, dried at 103 degrees C for 24 hours then weighed dry after cooling in a dessicator. A total of 657 data points were obtained.

Fiber Loss

Fiber loss is determined three ways: First by measuring the change in dry density of chips within the pile; secondly by comparing percent ash of samples throughout the study and finally by comparing changes in specific gravity throughout the study.

Dry Density

Samples contained in nylon mesh bags of a measured dry weight were placed in the experimental pile at the start of the study. These samples were to be removed from the pile at the study's end, dried, weighed, and compared to the initial weight.

Ash Content

Ash content was determined basically following ASTM Standard D 1102-56 (ASTM 1956). As the standard suggested, it was felt that at least three burns were needed for each sample. The use of crucibles for the ashing procedure, as described by the standard, was too slow for the large number of samples to be processed.

Heat resistant test tubes and metal racks were purchased instead, and the ashing was done in a muffle furnace with the capacity of 150 samples. The samples were ashed at six-hundred degrees C for thirty-six to forty-eight hours, and percent ash, + or - .005 percent ash content, was calculated as follows:

$$\text{Percent Ash} = \frac{\text{Weight of Ash}}{\text{Oven Dry Weight of Wood}} \times 100.$$

One thousand, three hundred and fourteen data points were obtained.

Specific Gravity

A procedure similar to that described in the Technical Section of the Pulp and Paper Industry (TAPPI) standard T18-OS-53 (TAPPI, 1953) was used to determine specific gravity. Using this procedure oven-dry bark samples were weighed and then quickly lowered into water to determine the displaced volume. Wood was first weighed then coated in shellac before it was dipped into kerosene to determine its displaced volume. The specific gravity, + or - .001, was calculated as follows:

$$\text{Bark Specific Gravity} = \frac{\text{Weight of Oven-Dry Bark (gms)}}{\text{Displaced Volume (cc) of Water}}$$

$$\text{Wood Specific Gravity} = \frac{\text{Weight (gms) of Oven Dry Wood}}{\text{Displaced Volume (cc) of Kerosene} \times .817}$$

Five hundred and sixty data points were obtained.

Higher Heating Value

After moisture content determinations, the bark and wood samples were ground to pass through a 20-mesh screen. Oven-dry heat of combustion, + or - .5 cal/gram, was then determined using a Parr Model 1241 Adiabatic oxygen bomb calorimeter using a procedure described by the American Society for Testing and Materials (ASTM) Standard D 2015-66 (ASTM 1972).

Temperature

Temperature, + or - 1 degree C, was recorded from digital output from thermocouples placed within the pile in zones 4, 5, 6, 12, 13 and also in the air surrounding the pile to record ambient temperature.

Packing Determination

Seven 3/4 inch galvanized steel pipes were placed in the pile as shown in Figures 1 and 2; a schematic diagram of the research pile indicated by positions A, B, C, D, E, F, and G. Pipe A contained 4 graduated rods. Band E had three rods, C and F, two rods, and D and G, one rod respectively. The end of each graduated rod was attached to a 2" x 2" aluminum chip which was allowed to move freely in a vertical position within the pile. The "chips" were all started at a predetermined height above the ground as shown in Table 1 and their vertical movement could be directly read off the graduated rods. This movement corresponds to the compaction in that zone. From the bulk density of

these in situ measures of packing, the packing density gradient could be determined. The measurements were confined to one quadrant of the test pile so that these measures would not be affected by particle sampling.

An additional attempt was made to estimate bulk density in each zone by using a laboratory simulation procedure similar to the one described in the Technical Section of the Pulp and Paper Industry, (TAPPI) standard T-21-OS-74 (TAPPI 1974). A plywood box holding 1.0 cubic feet of wood particles was built. Another box which fit tightly inside the first was used to support and evenly distribute packing weight. Loose packed chips were found to weigh 20.3 pounds per cubic foot. This measure was used to calculate the weight to be placed upon each box of chips by multiplying 20.3 by the height of the column of chips above each zone as it would be found in the test pile. Table 3 lists the zones represented and the corresponding weights. As successive weights, each representing a one foot column of whole tree chips were added, the amount of packing was measured from a scale which had been placed on the inside box. Weights were chosen to correspond to calculated weights pressing upon the aluminum "chips" during the in situ measurement testing.

pH

After heat of combustion was determined, the remainder of each sample was ground to pass through a

TABLE 3

Weight Placed on Boxes to Represent Height of Chip Column

Zone	Chip Colume Height (feet)	Weight (pounds)
7, 26, 33, 37	1.12	22.7
2, 15	3.37	68.4
11, 23	6.75	137.0
5, 12	11.25	228.3

40-mesh screen for pH and ash content determinations. The pH of water solubles was measured using a procedure similar to that outlined by Martin and Gray (1971). This may or may not be the actual pH of wood, if in fact it is feasible to assign a pH to a composite material such as wood. These pH measurements are, however, still very useful as indicators of relative changes in acidity of water soluble extractives during wood fuel storage (Curtis, 1980). Approximately two grams of ground material, wood and bark, was stirred into 25 ml of distilled water until well mixed. This mixture was allowed to stand 15 minutes before the pH was measured using a Fischer Model 150 portable pH meter. Two pH measurements per sample were made. Eight hundred and seventy-six data points were obtained.

Analysis of Data

ANOVA

Using SAS 1979 an analysis of variation on the means of each of the study variables was performed. The variables tested were moisture content, ash content, pH value, specific gravity, and calorific value. All tests in this study were carried out at the 0.05 probability level. Comparisons were made between wood, bark, zones, and regions.

Regression Analysis

A linear regression was performed on each of five

variables using SAS 1979. In each case the variable being studied was the dependent variable and time was the independent variable. A simple linear regression was chosen for use on weighted values rather than a multiple regression analysis because the character of the weighted data precluded the use of the later. Regressions and r values are listed in Appendix D.

Cluster Analysis

To facilitate the grouping of zones into regions all variables were subject of a cluster analysis using SAS 1979. A cluster analysis takes all values of a given variable from each zone and each sampling period and pairs them based on the smallest difference between values. These pairs are then matched with the pair closest to its value forming new pairs. This is repeated until there are only two groups left which may or may not be significantly different from each other. Once broken into groups of zones mean values of the groups were subjected to a Duncans multiple range analysis. Regions were established in this manner. Appendix E contains results of Duncans multiple range analysis.

Weighting Procedure

The values of each study variable for each zone were weighted by the dry weight (in pounds) of the material in the torus formed by rotating the zone around the central axis of the pile. The pile was

assumed symmetric for this reason. Appendix A gives torus volumes used to weight the samples.

Next the values of each study variable for bark and for wood were combined for each zone according to the percent of wood and bark in the sample. These twice weighted values then became the pile's adjusted value for each variable.

RESULTS AND DISCUSSION

Decay

The areas mainly affected by decay were the outer layers and the pile top as is diagrammed (shaded areas) in Figure 3. The decay, however, was found mostly in pockets and not in a single layer as this diagram may seem to indicate.

There were also isolated pockets of decay deeper within the pile. It is possible that the sampling method of boring into the pile may have been responsible for "seeding" the decay farther into the pile accelerating the activity.

Temperature

Temperature Gradients

Temperatures, in general, were higher in zones located near the center of the pile than those nearer the outside and bottom of the pile. Figure 4 shows the zones with minimum and maximum temperatures and their locations within the pile.

Temperature Within the Pile

Table 4 gives temperatures within each zone as a function of time. Also shown is the corresponding ambient temperature. The rise and fall of the pile temperature followed changes in ambient temperature due to seasonal variation.

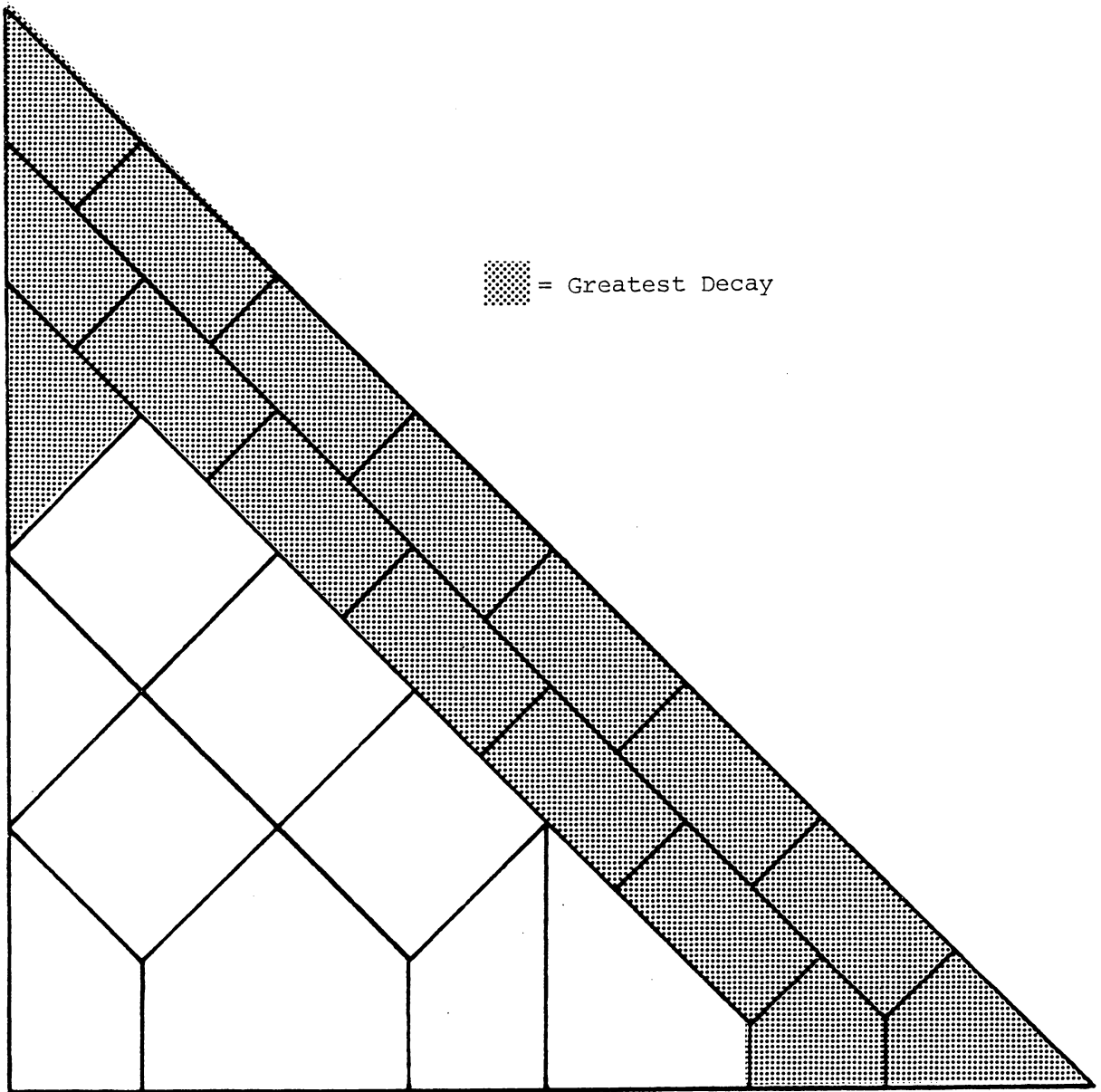


FIGURE 3. Schematic Profile of the Exposed Experimental Hardwood Whole Tree Chip Storage Pile Showing Outermost Region With Greatest Evidence of Decay

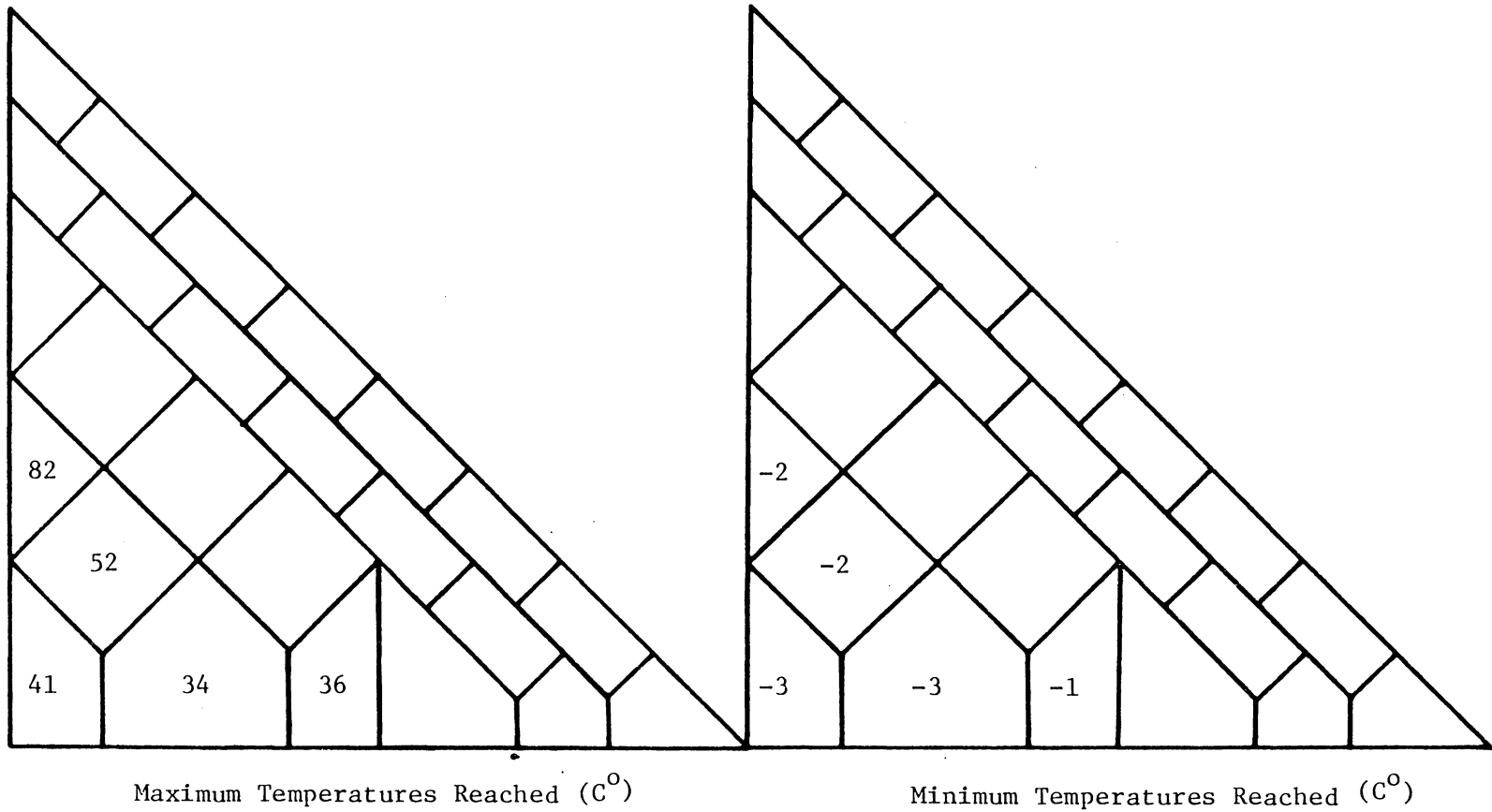


FIGURE 4. Schematic Profile of the Exposed Experimental Hardwood Whole Tree Chip Storage Pile Showing Maximum and Minimum Internal Temperatures Recorded

TABLE 4

Temperature in Each Zone Within Pile During Study (C^o)

	Date														
	12/19/80	1/09/81	1/22/81	2/04/81	2/18/81	3/04/81	4/16/81	5/01/81	5/15/81	5/29/81	6/11/81	6/25/81	8/25/81	10/28/81	12/16/81
	Week														
	0	3	5	7	9	11	17	19	21	23	25	27	36	45	52
Ambient	5	-6	0	-6	9	1	20	21	20	22	28	25	24	14	1
Zone 4	7	4	-1	8	6	15	29	20	28	29	26	36	25	8	9
Zone 5	5	2	-3	2	-1	7	31	20	28	31	34	33	26	8	10
Zone 6	5	3	-3	4	0	7	32	33	41	34	32	31	28	8	10
Zone 12	4	2	-2	4	-1	8	41	52	50	37	31	27	25	5	2
Zone 13	5	2	-2	6	3	11	48	53	59	82	31	26	28	3	2

The pile was built in the winter with frozen chips and the pile remained frozen for the first eleven weeks of the study, until March, after which the internal temperature began to rise above the ambient temperature. The rise in internal temperature was rapid and by the last week in May, week 23 of the study, a maximum pile temperature of 82 degrees C was reached in zone 13. After this point the temperature quickly dropped again. This phenomenon is in keeping with published studies attributing the rapid rise to microbial activity and its decline due to the death of the thermophiles which cannot, except for rare exceptions, endure temperatures above 70 degrees C. The internal pile temperature continued to fall until the end of the study essentially following seasonal changes in ambient temperature.

Moisture Content

Moisture Content Gradients

After twenty-six weeks the pile could easily be separated into layers, or regions, of statistically different moisture contents using a cluster analysis coupled with a Duncans multiple range test. These regions are shown in Figure 5, the shaded regions having moisture contents above percent. The outermost region, at an average depth of about 1.12 feet below the surface, consisted of zones 1, 7, 16, 20, 26, 33, and 37. The next region, 2.25 feet below

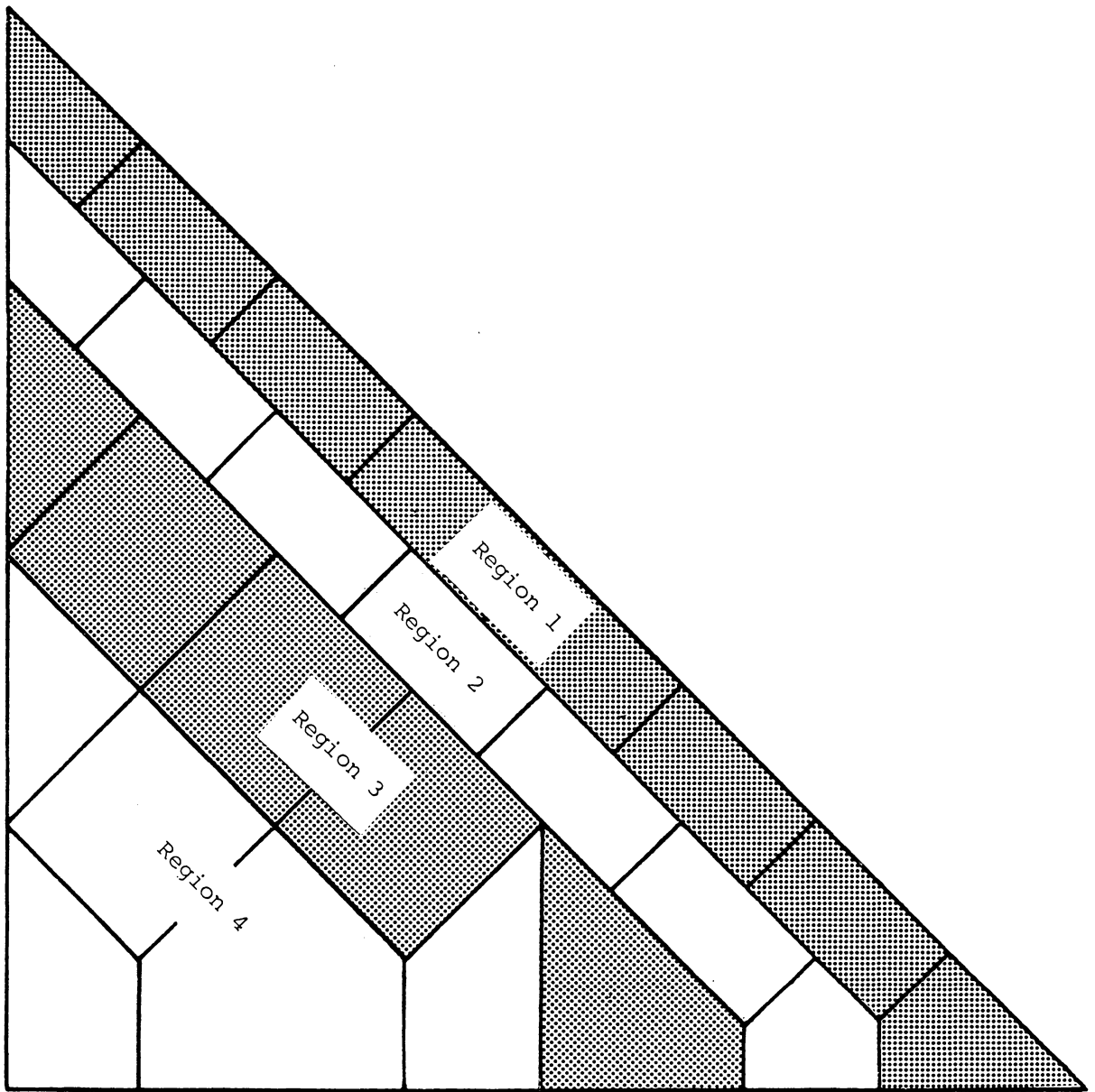


FIGURE 5. Schematic Profile of the Exposed Experimental Hardwood Whole Tree Chip Storage Pile Showing Regional Breakdown of Moisture Content During the Study Duration

the surface, contained zones 2, 8, 15, 19, 25, 30, and 34. Zones 3, 11, 14, 23, and 24 made up the next region 6.75 feet below the surface. The remainder of the zones, 4, 5, 6, 12, and 13, made up the innermost region 11.25 feet beneath the surface.

Figure 6 shows plotted points of average regional moisture contents as functions of storage time. The innermost region (11.25 feet below the surface) dried from 72.74 percent moisture content dry basis to 43.41 percent. During the same time all other regions picked up moisture with the outermost region (1.12 feet from surface) gaining the most. The 6.75 foot region increased from 64.36 to 72.76, the 2.25 foot region from 69.86 to 110.10 and the outermost region from 62.17 to 156.42.

The maximum moisture content a piece of wood can have is based upon the void spaces within the wood. Specific gravity is an indirect measure of these spaces. The wood in this study had an average specific gravity of .50 making the maximum moisture content possible 135 percent. It must be assumed, therefore, that for a moisture content of 152.42 percent to be reached as it was in the outermost regions of the pile, water must be held by cohesion and capillary action between the wood chips in the sample as well as within the chips themselves.

Spontaneous drying has been noted earlier in other

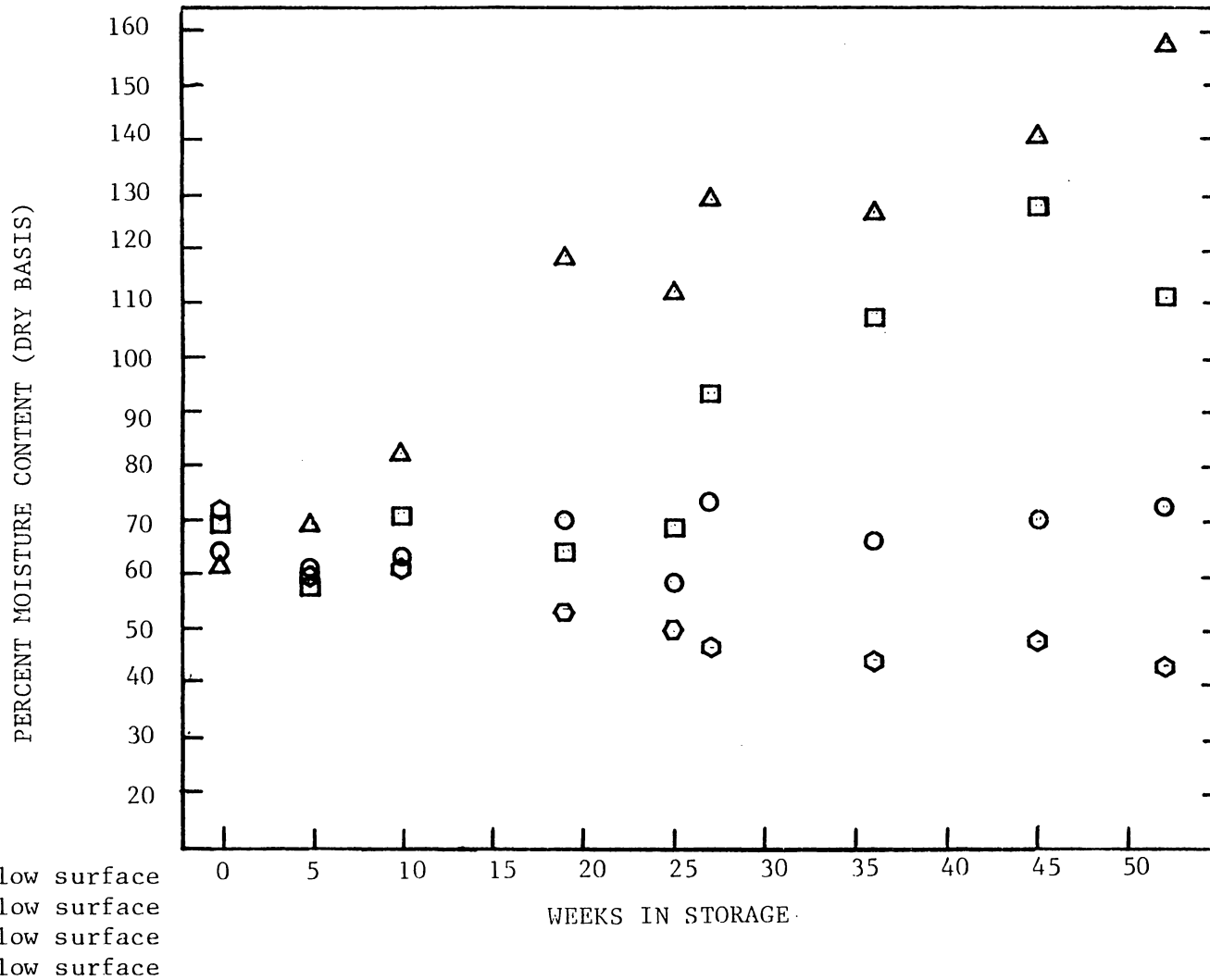


FIGURE 6. Plot of the Mean Regional Moisture Content of the Exposed Experimental Hardwood Whole Tree Chip Storage Pile as a Function of Storage Time

studies. The outer region increases in moisture content due to precipitation and some condensation from the inside of the pile. All these changes were expected and have been documented in other literature.

Moisture Content Within the Pile

Figure 7 shows that weighted average moisture content increased significantly with time, from a start of 67.04 percent dry basis to a final moisture content of 102.80 percent. A regression of the data yields this equation:

$$MC = (\text{weeks in storage} \times .82) + 63.0$$

This is an average increase of 3.6 percent per month, slightly higher than the 3.3 percent per month reported by Curtis (1980).

Fiber Loss

The pile was disassembled in December, 1981 to remove various testing devices and the nylon mesh bags used to determine the fiber loss. Unfortunately, because the pile was frozen it came apart in large chunks, ripping many bags and spilling their contents rendering them useless in this study.

Ash

Ash Content Gradients

One would expect that the outer regions of the pile having a greater moisture content, more evidence of decay, and greater exposure to the weather at the pile's surface would have a greater percentage of ash.

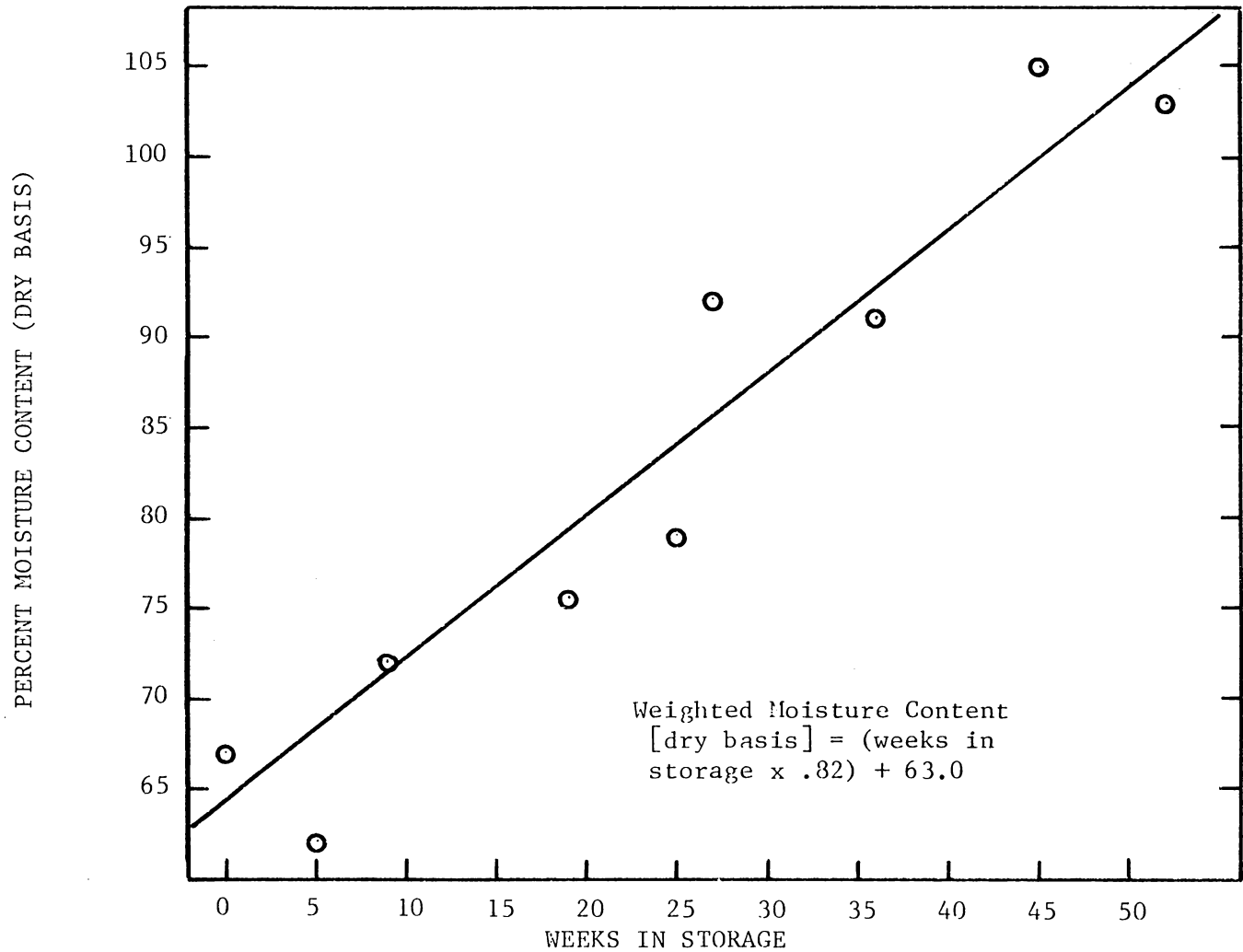


FIGURE 7. Plot of the Mean Weighted Moisture Content of the Exposed Experimental Hardwood Whole Tree Chip Storage Pile as a Function of Storage Time

Figure 8 diagrams the breakdown of the pile into these hypothetical regions of greater and lesser ash content based upon a Cluster analysis of the data. A Duncans multiple range analysis, however, failed to show a significant difference between the two regions.

Ash Content Within the Pile

Figures 9 and 10 are plots of weighted ash values as functions of time. The percent ash content of the wood agrees well with published values for ash in wood which are generally less than one percent. The percent ash content of the bark portion of the pile was nearly six times as great with values between 6.0 and 7.7 percent. This also agrees with literature. When weighted and combined the total ash content is between one and two percent. Both wood and bark samples increased in ash content over time.

This trend becomes more pronounced as shown in Table 5 when the ash content average of weeks 0, 5, 9 and 19 are combined. These four weeks constitute the weeks before a significant temperature rise was noted within the pile and while the pile was for the most part still frozen. The remainder of the sampling weeks followed the week of the maximum temperature and greatest microbial activity, week 23. It is this increased fungal activity that accounts for a trend of increasing ash content for both wood and bark. A regression of the data results in:

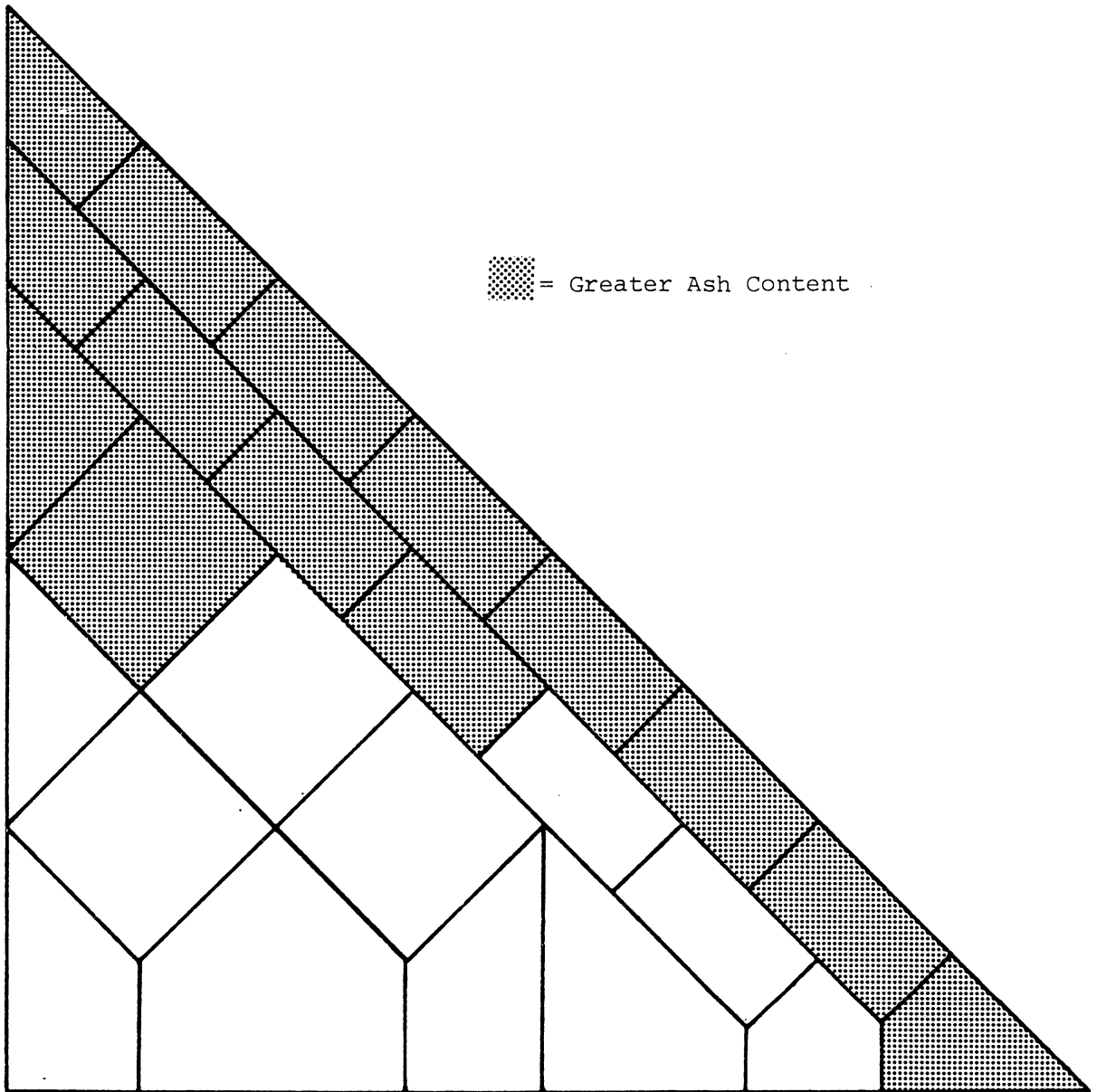


FIGURE 8. Schematic Profile of the Exposed Experimental Hardwood Whole Tree Chip Storage Pile Showing Outermost Region of Greater Ash Content

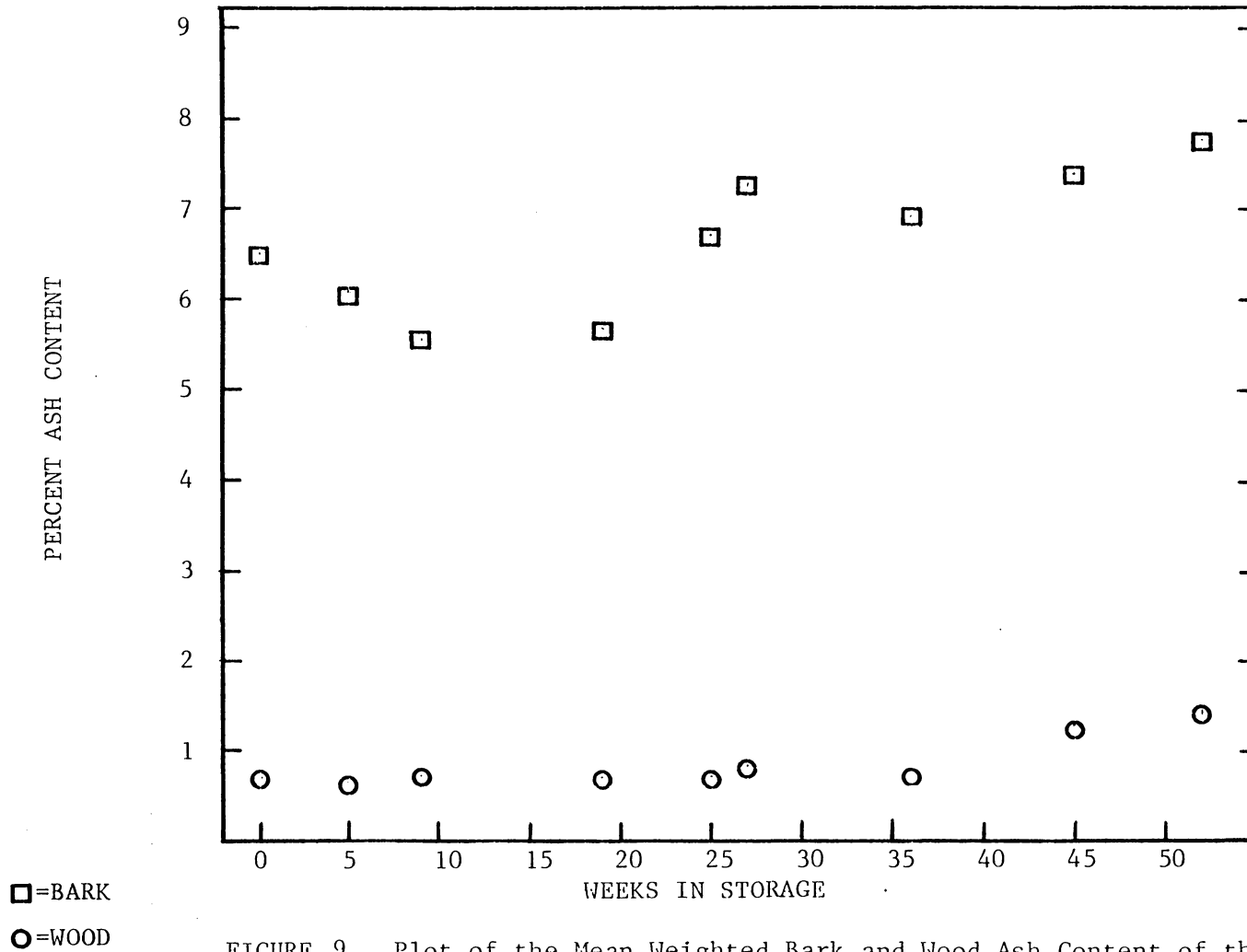


FIGURE 9. Plot of the Mean Weighted Bark and Wood Ash Content of the Exposed Experimental Hardwood Whole Tree Chip Storage Pile as a Function of Storage Time

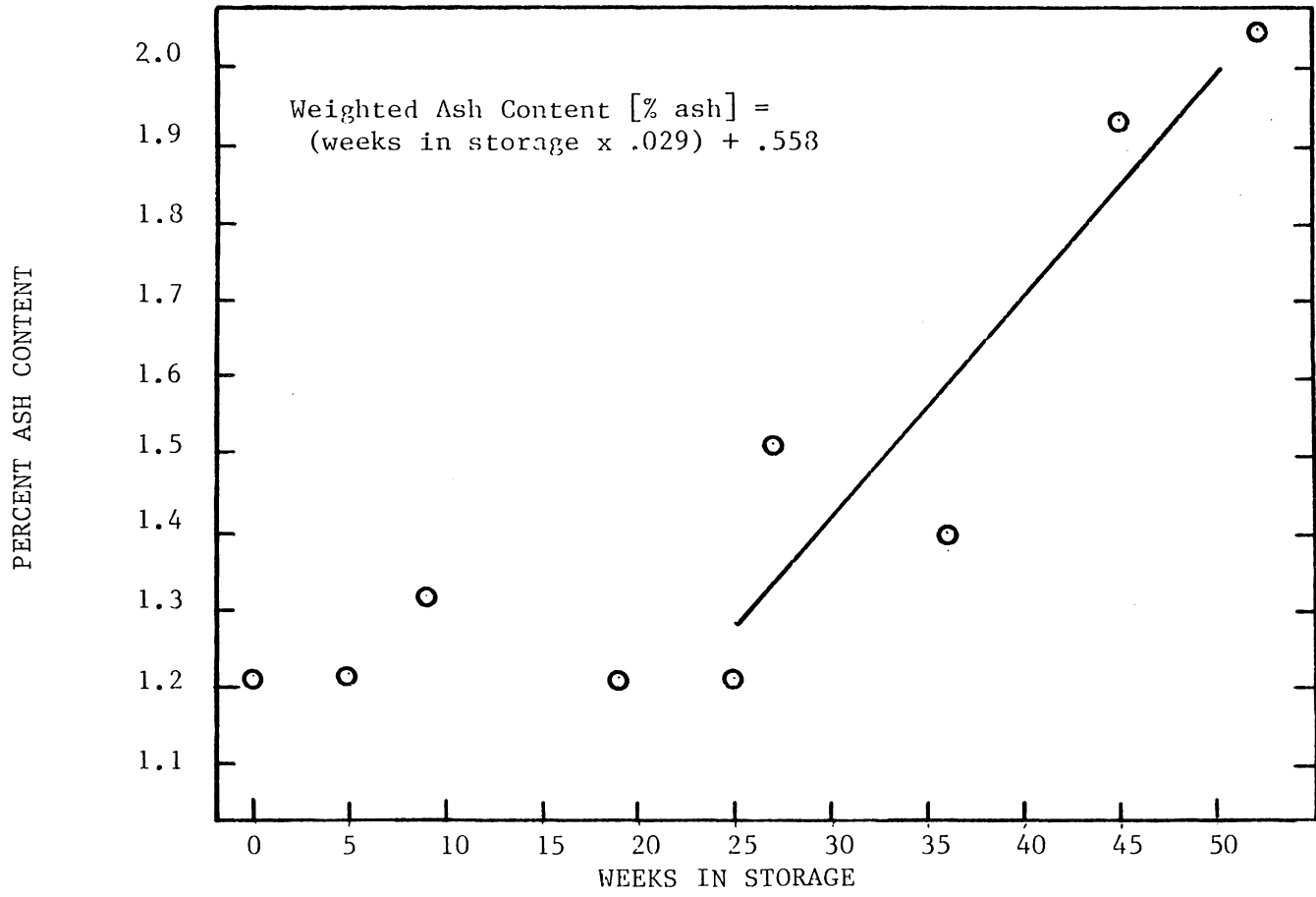


FIGURE 10. Plot of the Mean Weighted Ash Content of the Exposed Experimental Hardwood Whole Tree Chip Storage Pile as a Function of Storage Time

TABLE 5

Mean Weighted Percent Ash Content By Week

Week	Bark	Wood	Combined
0	6.88	.71	1.21
5	6.43	.65	1.22
9	6.08	.72	1.32
19	5.97	.72	1.21
0, 5, 9, 19, Mean			1.24
25	7.14	.69	1.21
27	7.72	.81	1.52
36	7.35	.77	1.40
45	7.90	1.29	1.94
52	8.31	1.35	2.07

TABLE 6

Unweighted Weekly Mean Percent Ash Content and Standard Deviation

Week	Inner Region	SD	Outer Region	SD	Total	SD
0	1.13	.13	1.28	.24	1.22	.21
5	1.11	.11	1.33	.24	1.23	.22
9	1.24	.11	1.51	.44	1.40	.36
19	1.08	.10	1.43	.27	1.28	.28
25	1.08	.10	1.41	.25	1.26	.26
27	1.45	.14	1.60	.22	1.53	.20
36	1.27	.14	1.46	.18	1.37	.18
45	1.56	.32	2.41	.68	2.02	.69
52	2.04	.79	2.20	.39	2.12	.60

$$\% \text{ Ash Content} = (\text{weeks in storage} \times .029) + .558$$

This is a monthly increase of ash content of 0.1 percent or nearly doubling the ash content from one to two percent over the span of a year. These figures correspond well with those of Curtis (1980). Table 6 lists the raw data means by week and their standard deviations. Decreases in ash content can be attributed to experimental error due to sampling. It is doubtful that degradation proceeds uniformly within chips of different size and species of hardwood; hence the ratio of decayed wood can be different from sample to sample. Throughout the study there was no layering of the pile into regions based on ash content.

Specific Gravity

Specific Gravity Gradients

As with ash content one would expect the outermost and uppermost regions of the pile to have a lower specific gravity primarily due to decay, increased moisture content and exposure to weather breaking down the wood substance. A Cluster analysis was used to break the pile into regions of higher and lower specific gravity. The hypothetical regions shown in Figure 11 are similar to those of ash but as with ash a Duncan's multiple range analysis failed to show the regions as being significantly different.

Specific Gravity Within the Pile

Figure 12 is a plot of weighted bark and wood specific gravities as functions of time. The specific gravity of weighted bark for the entire study ranged between .48 and .55. Weighted wood ranged from .47 to .52, slightly but not significantly lower than bark. In order to reveal any trends it was necessary to combine the average specific gravity of weeks 0, 5, 9 and 19. This grouping was chosen because it was felt that the frozen pile remained dormant during this period. Table 7 gives the specific gravity of weighted bark, weighted wood and combined weighted wood and bark. Figure 13 is a plot of combined weighted specific gravity as a function of time. The values started at 0.50 and fell after 26 weeks to 0.47. A

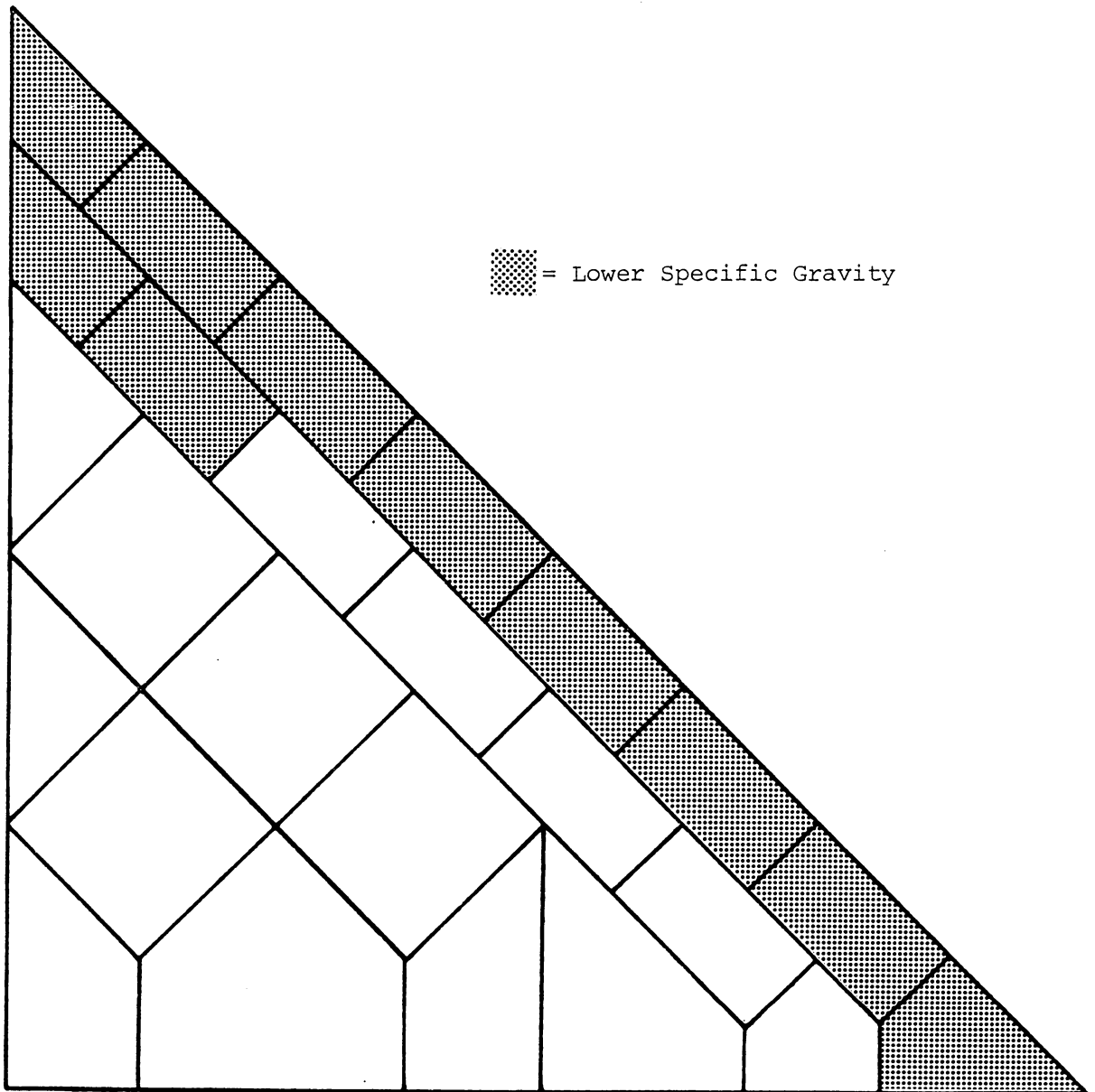


FIGURE 11. Schematic Profile of the Exposed Experimental Hardwood Whole Tree Chip Storage Pile Showing Outermost Region of Lower Specific Gravity

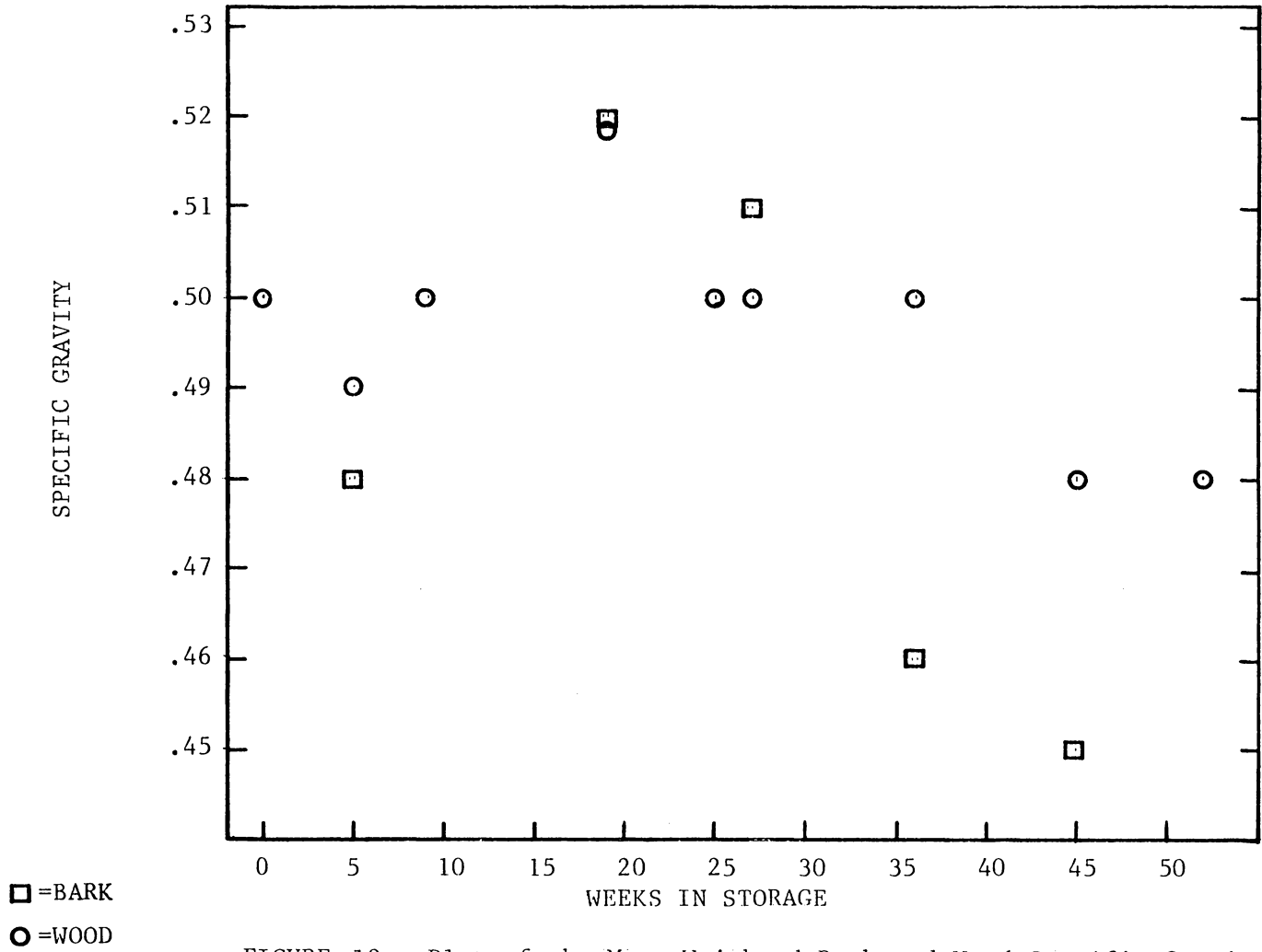


FIGURE 12. Plot of the Mean Weighted Bark and Wood Specific Gravity of the Exposed Experimental Hardwood Whole Tree Chip Storage Pile as a Function of Storage Time

TABLE 7

Mean Weighted Specific Gravity By Week

Week	Bark	Wood	Combined
0		.50	.50
5	.50	.49	.49
9		.50	.50
19	.55	.52	.52
0, 5, 9, 19, Mean			.50
25		.50	.50
27	.55	.50	.50
36	.49	.50	.50
45	.48	.48	.48
52		.47	.47

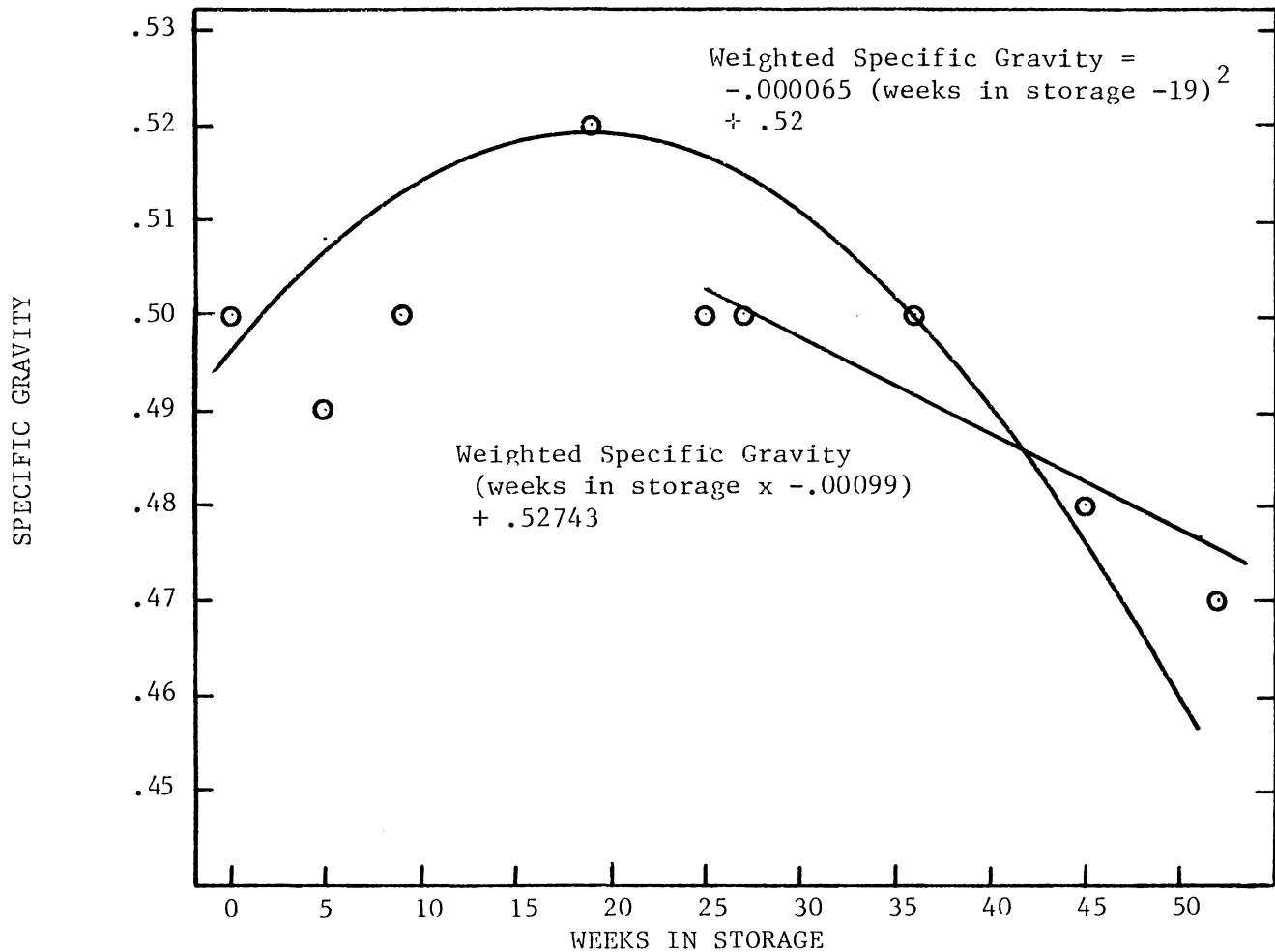


FIGURE 13. Plot of the Mean Weighted Specific Gravity of the Exposed Experimental Hardwood Whole Tree Chip Storage Pile as a Function of Storage Time

regression of the data revealed:

$$SG = (\text{weeks in storage } x - .00099) + .52743$$

This showed a decrease of .025 in 6 months indicating a wood substance loss of about 0.83 percent per month below the generally reported loss of 1 percent per month of storage noted in the literature. It must be noted that the change is only a trend.

A better fit of the data is achieved when it is fit to the parabola with the equation:

$$SG = -.00065 (\text{weeks in storage } - 19)^2 + .52$$

This would indicate two separate phenomena occurring over time, the first increasing specific gravity, the next causing it to decline.

It is possible that the cell walls of the wood chips collapse under the weight of the pile resulting in a smaller volume of the chip per weight of the chip. An increase in specific gravity would result. This was taking place while the pile was still frozen and dormant.

A decrease in specific gravity was noted after week nineteen corresponding with greater biological activity signaled by an increase of internal pile temperature. Biological breakdown and weathering would account for lower specific gravity for the last six months of the study.

Table 8 gives the raw data means and standard deviations for the specific gravity. The specific

TABLE 8

Unweighted Weekly Mean Specific Gravity and Standard Deviation

Week	Inner Region	SD	Outer Region	SD	Total	SD
0	.50	.03	.49	.04	.50	.04
5	.50	.03	.50	.03	.50	.03
9	.51	.03	.50	.03	.50	.03
19	.52	.05	.54	.05	.53	.05
25	.49	.03	.51	.02	.50	.03
27	.51	.04	.51	.04	.51	.04
36	.50	.03	.49	.03	.50	.03
45	.48	.03	.47	.03	.48	.03
52	.48	.05	.46	.05	.47	.05

gravity of different species of hardwood varies; this is coupled with natural variation of specific gravity within a species. Any single week's sampling will contain a varying ratio of different woods causing fluctuation in the total specific gravity. There was no layering of the pile into different regions apparent during the study period.

Higher Heating Value

Higher Heating Value Gradients

Due to exposure to weather decay and increased moisture content it is expected that there would be a lower value for the higher heating value towards the upper and outermost region of the pile very similar to regions established with ash content and specific gravity. The hypothetical regions shown in Figure 14 as established by a Cluster analysis bears this out. However, when subjected to a Duncans multiple range analysis the regions failed to be significantly different.

Higher Heating Value Within the Pile

Figure 15 shows a plot of the heating values of bark and wood in kilojoules per kilogram as functions of time. The only significant difference in the higher heating value noted was an average difference of about 1,074 kilojoules per kilogram between the bark and wood constituents of the pile with the wood value averaging 19,337 kilojoules per kilogram and the bark, 18,262

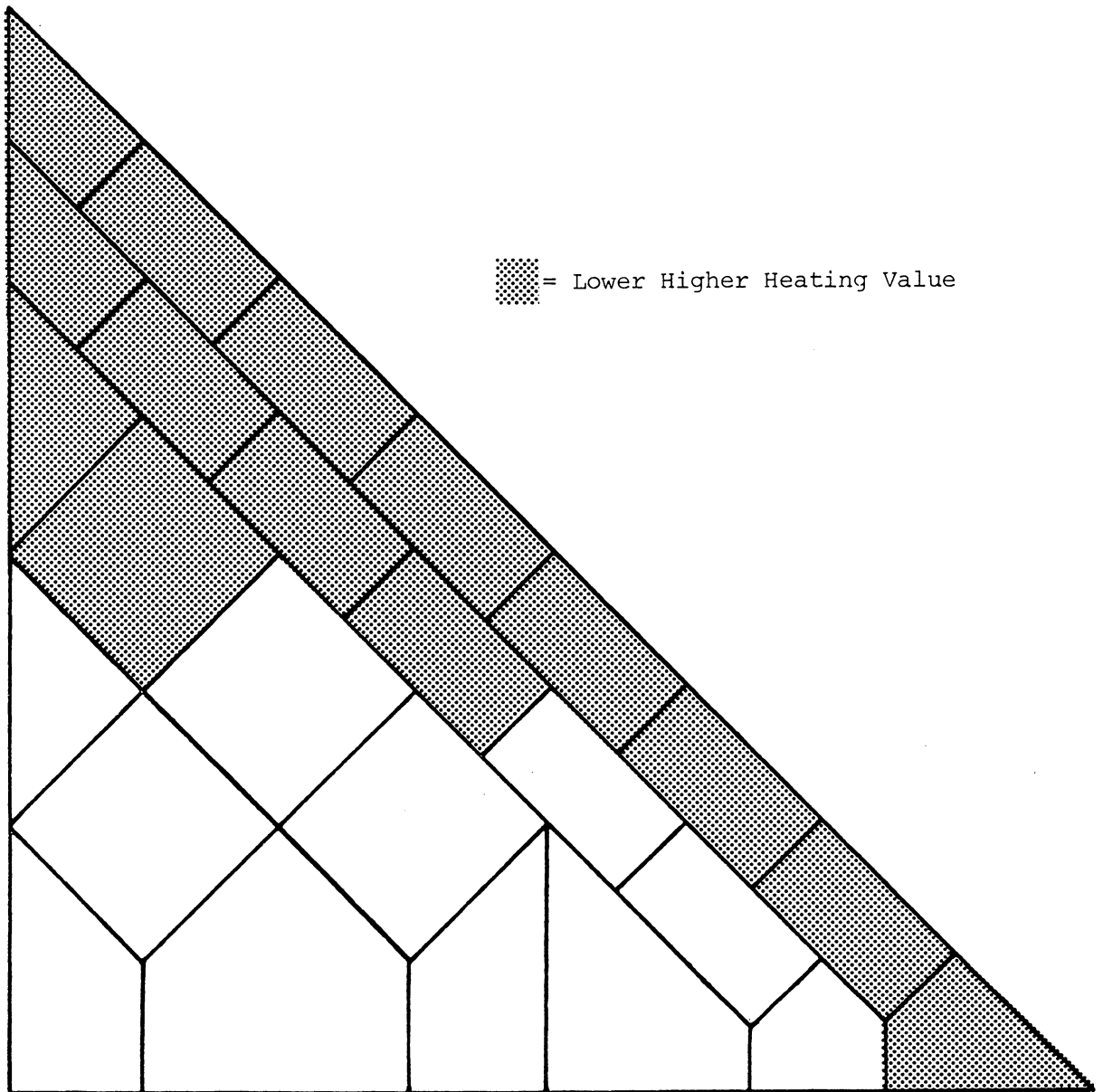


FIGURE 14. Schematic Profile of the Exposed Experimental Hardwood Whole Tree Chip Storage Pile Showing Outermost Region of Lower Higher Heating Value

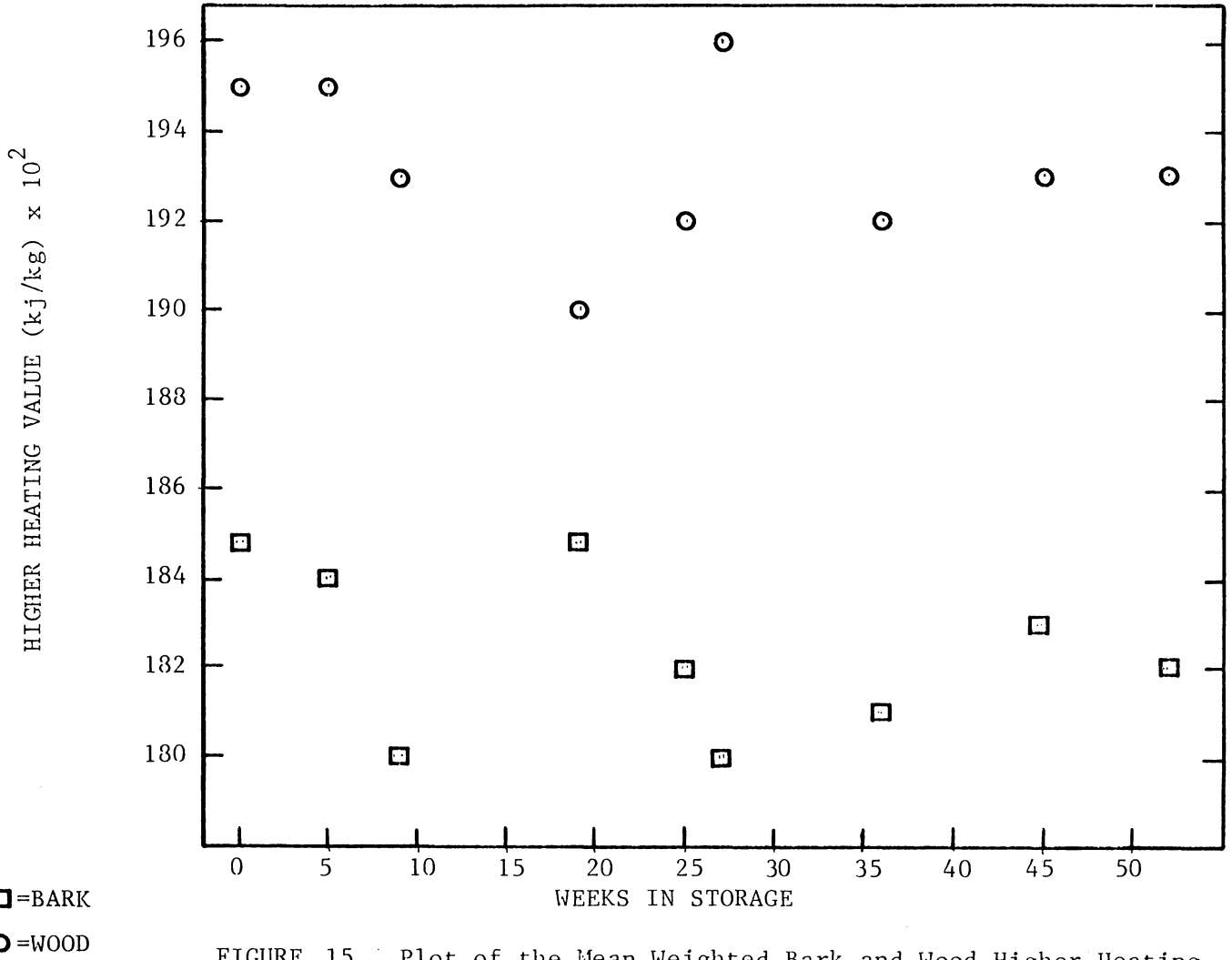


FIGURE 15. Plot of the Mean Weighted Bark and Wood Higher Heating Value of the Exposed Experimental Hardwood Whole Tree Chip Storage Pile as a Function of Storage Time

kilojoules per kilogram.

The higher heating value of the entire pile showed no noticeable trends. The regression for this data is:

$$\text{HHV} = (\text{weeks in storage} \times .25) + 1.9 \times 10^4$$

Table 9 gives the raw data means and standard deviation in kilojoules per kilogram as functions of time. The weighted value plotted and shown in Figure 16 is between 18,993 kilojoules per kilogram and 19,428 kilojoules per kilogram. Curtis (1980) found a decrease in higher heating value but said that it would be the result of varying amounts of bark, wood and foliage in his samples. White and DeLuca (1978), however, found an increase of higher heating value over time but did not work with whole tree chips and their storage time was only six months. The higher heating values found in this study, though showing no significant trend, agree in magnitude with higher heating values reported in the literature surveyed. Weekly fluctuations of higher heating value can be attributed to sampling error due to species mix. One species can have a greater higher heating value than others and if species mix is inconsistent sampling errors can occur. Kilojoules per kilograms can be converted to BTU's per pound using the chart and equations in Appendix B.

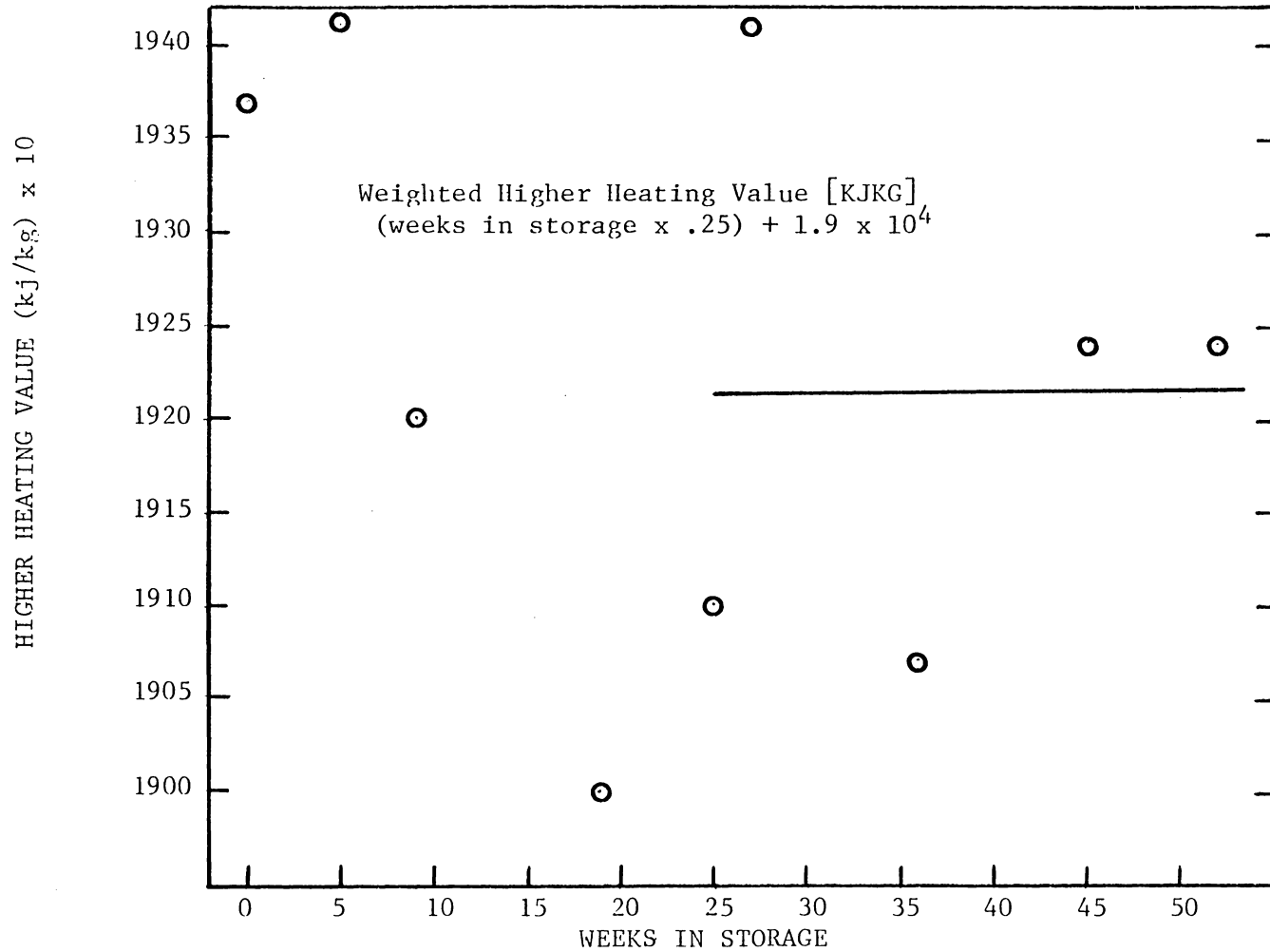


FIGURE 16. Plot of the Mean Weighted Higher Heating Value of the Exposed Experimental Hardwood Whole Tree Chip Storage Pile as a Function of Storage Time

TABLE 9

Unweighted Weekly Mean Higher Heating Value and Standard Deviation
(kj/kg x 10³)

Week	Inner Region	SD	Outer Region	SD	Total	SD
0	19.5	.70	19.2	.86	19.4	.80
5	19.5	.39	19.3	.32	19.4	.36
9	19.3	.37	19.0	1.17	19.1	.93
19	19.2	.53	19.0	.23	19.1	.40
25	19.4	.35	19.0	.34	19.2	.38
27	19.3	.42	19.3	.47	19.3	.45
36	19.2	.48	19.0	1.16	19.1	.91
45	19.4	.35	19.2	.28	19.3	.33
52	19.4	.39	19.2	.30	19.3	.35

pHpH Gradients

To see if the pH of water solubles followed the regions seen in the other variables due to exposure a Cluster analysis was performed on the data resulting in the hypothetical regional breakdown shown in Figure 17. A Duncans multiple range analysis failed to prove that the regions were significantly different.

pH Within the Pile

Figures 18 and 19, plots of weighted pH of water solubles as a function of time, indicate that there was a very slight trend for pH to decrease over time at a rate of -.006 per month. The regression for this trend is:

$$\text{pH} = (\text{weeks in storage} \times -.00152) + 4.20$$

The bark increased from a pH of 3.7 to one of 3.9 while wood increased from 3.8 to a pH of 4.0. The raw data and its standard deviations is given by week in Table 10. The findings of Curtis (1980) also reports a similar trend. However, White and DeLuca (1978) reported the inverse, a decrease in the pH of water solubles.

Weekly variation of pH could result from differing amounts of microbial activity and cell respiration. If future studies confirm the lack of any significant change in pH over time, pH can possibly be removed from consideration as an important parameter of outside

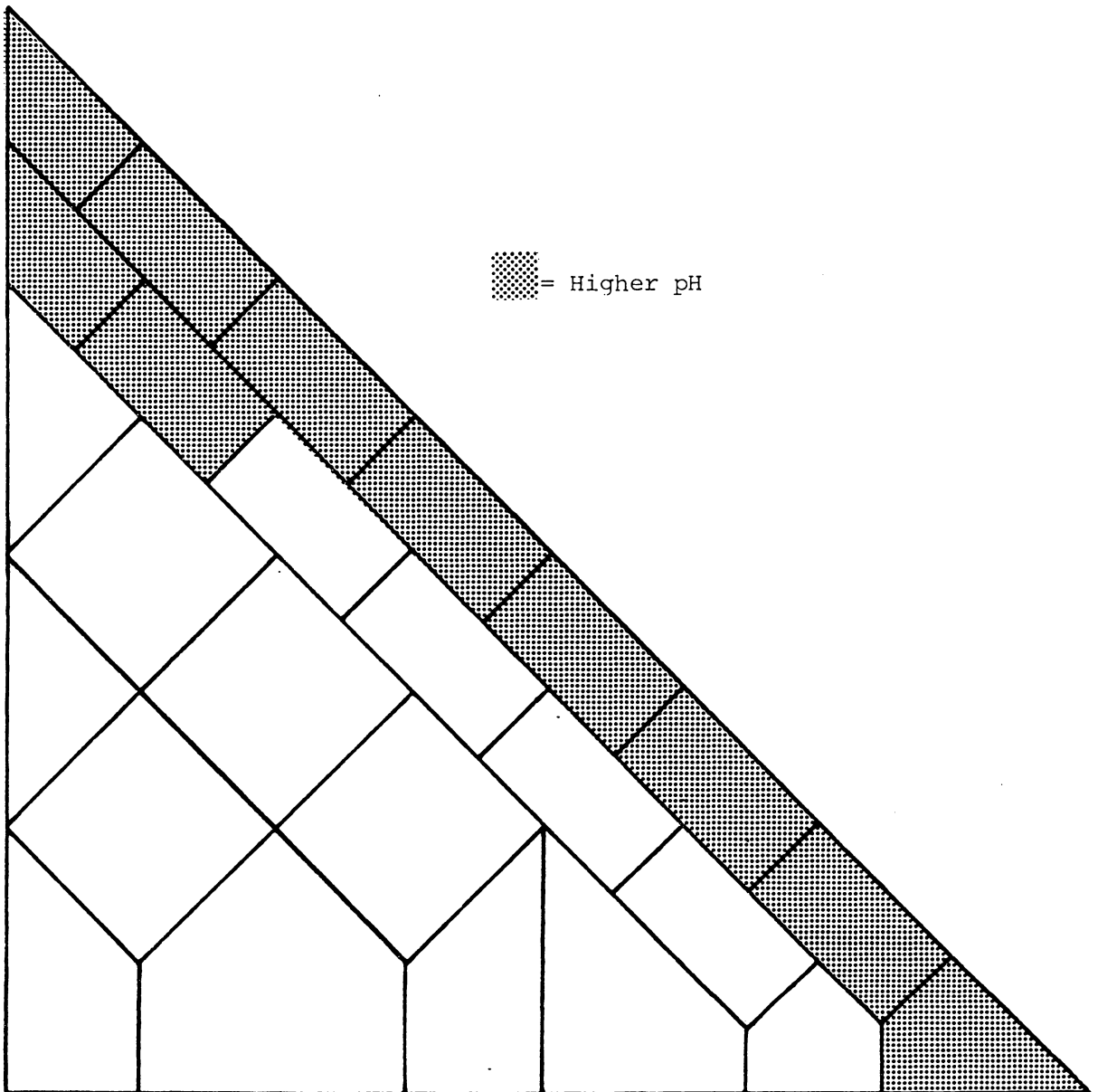


FIGURE 17. Schematic Profile of the Exposed Experimental Hardwood Whole Tree Chip Storage Pile Showing Outermost Region of Higher pH

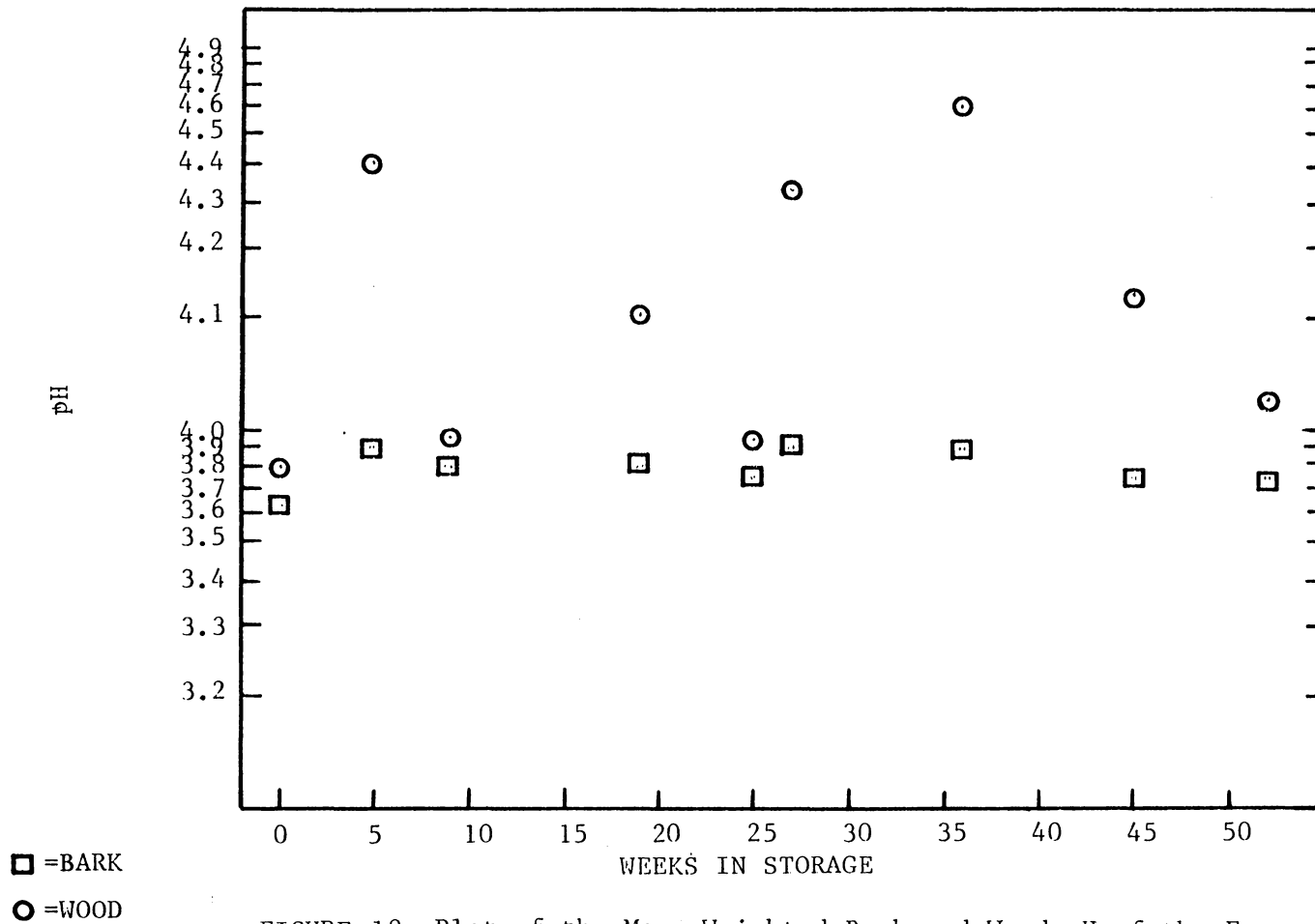


FIGURE 18. Plot of the Mean Weighted Bark and Wood pH of the Exposed Experimental Hardwood Whole Tree Chip Storage Pile as a Function of Storage Time

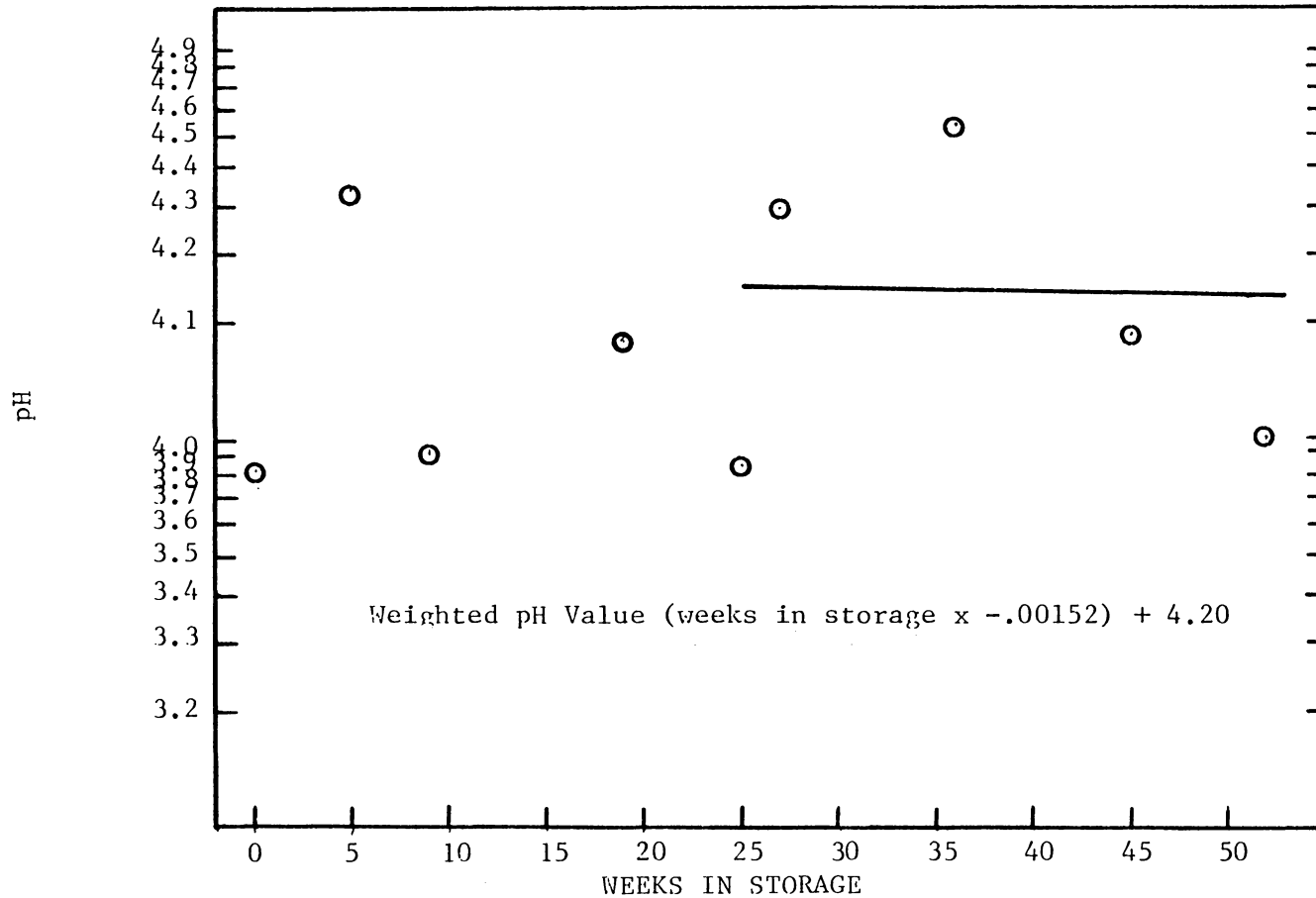


FIGURE 19. Plot of the Mean Weighted pH of the Exposed Experimental Hardwood Whole Tree Chip Storage Pile as a Function of Storage Time

TABLE 10

Unweighted Weekly Mean pH Value and Standard Deviation

Week	Inner Region	SD	Outer Region	SD	Total	SD
0	3.7	.14	3.8	.13	3.8	.14
5	4.2	.17	4.2	.17	4.2	.17
9	3.8	.13	4.0	.16	3.9	.17
19	4.0	.09	4.1	.15	4.0	.12
25	3.9	.13	4.0	.17	3.9	.16
27	4.2	.11	4.2	.11	4.2	.11
36	4.3	.24	4.4	.23	4.3	.24
45	4.0	.14	4.1	.13	4.0	.14
52	3.9	.10	4.0	.10	3.9	.11

storage.

Pile Weight

The load cell placed in the center of the pile at the base was used to determine the weight of the chips above it. Failure to accurately calibrate the load cell resulted in the data obtained from it being deemed inaccurate and hence unreliable for use in this study.

The Effects of Weather

Precipitation and temperature are the major means by which weather influences chip storage. During the study period, 35.64 inches of rain fell in the area of the storage site. Appendix C gives the monthly rainfall. The area of the base of the pile was 1,017 square feet. This means that in one year's time 188,507 pounds of water was added to the pile. The amount of dry material in the pile by the end of the study was estimated to be 90,574.9 pounds. The water would have been capable of raising the moisture content of the pile to 208 percent. However, due to evaporation and runoff, the pile's moisture content raised to only 94.37 percent.

Of the two factors, evaporation and runoff, evaporation seems to be the most significant. According to the U.S.D.A., during an average year around the test site 24.30 inches of water will evaporate. If it is assumed that evaporation takes place off the test pile as it does the testing

apparatus used to record area evaporation, then 68.1 percent of the rainfall on the pile would be lost due to evaporation. Raising the pile's total moisture content from its initial 63.2 percent to the final 94.3 percent would have required 14.6 percent of the rainfall upon the pile to be absorbed by it. The remaining 12.3 percent of the rainfall could be accounted for by runoff. The amount of runoff is probably due to the slope of the pile of about 45 degrees. This slope coupled with a possible shingle-like effect, shape, and orientation of the pile chips can possibly account for the runoff of rainwater and the small amount of rainwater percolation into the innermost regions of the pile. It is probable that the pile's moisture content would increase until the pile's outer surface is completely saturated at which time it would level off showing only a slight increase as water percolated into the pile raising the moisture content of the overall pile. The experimental pile was disassembled before this could be tested.

When the pile was built in December the ambient temperature was below freezing and, as a result, the chips were frozen when piled. The pile remained frozen for the first four months of the study. This prevented any biological activity which in turn caused the ash content, specific gravity and calorific value to remain constant.

Once the pile warmed it continued to heat up internally to temperatures above ambient but then cooled down and for the last six months of the study remained near ambient.

Bulk Density

Laboratory Simulation

Immediately after placing weight upon the chips a measurement was taken and used to determine the bulk density at the beginning of the study. Figure 20 is a plot of mean regional packing density as a function of time. All zones exhibited a significant increase in packing. Those with the greater weight increased most. Table 11 contains both the initial and final packing densities. The zones represented were averaged and used to determine values for all zones having the same height of chips above it. These layers are described by these equations:

$$\begin{array}{l} 1.12' \text{ below surface,} \\ PD = (\text{weeks in storage} \times .043) + 23.26 \end{array}$$

$$\begin{array}{l} 2.25' \text{ below surface,} \\ PD = (\text{weeks in storage} \times .055) + 24.64 \end{array}$$

$$\begin{array}{l} 6.75' \text{ below surface,} \\ PD = (\text{weeks in storage} \times .062) + 27.04 \end{array}$$

$$\begin{array}{l} 11.25' \text{ below surface,} \\ PD = (\text{weeks in storage} \times .067) + 27.54 \end{array}$$

The packing density of zone six was determined by extrapolation of these regressions.

These numbers were used along with zonal volumes to determine the weight of wood in each zone for

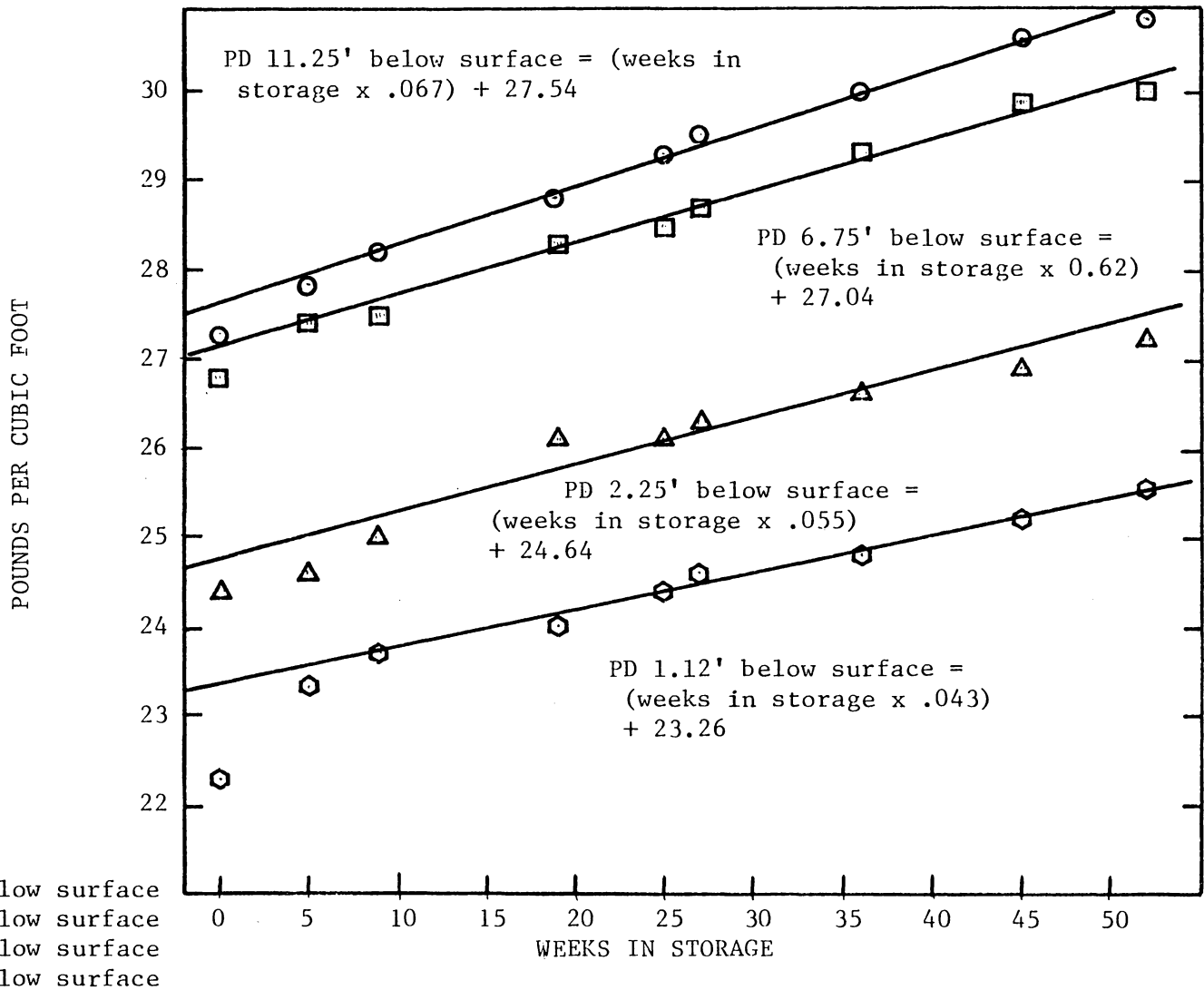


FIGURE 20. Plot of the Mean Regional Packing Density Based on Laboratory Measurements as a Function of Storage Time

TABLE 11
Initial and Final Mean Densities (pounds/ft³)*

Zones	Column Height	Initial	Final	Δ
1, <u>7</u> , 16, 20, <u>26</u> , 29, <u>33</u> , <u>37</u>	1.12	23.3	25.5	+2.2
<u>2</u> , 8, <u>15</u> , 19, 25, 30, 34	3.37	24.4	27.2	+2.8
3, 4, <u>11</u> , 14, <u>23</u> , 24	6.75	26.8	30.8	+4.0
<u>5</u> , <u>12</u> , 13	11.25	27.4	32.7	+5.3
6	15.75	29.7	35.0	+5.3

* Underlined zones are measured zones.

determining net heating value (NHV) at the experimental wood chip pile.

Looking at Figure 20 it seems evident that packing density is a function of time as well as weight studies using only weight to determine packing density as DeMiller (1980) can have an error of as much as nine percent over a period of a year. Figure 20 also seems to indicate that there is an upper limit to the amount of weight that will cause a change in packing density. A weight of 68.4 pounds caused an increase in packing density of 2.9 pounds per cubic foot and a weight of 137 pounds caused 4.1 pounds per cubic foot, a weight of 228 pounds only caused a change of 5.4 pounds per cubic foot. This phenomenon needs to be pursued further with more data to substantiate any real trends.

In Situ Bulk Density Determinations

Movable aluminum chips were placed within the pile and monitored for the studies' duration. As with the box study loose packed chip density was determined to be 20.3 pounds per cubic foot. When the pile was finished being built the horizontal distance each chip moved was measured.

Because the chips were stacked one above another it was necessary to subtract from the movement of each chip the combined movement of the chips below it. It was assumed that the movement of any chip was the result of its own movement and that of the chip or

chips below it. However, when these connections were applied to the data some zones exhibited a decrease in bulk density. Figure 21, a schematic profile of the pile showing initial and final calculated bulk densities for in situ packing, shows this and also shows that there was no change either positive or negative greater than one pound per cubic foot. Negative packing densities and changes of less than one pound have not previously been reported in literature. This unique occurrence may in part be due to experimental error due to the aluminum chips' inability to move freely as do the wood chips in the pile because of mechanical restrictions.

There are, however, other explanations which are worth noting. One phenomena is known as arching or bridging. Particles orient themselves in such a manner as to form an arch capable of supporting itself. In a structure of cone shape such as a chip pile the arch would form a dome. If indeed this does occur it is possible to have chips beneath a dome relieved of pressure from the chips above it, therefore, become less packed and possibly decrease in packing density. This effect would become more pronounced if the chips, being of irregular shape and size, would orient themselves in such a manner as to become interlocked. This is not unlikely considering that a chip will continue to move until they meet some resistance. A

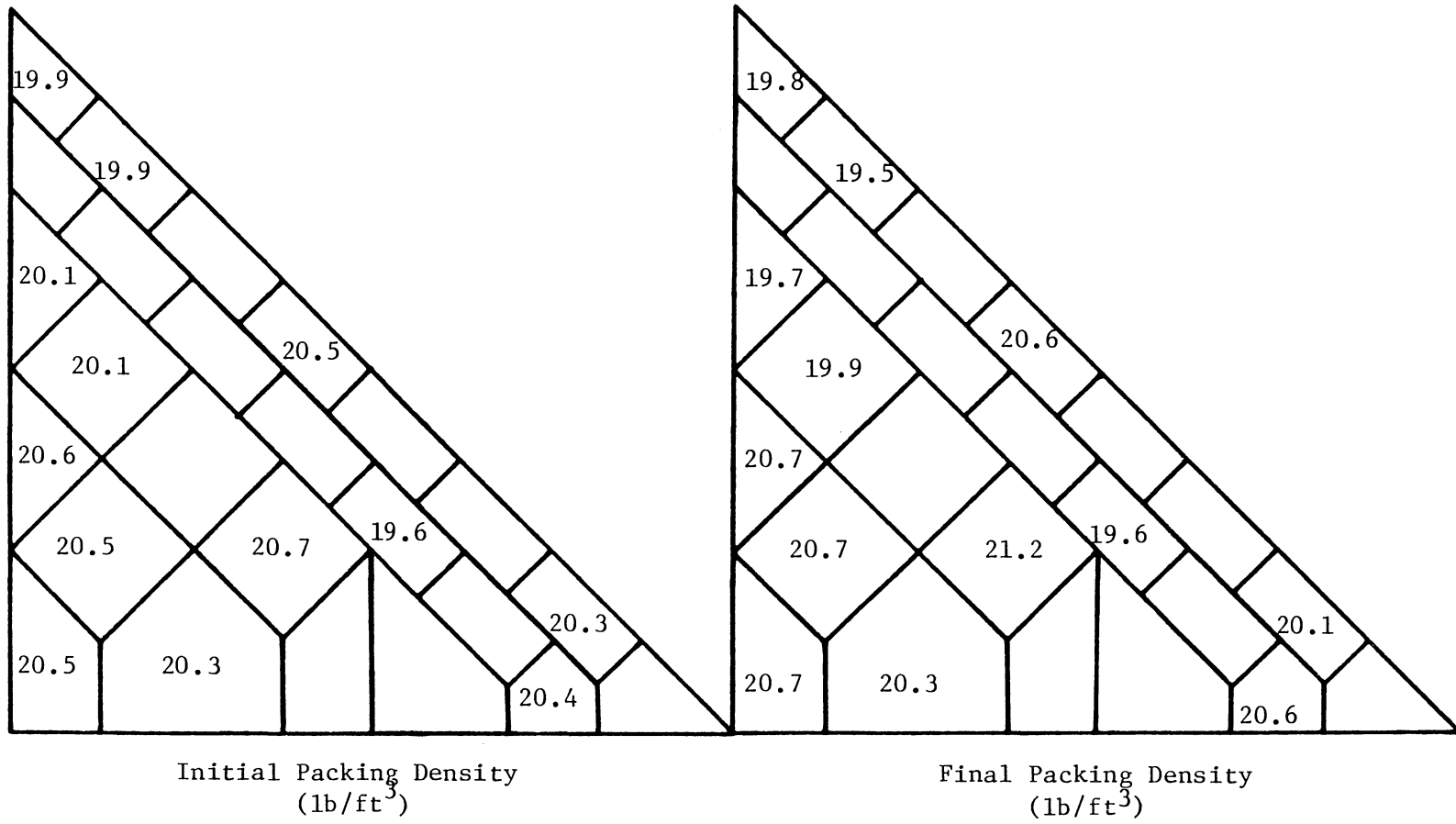


FIGURE 21. Schematic Profile of the Exposed Experimental Hardwood Whole Tree Chip Storage Pile Showing Initial and Final Packing Densities Based on In Situ Measurements

chip on the surface needs only a small resistance to stop its downward movement due to gravity whereas a chip within the pile has pressure being applied to it from chips above and around it and, therefore, it needs greater resistance to stop it enhancing the possibility of it interlocking and arching. The surface chips are wetter and may, therefore, adhere to one another. This might solidify any domes within the pile and, once solid, no further packing can occur giving only a slight increase in bulk density in some areas and possibly a reduced bulk density in zones under domes.

Figure 22 shows a schematic profile of the pile indicating the net changes in in situ bulk density by zone. Based on the arching theory it is improbable that there is a decrease in packing density in zones near the surface because an arch cannot form above them. An arch can, however, form beneath them and account for the lessened packing density in zones lower in the pile. If this arch did indeed form then the aluminum chip movement beneath this arch should not be subtracted from any chips lying above it; the arch, in fact, forming a new base for calculation. This being the case, a negative bulk density on the surface could be a result of the mathematical model used to compute it and not a true reflection of in situ packing. Due to the impossibility of distinguishing experimental error from mathematical error and the lack of

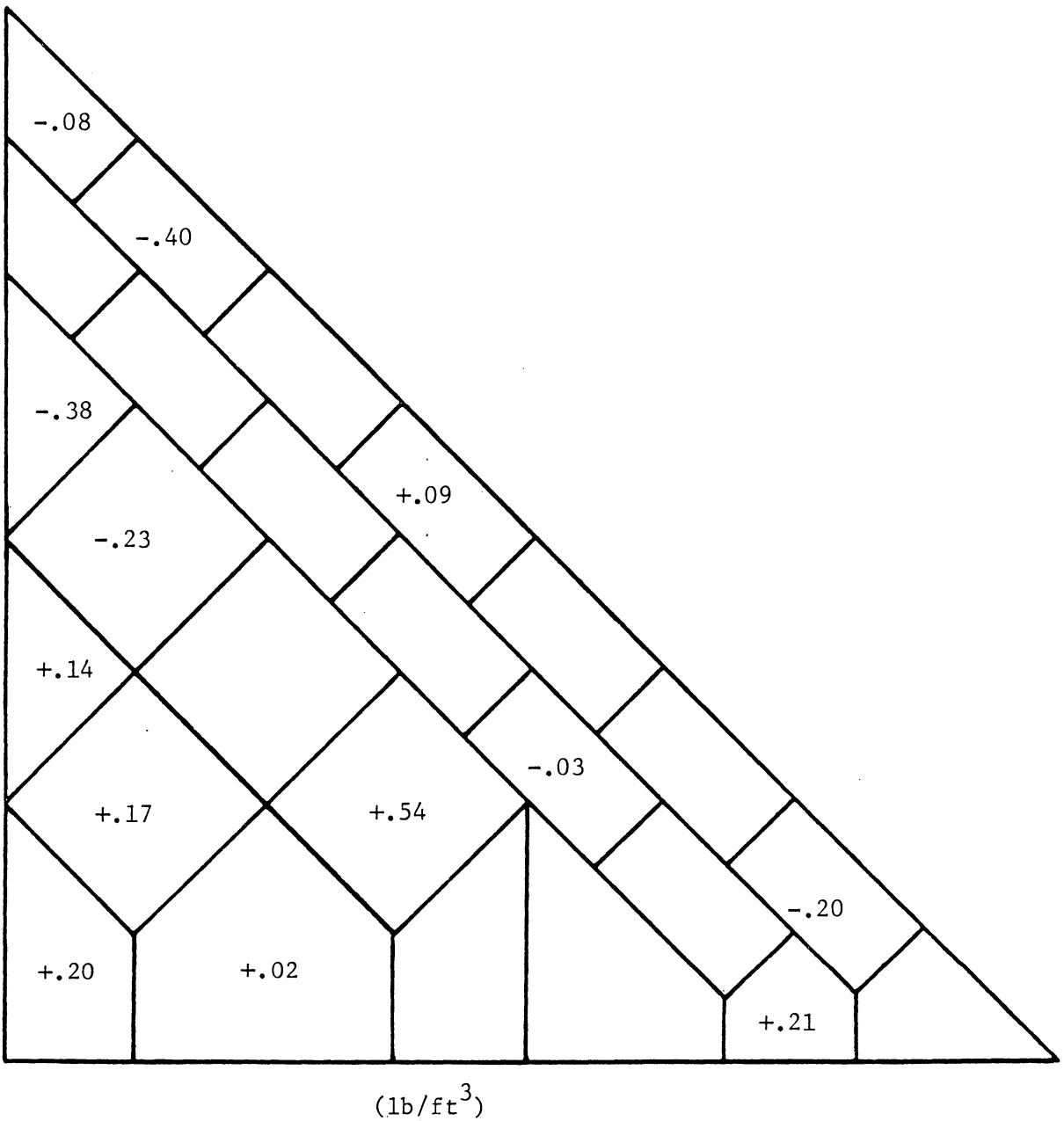


FIGURE 22. Schematic Profile of the Exposed Experimental Hardwood Whole Tree Chip Storage Pile Showing Net Changes of Packing Densities Based on In Situ Measurements

substantiating published literature on in situ packing densities whenever a measurement of packing density is needed in this study the laboratory simulation of packing density will be used.

Estimation of Available Energy

Net Heating Value

Net heating value is the BTU's available per pound of wet material taking into account boiler efficiency and latent heat of evaporation. Net Heating Value (NHV) was calculated using a formula published by Levi and O'Grady (1980).

$$\text{NHV} = \text{HHV} (1 - \text{MC}/100) - \text{LH}_2\text{O} \times \text{MC}/100$$

where:

HHV = Higher heating value, calorific value in BTU/lb
 MC = Moisture content on a wet basis
 LH₂O = Heat to vaporize and superheat one pound of water. In this case 1,200 BTU/lb superheated steam, 400 degrees F at 1 atmosphere pressure.

Total Net Heating Value

Total net heating value is the combined energy of all the material in the pile given in kilojoules.

TNHV = NHV x pound of wood and water in each zone converted to kilojoules by multiplying by 1.0543.

Figure 23 is a plot of Total Net Heating Value (TNHV) as a function of time. TNHV remained constant during the first five months of the study. This corresponds with the time when the pile was frozen and dormant. This dormant state was followed by a drop in

TNHV lasting nearly five months. After about ten months the TNHV seemed to level off remaining relatively constant until the end of the study. It was found that over a year the TNHV of the entire pile dropped from 7.29×10^8 kilojoules to 6.72×10^8 kilojoules. The regression of this data is:

$$\text{TNHV} = (\text{weeks in storage} \times -1.27 \times 10^6) + 7.32 \times 10^8$$

Nearly 70 percent of the loss of TNHV occurred during the middle five months of the study. The regression of the data shows the loss to be $.055 \times 10^8$ kilojoules per month or $.66 \times 10^8$ per year. (For conversions from kj to BTU's see Appendix B). This is a 13.0 percent loss in one year. During this same time the wet basis moisture content increased thirty-four percent, and the higher heating value decreased .74 percent. These numbers indicate that 88.5 percent of the loss in TNHV is due to moisture content increase. A lower higher heating value accounted for 11.5 percent loss in TNHV.

Economic Impact

This loss in TNHV will be reflected by higher fuel cost for anyone storing wood fuel outside unprotected. If one discounts the inactive period of this study eighteen percent more fuel would have to be purchased if it is to be stored for more than five months. If the initial cost for the fuel is \$10 per green ton then effectively the cost per ton will be \$11.30 when

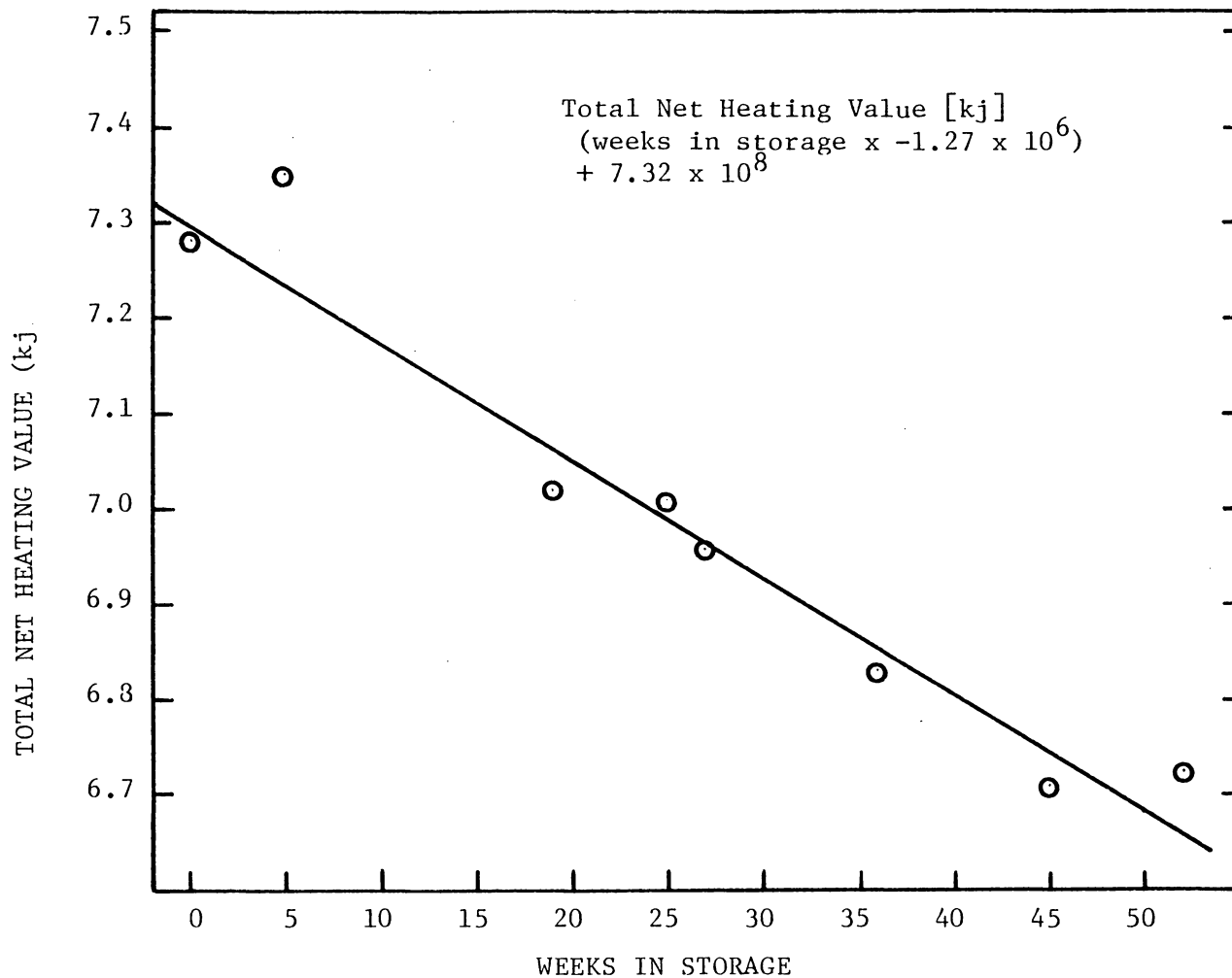


FIGURE 23. Plot of the Total Net Heating Value of the Exposed Experimental Hardwood Whole Tree Chip Storage Pile as a Function of Storage Time

accounting for losses over time. However, once this initial cost is computed it will remain constant for times greater than five months. This cost drops dramatically if the pile is not allowed to pick up moisture and losses over the year are kept to the 2.0 percent due to loss of higher heating value and fiber loss.

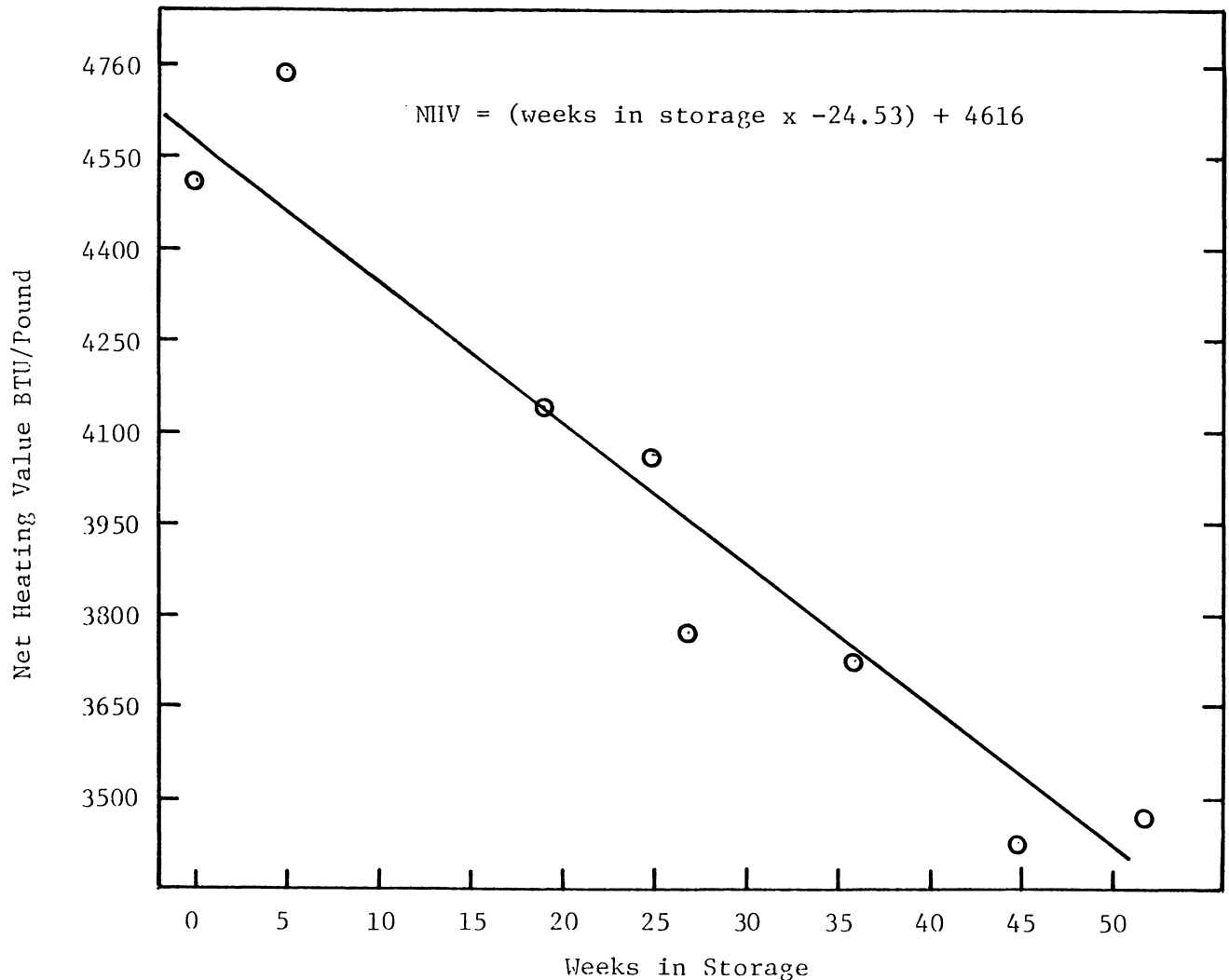


Figure 24. Plot of the Net Heating Value of the Exposed Experimental Hardwood Whole Tree Chip Storage Pile as a Function of Storage Time.

SUMMARY

1. Decay: The outer layers of the pile were the areas primarily affected by decay.

2. Temperature: Temperatures were higher in zones located near the center of the pile where temperatures reached 82 degrees C. The pile remained frozen for the first eleven weeks of the study thawing out by early March.

3. Moisture Content: After six months, 4 layers of significantly different moisture content developed. From an initial moisture content of 68 percent the outermost layer, up to 2.25 feet below the surface, increased in one year to 156.42 percent while the innermost layer dried to 43.41 percent. The weighted mean moisture content increased from 67.04 percent to 102.80 percent and is described by this equation:
$$MC = (\text{weeks in storage} \times .82) + 63.0.$$
This is significant.

4. Fiber Loss: Net bags placed in the pile were

unfortunately rendered useless during disassembly of the pile.

5. Ash Content: Ash content for wood was generally under one percent while bark was six to ten times as great. Weighted ash content showed an increase from 1.21 to 2.07 percent and is described by this equation:

$$\% \text{ Ash Content} = (\text{weeks in storage} \times .029) + .558$$

The change is not statistically significant nor were significant gradients found within the pile.

6. Specific Gravity: Specific gravity for wood was slightly but not significantly lower than for bark, both around .50. Weighted specific gravity decreased from .50 to .47 and is described by this equation:

$$\text{SG} = (\text{weeks in storage} \times -.00099) + .52743$$

The change is not statistically significant nor were any significant gradients found within the pile. The equation:

$$\text{SG} = -.00065 (\text{weeks in storage} - 19)^2 + .52$$

provides a better fit to the data and can be explained by cell wall collapse resulting in increased specific gravity while the pile was frozen. biological breakdown of the wood after

the pile was thawed would account for decreased specific gravity until the end of the study.

7. Higher Heating Value (HHV): The mean HHV of 19,337 kj/kg for wood was significantly higher than the HHV at 18,262 kj/kg for bark. The weighted HHV exhibited no noticeable trends and has an equation of:

$$\text{HHV} = (\text{weeks in storage} \times .25) + 1.9 \times 10^4$$

No significant gradients were found within the pile.

8. pH: There was no significant difference between the pH of wood and the pH of bark. The weighted pH is described by this equation:

$$\text{pH} = (\text{weeks in storage} \times -.00152) + 4.20$$

rose from pH 3.8 to pH 4.0 but it was not a significant decrease. No significant pH gradients developed within the pile.

9. Weather: 35.64 inches of rain fell in the area of the storage site during the year. During the year an average of 24.30 inches of water will evaporate in the area of the storage site.

10. Bulk Density: Packing density based on laboratory experiments significantly increased over time for all layers within the pile. The regression for each layer is given below:

$$\begin{array}{l} 1.12' \text{ below surface,} \\ PD = (\text{weeks in storage} \times .043) + 23.26 \end{array}$$

$$\begin{array}{l} 2.25' \text{ below surface,} \\ PD = (\text{weeks in storage} \times .055) + 24.64 \end{array}$$

$$\begin{array}{l} 6.75' \text{ below surface,} \\ PD = (\text{weeks in storage} \times .067) + 27.04 \end{array}$$

$$\begin{array}{l} 11.25' \text{ below surface,} \\ PD = (\text{weeks in storage} \times .710) + 27.54 \end{array}$$

In situ measurements were complicated and may be due in part to experimental error and arching. Laboratory results were used to determine the TNHV.

11. Total Net Heating Value (TNHV):

It was found that over a year the TNHV of the entire pile dropped from 7.29×10^8 kilojoules to 6.72×10^8 kilojoules. This loss is significant and described by the equation:

$$\begin{array}{l} TNHV = (\text{weeks in storage} \times -1.27 \times 10^6) \\ \quad + 7.32 \times 10^8 \end{array}$$

This loss is 8.0 percent in one year or 1.14 percent per month, 88.5 percent of this loss can be attributed to increased moisture content with lower HHV accounting for 11.5 percent.

CONCLUSIONS

1. The assumption that compaction is a uniform function of the distance from the surface of the pile may not be valid in piles constructed with overhead gravity feed mechanisms. Evidence also indicates that packing is time dependent and not static as is normally assumed. Arching appears to cause areas of high and low packing within these piles. Such fluctuations may prevent accurate assessment of true packing density gradients and assessments of wood chip inventories.
2. Percent ash content was used in this study as a measure of material loss. Although the percent ash of between one and two percent in this study agrees well with literature the monthly increase of 0.1 percent ash content does not correspond well with previous studies monitoring material loss. Literature generally records a material loss of between 1 percent and 2 percent per month. This would seem to indicate that ash content is not sensitive enough to be recommended as a measure of material loss and was not used in

this study.

3. Previous studies indicate that moisture content gradients will form within a storage pile. These gradients were seen in saturated outer layers five feet thick. In this study the experimental pile developed relatively steeper gradients closer to the pile's surface. The outermost layer, confined to a depth of 2.25 feet, became completely saturated and had a final moisture content of 156.42 percent. A second layer, between 2.25 and 4.5 feet increased to a 110.10 percent moisture content. A stable layer where the moisture content only increased from 64.26 to 72.76 percent was found between 4.5 and 9 feet. The innermost layer from 9 feet to pile center exhibited the spontaneous drying found in literature. Moisture content in this layer decreased from 72.76 percent moisture content to 43.41 percent after a year's time. Steeper gradients in this pile compared to those of literature could be due to differences in rainfall, a heavier rainfall being responsible for creating a thicker outermost saturated layer.

4. The relationship between available energy and time in a previous study (Curtis, 1980) was an inverse time function showing a 23 percent decrease in total available energy over a one year period. This current study also recorded a 23 percent loss in heating value per unit of material, though the loss was more linear over time. This high energy loss can be misleading. Previous studies took into account the loss of available energy due to increased moisture content while ignoring the increased mass caused by increased water within the pile. This would yield low energy per pound of material without accounting for a net increase in poundage of material in the total pile. This study took into account all the material in the pile, both wood and water, when evaluating changes in total net available energy. This yielded a one year loss of 13.7 percent of the total pile's available energy.

Figure 24 shows a straight line regression and plot of net heating value. To better compare this to the inverse time function noted by Curtis it might prove beneficial to eliminate the data before week 25 when the pile was frozen. This would better reflect the summer period of storage

time experienced during Curtis' study. When this is done it is possible to fit an inverse time regression to the data.

RECOMMENDATIONS

Recommended Storage Procedures

Please note that these recommendations are based on a storage time of only one year of hardwood whole tree chips and that other materials may behave differently.

Pile Size and Shape

Because of the surface area to volume ratio and the fact that spontaneous drying occurs within a conical pile and moisture is accumulated on the surface it seems reasonable to build a pile cone shaped as large as possible keeping in mind the increased danger of increased temperatures within larger piles. This study and literature seem to indicate a pile height of twenty feet with sides sloping 45 degrees to increase runoff of rainfall.

Seasonal Considerations

It appears that if chips are piled frozen they will remain that way for a short while even though ambient temperature is above freezing. This delays degradation of the fuel material. Therefore, constructing a storage pile in winter might be best.

Piling Method

Gravity flow is recommended for the building of piles to eliminate packing by dozers and stratification of fines by pneumatic systems.

Standby Storage

The results of this study indicate that most changes in the pile occur rapidly during a short five month period and level off thereafter. It follows that to minimize fuel losses fresh green fuels should be used as soon as possible after their arrival at the plant and an inventory should be maintained on a standby storage system.

Recommendations for Future Research

In Situ Measurements

1. A measurement technique is needed to accurately determine the packing density within a pile. This would benefit management of pile inventory and weight.
2. A method for recording wood substance losses not dependent upon the disassembly of an entire pile to obtain preweighted bagged samples.

Drying of Wood Fuels

Drying wood fuels and keeping it dry is the most important way to minimize energy losses during storage. One can either dry the material artificially or find a way to maximize spontaneous drying. Once dry an economical way is needed to be found to keep the pile dry by covering it or coating it in some manner keeping in mind the need for air flow in the pile.

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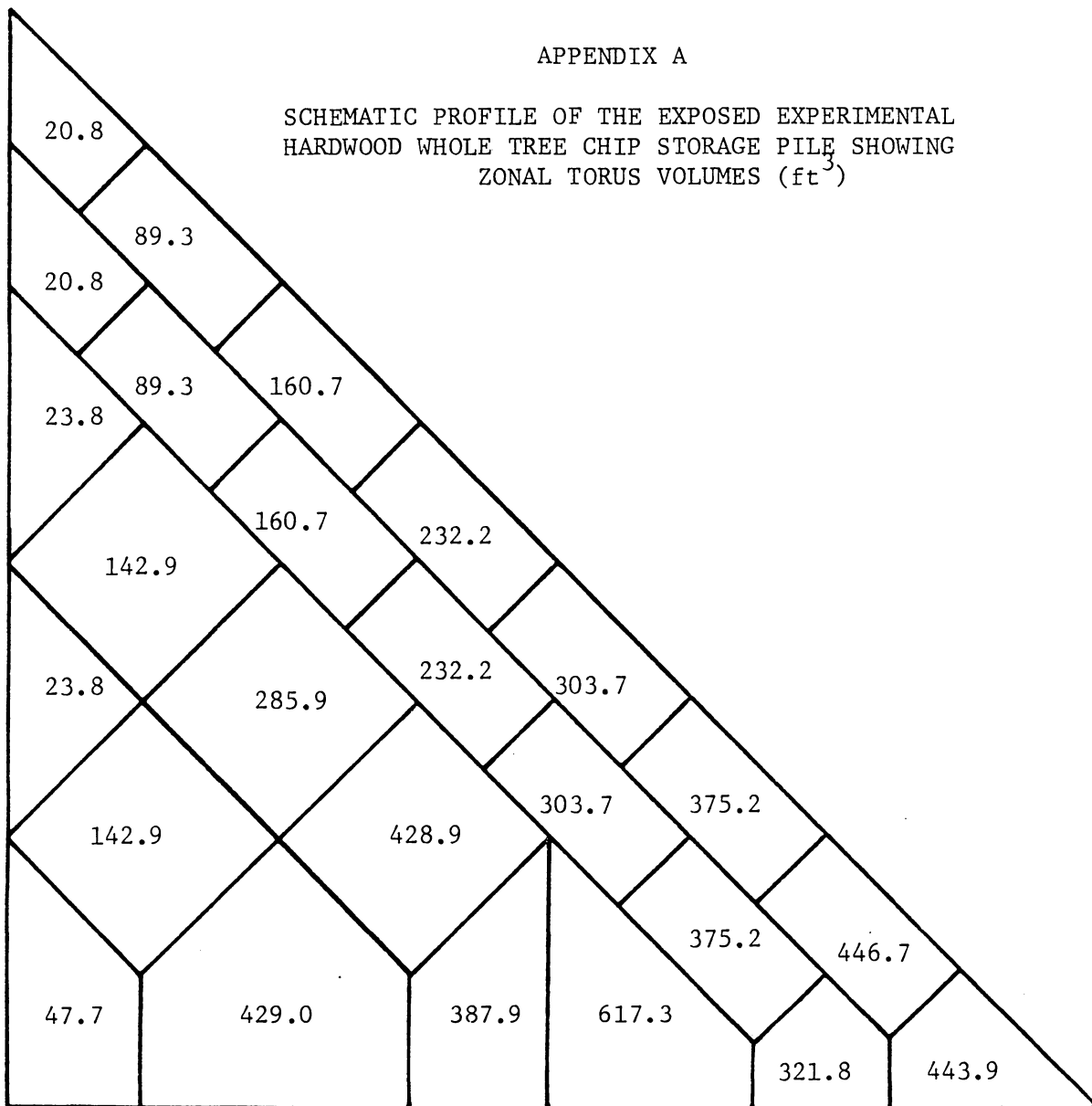
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APPENDIX A

SCHEMATIC PROFILE OF THE EXPOSED EXPERIMENTAL
 HARDWOOD WHOLE TREE CHIP STORAGE PILE SHOWING
 ZONAL TORUS VOLUMES (ft³)

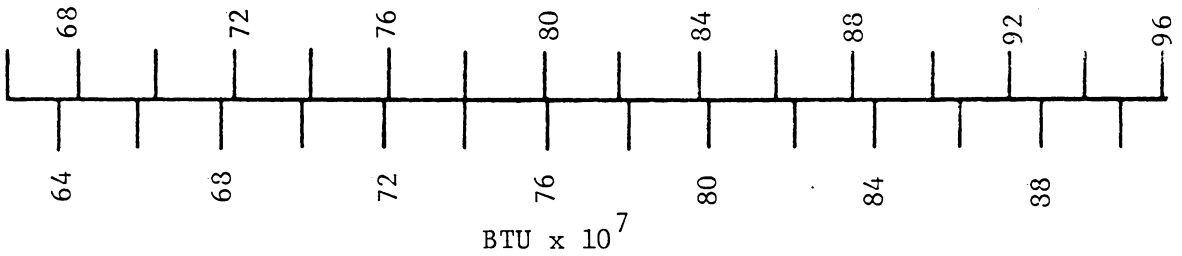


APPENDIX B

EQUATIONS AND LINE GRAPH FOR THE CONVERSION OF KILOJOULES
TO BTU'S AND KILOJOULES/KILOGRAM TO BTU/POUND

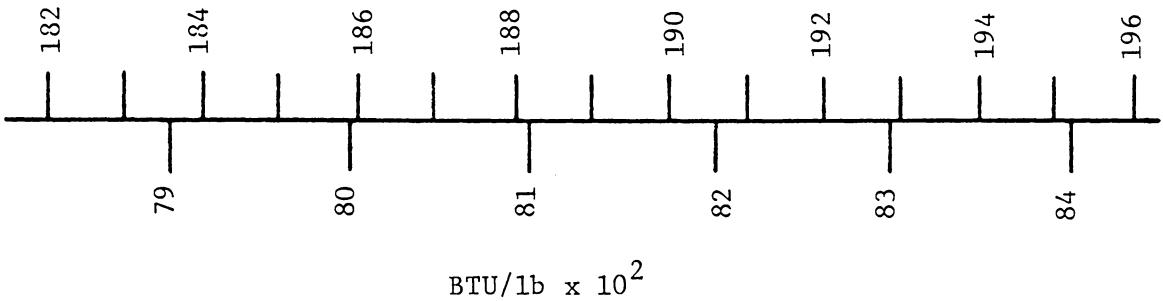
$$\text{kJ} \times .9486 = \text{BTU}$$

$$\text{kJ} \times 10^7$$



$$\text{kJ/kg} \times .4302 = \text{BTU/lb}$$

$$\text{kJ/kg} \times 10^2$$



APPENDIX C

MONTHLY RAINFALL DURING STUDY DURATION

Month	Inches
December 19-31	.26
January	.60
February	2.78
March	2.84
April	2.86
May	4.81
June	2.31
July	5.66
August	2.91
September	3.53
October	4.35
November	.49
December 1-16	1.24
TOTAL	35.64

APPENDIX D

SUMMARY OF REGRESSION ANALYSIS

Equation	r^2 value
Weighted Moisture Content [dry basis] = (weeks in storage x .82) + 63.0	.91
Weighted Ash Content [% Ash] = (weeks in storage x .029) + .558	.84
Weighted Specific Gravity (weeks in storage x -.00099) + .52743	.72
Weighted Specific Gravity = -.000065 (weeks in storage - 19) ² + .52	.43
Weighted Higher Heating Value [KJ/KG] (weeks in storage x .25) + 1.9 x 10 ⁴	.00
Weighted pH value (weeks in storage x -.00152) + 4.20	.00
<u>Packing Density [pounds/ft³]</u>	
PD 1.12' below surface = (weeks in storage x .043) + 23.26	.98
PD 2.25' below surface = (weeks in storage x .055) + 24.64	.93
PD 6.75' below surface = (weeks in storage x .062) + 27.04	.98
PD 11.25' below surface = (weeks in storage x .067) + 27.54	.98
Total Net Heating Value [kj] (weeks in storage x -1.27 x 10 ⁶) + 7.32 x 10 ⁸	.95
Net Heating Value BTU/LB (weeks in storage x -24.54) + 46.16	.92

APPENDIX E

Summary of Duncans Multiple Range Analysis

Regions With Mean Values Connected by Vertical Bar Are Not Significantly Different at .05 Alpha Level

MOISTURE CONTENT

Week	0		5		9		19		25	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Region 1	62.17	3.55	68.99	16.73	82.00	12.93	117.75	12.21	112.84	24.03
Region 2	69.87	3.91	57.44	6.80	70.20	11.27	60.79	19.20	68.51	9.47
Region 3	64.37	3.33	61.03	2.19	63.42	7.40	66.03	12.28	57.99	9.13
Region 4	72.74	5.19	58.45	5.19	63.48	4.53	53.02	9.13	49.65	2.93

Week	27		36		45		52	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Region 1	128.32	17.73	125.99	22.38	140.70	44.58	156.43	12.27
Region 2	93.71	18.73	107.55	24.19	128.75	25.32	110.10	38.70
Region 3	74.50	10.52	65.80	28.40	69.04	9.00	72.76	25.00
Region 4	46.28	2.70	44.73	5.45	47.80	5.06	43.41	3.74

APPENDIX E

CONTINUED

ASH										
Week	0		5		9		19		25	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Outer Region	1.28	.24	1.33	.24	1.51	.44	1.43	.27	1.41	.25
Inner Region	1.13	.13	1.11	.11	1.24	.11	1.08	.10	1.08	.10
Week	27		36		45		52			
	Mean	SD	Mean	SD	Mean	SD	Mean	SD		
Outer Region	1.60	.22	1.46	.18	2.41	.68	2.20	.39		
Inner Region	1.45	.14	1.27	.14	1.56	.32	2.04	.79		
SPECIFIC GRAVITY										
Week	0		5		9		19		25	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Outer Region	0.49	0.04	0.50	0.30	0.50	0.03	0.54	0.05	0.51	0.02
Inner Region	0.50	0.03	0.50	0.03	0.50	0.03	0.52	0.05	0.50	0.03
Week	27		36		45		52			
	Mean	SD	Mean	SD	Mean	SD	Mean	SD		
Outer Region	0.51	0.04	0.49	0.03	0.50	0.03	0.46	0.05		
Inner Region	0.51	0.04	0.50	0.03	0.50	0.03	0.48	0.05		

APPENDIX E

CONTINUED

HIGHER HEATING VALUE											
Week	0		5		9		19		25		
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Outer Region	19241.41	861.16	19335.03	397.73	19004.41	1173.44	19076.13	233.98	19036.84	341.71	
Inner Region	19490.91	697.39	19496.92	271.82	19249.10	372.83	19243.45	424.99	19368.50	348.40	
Week	27		36		45		52				
	Mean	SD	Mean	SD	Mean	SD	Mean	SD			
Outer Region	19334.27	471.38	19038.30	1156.18	19224.38	282.61	19248.11	300.65			
Inner Region	19319.83	421.14	19190.10	483.38	19435.74	346.67	19396.63	387.88			
pH											
Week	0		5		9		19		25		
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Outer Region	3.84	0.13	4.28	0.17	4.00	0.16	4.10	0.15	3.98	0.17	
Inner Region	3.78	0.14	4.19	0.17	3.83	0.13	4.05	0.09	3.87	0.13	
Week	27		36		45		52				
	Mean	SD	Mean	SD	Mean	SD	Mean	SD			
Outer Region	4.23	0.12	4.42	0.23	4.09	0.13	4.05	0.10			
Inner Region	4.24	0.11	4.35	0.24	4.04	0.14	3.10	0.10			

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