CHANGES IN ENVIRONMENT, GRAIN QUALITY, AND INSECT POPULATIONS IN PEARL MILLET, PENNISETUM AMERICANUM (L.) LEEKE, STORED IN AIRTIGHT CONTAINERS OR UNDERGROUND PITS

BY

CLETUS TANGWE ASANGA

B.S. AGRONOMY, OKLAHOMA STATE UNIVERSITY 1983
B.S. HORTICULTURE, OKLAHOMA STATE UNIVERSITY 1983

A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Entomology

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1985

Approved by:

Robert W Mills
Major Professor

DEDICATION

TO

My Wife Regina Lum Asanga

For her perseverance and devoted care of our four children and aging parents during my 43 months away from home. Her love letters and animating sweet words during our telephone conversations encouraged me through these studies. I am sure she will be proud of the end results.

TABLE OF CONTENTS

LIST OF TABLES

EXPERIMENT I

EXPERIMENT II

LIST OF FIGURES

INTRODUCTION

Post-harvest losses of food grain, though difficult to access and quantify accurately because they are not as apparent as those of a growing crop, are unacceptably high all over the world and more so in the developing countries where no systematic control measures are employed against the major grain storage pests including my country, Cameroon. It had long been reported (Cotton, 1950) "that insects are a major cause of loss in stored grains and seeds."

Although Cameroon is proud of being self-sufficient in food production on a continent presently stricken by widespread hunger, much still needs to be done to reduce the important post-harvest losses, in order to increase the per capita income of the farmers who make up over 70% of the total population. It is intended that physical grain pest control measures, particularly hermetic above and underground storage methods which have been found to be successful in several countries around the world, will be introduced in Cameroon (an important cereal and pulse producing country).

The use of chemicals for stored-product pest control is both hazardous and costly, especially to the less educated and poor peasant farmers in developing countries. Before the development and use of chemical control measures, man had recognized the grain insect pest problem and attempted physical control measures such as storage in gourds and calabashes, admixture with ashes, and underground storage. Airtight storage either below or above ground is an effective physical control method against grain pests even in relatively high moisture grain (Hall, 1970). However, this subject has been largely neglected by both historians and grain storage scientists, as pointed out by Sigaut in 1980 after he made an extensive survey of the use of underground grain storage around the world, and found that it is still the main method of long-term grain storage in many countries. Recently, Sterling et al. (1983) confirmed Sigaut's opinion, and added that it has become necessary for grain storage technicians "to perform the

required basic research and collaborative development of effective processes for incorporating underground food storage techniques into regional practice." Again in the same year, some stored-product entomologists from Canada and the U.S. (White et al., 1983), carefully examining the "Future Directions and Current Problems for Stored-Product Entomology", identified nine essential elements of a long-term research program including the "development of alternative control strategies for use in an integrated approach such as. . .controlled atmospheres or hermetic storage." It is for the above reasons that the present research was conducted and pearl millet, Pennisetum americanum(L.) Leeke, was selected because it has not yet been used for similar studies, and is an important crop in Cameroon.

The objectives of the study were:

1. to investigate the effects of two airtight storage methods (storage in hermetically sealed metal containers and in underground pits) on insect pests and on pearl millet grain quality.
2. to investigate the effectiveness of two types of pit wall linings on control of pest organisms and grain quality maintainance.
3. to determine the changes in concentrations of the respiratory gases (CO_2 and O_2), temperatures, and relative humidities in the intergranular atmosphere both in the laboratory containers and in pits, and the effects on insects, fungi and grain quality.
4. to investigate the volumetric water changes in the soil around the two types of pits.

Generally, the data in this thesis are condensed from the extensive data collected from the two experiments. Some of the detailed data are included in appendices.

Importance of Cereals and Pulses. It is important to consider the storage of pulses (dried edible seeds of legume crops such as beans, peanuts, cowpeas, etc.) along with cereals since in many cases, particularly in the tropics, these pulses are handled and stored in the same places with cereals and share similar storage problems. Hermetic storage principles and practices apply to both of these important groups of human food; though most of the discussions are on the cereals. In developing countries, cereals, pulses, and their products are usually stored for long periods of time. Purseglove (1972) reported that "cereals or grain crops are the most important sources of plant food for man." He also stated that "settled agriculture was made possible by the domestication of barley and wheat." Concerning the distribution of cereals, he stated that "All the important early civilizations were based on some kind of cereal-wheat and barley in the Middle East and Mediterranean, rice in southern and eastern Asia, and maize in the New World." He had earlier (Purseglove, 1968) reported that pulse crops "are the next in importance to cereals as sources of human food and contain more protein than any other plant product."

The Place of Millet in World Cereal Production. As far as total world production of cereals is concerned, wheat, rice, and maize are the major three in order of importance while millets are considered as minor crops, but important "in parts of Asia, Africa and the Soviet Union" (Martin et al., 1976). According to the FAO production report (1983), the total world production of cereals was 1,638,847,000 tonnes in 1983 and that of millet was 29,563,000 tonnes for the same period (including 18,709,000t in Asia, 8,415,000t in Africa and 2,200,000t in USSR).

Historical Background of Pit Storage. Underground pit storage is an ancient practice which declined with the advent of modern civilization, but is still used in some parts of the world, particularly developing countries with dry climates

and less developed technology. Historical accounts of underground pit storage have been given by several workers (Gilman and Boxall, 1974; Ambler, 1977; Will and Hyde, 1917; and Luders, 1970). Gilman and Boxall made a historical survey of underground pit storage around the world in which they divided the distribution of pits into five geographical regions. The distribution according to their report involved all continents except Australia and North America; but other reports (Ambler, 1977 and Will and Hyde, 1917) are mainly on the use of pit storage by the pre-historic settlers of the USA (the Anasazis) who lived in caves during the last 2000 years, and the Indians of the Great Plains, respectively. Gilman and Boxall report that the oldest examples of pit storage dating back to Roman times are found in the Middle East.

Evolution and Use of Pits and Airtight Grain Storage. Luders (1970) reviewed the available information on grain storage in air-tight structures, both above and below ground around the world up to the date of the report. He claimed that the first modern revival of the ancient practice of underground storage was done in France in 1850 when one Dayere stored grain in six concrete-lined pits unattended for five years, and a Paris-based company in 1871 also stored oats in similar structures with some of the structures only half below ground. The latter type of structure is probably comparable to the present bunker storage structures that are becoming common in Australia and also used in the U.S. for storage. Luders reported that a French publication claimed that maize remained in a silo from 1528 to 1707 in France and "yielded good bread." The French are also credited by Luders with undertaking the first hermetic above-ground storage studies in 1937.

More recent studies (Sigaut, 1980 and Sterling, et al., 1983) have confirmed that underground pit storage was the main method of long-term grain storage since pre-neolithic times up to early 19th century especially in Spain and Morocco in the west, and all the way to India and China in the east, including S.E. Europe, Saudi Arabia and other countries in the area. Also, Wendorf et al. (1985) in

their archeological account of the human adaptation in the Nubian Desert of North Africa some 500,000 years ago, reported the existence of slab-lined storage pits in a few of the earliest neolithic settlement sites. It is presumed that cereal grains were stored in the pits since the report mentioned the presence of "domestic cereals—namely, six-row barley." Experiments were started in 1964 in Britain to assist archaeologists in interpreting the types and effectiveness of the ancient storage pits (Reynolds, 1967, 1969; Bowen and Wood, 1968; and Lacey, 1972). In the experiments, the researchers simulated most of the ancient pit storage practices and then monitored the CO_2 concentrations in the pits and assessed the grain quality using mold enumeration and viability test techniques. Some of the conclusions so far reached (Hill et al., 1983) are:

1) corn may have been stored in ears;

2) amount of grain stored was reduced by the pit lining/masonry;

3) the life of a pit may depend on the type of lining and covering.

Underground pit storage was not common in the Central and South American regions, but was recommended and used in Argentina during World War II and later in Paraguay to solve the problem of famine reserves (Shellenberger and Fenton, 1952 and Luders, 1970). These so-called famine reserve storage pits introduced the use of large commercial storage pits of over 150 tons capacities and presently many have capacities of over 1,500 tonnes (DeLima, 1978). Famine reserve pits have also been constructed in other countries including Nigeria in 1955 (Choyce, 1960) and Kenya (DeLima, 1978).

Entomology of Hermetic Storage. Pruthi and Singh (1948) reported that the concept of asphyxiating insects in hermetic atmospheres was postulated by Dendy (1918). Since then numerous investigations have been carried out on the effects of air-tight storage of grain on insect pests, notably Bailey (1955, 1956, 1957, 1965), Hyde (1969a), Navarro (1978), and Burrell (1980). These experiments elucidated the important role that air exchange plays on the growth and reproduction of several stored-product insects. Conflicting evidence on this subject had

earlier been reported by Cole (1906) when he conducted a series of experiments to demonstrate the importance of moisture on the growth and reproduction of grain weevils. Cole placed 10 rice weevils in a vacuum container exhausted of air using a double-action vacuum pump. The rice weevils were provided with grain but they all died after 10 days without feeding. When he repeated the experiment and moistened the vacuum atmosphere with water from which O_2 had earlier been extracted, up to 5 of the insects survived up to 23 days when the experiment was stopped. Cole concluded that the death of the weevils was caused by severe dessication rather than by asphyxiation. Bailey (1955, 1956, 1957, 1965) on the contrary, demonstrated clearly in his experiments on airtight storage, that the weevils he used to infest the grain died from asphyxiation in the hermetically sealed containers. Bailey studied the independent and joint effects of lowered O_2 and increased CO_2 tensions on adult and immature stages of rice weevils using wheat in air-tight containers for 14-day periods. When the O_2 was maintained at a concentration of 21%, no mortality accurred with increase in CO_2 up to 25%. The lethal concentration of O_2 was observed to be 4% when CO_2 was maintained around atmospheric level, but no mortality occurred at 5% O_2 and above. When the O_2 was held a little above the lethal dilution (5%), 100% mortality was obtained with 13.2% CO_2 but not at 11.5% CO_2. Bailey concluded that the death of the insects in airtight containers was due to the depletion of O_2 and that the associated accumulation of CO_2 played only a minor role.

The Principles of Airtight Storage. Several workers have explained the scientific principles of hermetic storage of grain (Hall and Hyde, 1954; Hyde and Burrell, 1969, 1982; Hyde, 1973a; Banks and Annis, 1977, 1980; Burrell, 1980; and Banks, 1981). All agree the basic principle of airtight storage is based on depletion of O_2 in the container to a level that will inactivate or kill the harmful O_2-dependent organisms (mainly insects and most fungi) before serious damage is caused to the grain. Although O_2 is usually depleted by the organisms themselves through respiration, it is sometimes desirable to create an O_2-free

atmosphere artificially (Banks and Annis, 1977, 1980; Banks, 1981; and Hyde, 1973a). It is well known that the respiratory process involves the breakdown of carbohydrates (chiefly in form of simple sugars) with the release of energy for metabolism, either using O_2 in the process (aerobic respiration) or without using O_2 (anaerobic respiration) depending on the type of organism. The representative equations for the two types of respiration are as follows (Hyde, 1973a):

aerobic: $C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + 677kcals.$

anaerobic: $C_6H_{12}O_6 \longrightarrow 2CO_2 + 2C_2H_5OH + 22kcals.$

Hyde (1973a) further explains that the first type of respiration is more efficient and is used by most organisms, including the stored-product insects, fungi, and grain while the second type is less efficient and involves mainly yeast and bacteria which require high moisture and temperature to grow. According to Hyde, anaerobic respiration (or fermentation) is responsible for the continued deterioration of high moisture grain after O_2 is exhausted, producing lactic acid, acetic acid and alcohols which impart the musty odor to the grain. In semi-underground silos (bunker storage systems), the temperatures of high moisture grain are lowered, thus reducing development of odors and other changes in chemical properties of the grain (Hyde and Burrell, 1982). She reported that moisture and temperature are factors that greatly affect respiration and are difficult to separate, and that the respiration of the grain and that of insects and molds are also difficult to separate although she included a table of respiratory quotients of wheat of varying moisture contents and temperatures and those of Sitophilus oryzae(L) published by Lindgren (1935). Hyde and Burrell (1982) also postulated that most fungi will not develop at 70% RH which corresponds to a grain moisture content of 14% and that the respiration of grain at a mc below this is negligible, but at high temperatures (>40°C) the grain will

deteriorate and lose viability in 280 days. However, the upper limit is said to be at about 55°C, above which the respiration of insects, molds and grain will cease (Girish, 1970).

Experiments on Modern Airtight Storage. With the above outlined scientific principles of successful airtight storage in mind, many workers have conducted experiments particularly in developing countries where postharvest losses are great. In tropical Africa, Swaine (1954, 1957), Anon (1959, 1960), Choyce (1960), Prevett (1963), O'Dowd (1971), Boxall (1974), and DeLima (1978), have studied and tried to improve the traditional storage methods in order to reduce losses, mainly by introducing pit storage and or suggesting improvements of the traditional types of pits. These studies were done in Nigeria, Ethiopia, Somalia, Tanzania and Kenya. According to studies by Boxall (1974) in Ethiopia, 62% of the farmers use pits exclusively and a further 8% use them in combination with other storage methods. He suggested that roofing improvements of the traditional pits needed to be done by replacing wood and mud lids with metal and polyethylene sheets or by building a shelter over the pits, and that wall lining improvements be done by using bamboo matting, polythene sacks or concrete. DeLima (1978, 1980) made similar suggestions for pits in Somalia and Ethiopia and also reported that several large scale, long-term trials using semi-underground hermetic structures of about 1500 tonnes capacity in Kenya gave encouraging results during up to 3 years of storage (only negligible losses due to insects occurred). Anon (1959, 1960) reported that the three species of insects in Guinea corn stored in experimental pits in the Kano area of northern Nigeria were not killed because lethal concentrations of O_2 or CO_2 were not created. Oxygen concentrations dropped only to 10% and CO_2 was not detectible in the pits. Obviously, the pits were not airtight.

A long-term, large-scale pit storage experiment was also carried out in northern Sudan where pit storage is a common practice (Khalifa, 1960). The experiment, in Kassala Province in 1953, consisted of six 100-ton pits filled

with two of the common varieties of dura millet, Sorghum vulgare (3 pits per variety) and left for about 6 years. Some of the pits were filled with loose grain and others with sacked grain, and pit walls were not sealed. Data were collected during 1957-1959 on grain mc, insects and seed viability, but there was no equipment to monitor temperatures and gas concentrations. Some live insects were found up to the end of the experiment (6 years) and the investigator assumed that there was gas exchange during the storage period since pit walls were found to be cracked when they were emptied. Comparing results to those from open-air storage in pyramid heaps, which is the other main storage method in Sudan, Khalifa concluded that underground pit storage is ideal for that area provided the grain is not left in the pits longer than 5 years.

In India, pit storage is common in the rural areas and the pits are reported to vary from village to village in size, shape, masonry, and lining, and are identified by local names (Ramasivan et al., 1966, 1968). Pruthi and Singh (1948) classed the various types of pits under two major types viz 'Khattis'-pits with necks and 'Banda'-pits without necks. Ramasivan et al.(1966) described seven types of pits under the given traditional names but Pushpamma and Chittemma (1981) mentioned another type, 'Pathara', common in the Andra Pradesh area indicating that there may be other types of pits not described. Girish et al. (1972) conducted studies "to determine the losses and eco-climatic conditions of food grain viz temperature, oxygen concentration, moisture content, germination, damaged grain, insect fauna, free fat acidity and alcholic acidity, in some of the underground storage structures" in India. They grouped the study pits under two types, "pucca khatties" (those with brick masonry and plastered with cement) and "kaccha khatties" (pits without wall construction). According to their results, grain remained cooler in the "kaccha khatties" than in the "pucca khatties" but the O_2 concentration in both types was much lower than ambient. Insects were found only in the top layer in both types and spoilage was correspondingly more in the top.

Apart from underground pit storage, some workers have recommended small airtight containers and other cheap aboveground structures (Wright and Southgate, 1962 and Baker, 1973). Some of the airtight containers and structures recommended by Baker include concrete structures, flexible structures having plastic and butyl linings, plastic sac containers, gourds (dried fruits of Cucurbitaceae), metal drums, bins, and other sealable containers. Among the flexible structures, silos of flexible butyl rubber bags seem promising for the tropics (Hyde, 1973a).

The use of polyethylene as pit lining material to improve airtightness has been investigated by Donahaye et al. (1967). They stored 50 tons of barley in an underground pit "hermetically sealed inside a polyethylene liner." The O_2 concentration decreased to 1.0 and 1.3% in the lower and upper parts of the pit, respectively, and CO_2 increased to about 15% after seven weeks, followed by a reversal of the trend in the next two weeks; this was probably due to rodent damage discovered later. Many cheap plastic models have also been designed at the Slough Laboratory in England to suit a variety of uses in developing tropical countries (Wright and Southgate, 1962).

The storage of high moisture grain has received special research attention from several workers including Hyde and Oxley (1960), Hyde (1969b, 1970), and Wills et al. (1983). It has been reported (Hyde and Oxley, 1960 and Hyde, 1973b) that in the case of high moisture grain (>16% mc) in airtight containers, there is anaerobic production of CO_2 up to 95%, after exhaustion of O_2 by aerobic organisms which died or became dormant. Hyde and Oxley (1960) conducted a detailed study of high moisture grain storage in both laboratory and commercial scale structures using barley and wheat of 17-24% mc. They reported that no molds developed except when containers leaked, and that the grain was "bright and free-flowing, even after prolonged storage." The grain in the commercial size "10-ton bins reflected the mean temperatures of the surroundings" (i.e. there was no spontaneous heating). They monitored O_2 and CO_2 concentrations and observed

that the maximum CO_2 concentrations increased with increased mc of grain (e.g. 34-40% CO_2 concns at grain mc of 17% and up to 90-95% at grain mc of 22-24% while at 14% grain mc it was only 2% after 18 months).

Similar underground pit storage of high moisture grain had also been done earlier. Bechtel et al. (1945) used 4 ft wide X 5 ft deep burlap-lined pits dug in silty clay loam soil at the Kansas Experiment Station (Manhattan) to store newly-threshed Atlas Sorgo grain of high mc for 8 months. The grain stored satisfactorily with moderate losses which they believed could be reduced in large pits (with greater volume to wall ratio), and that the animal feed nutritive value remained good.

Use of Added CO_2 and O_2 Mixtures in Hermetic Storage. Calderon and Navarro (1980) studied the effects of CO_2 and O_2 mixtures on the adults and eggs of red flour beetles and lesser grain borers. They exposed the eggs and adults of the two species for 24-144 hrs in atmospheres containing mixtures of 2-8% O_2 and 5-30% CO_2 at 26°C and 55% RH as well as in atmospheres containing pure O_2. They observed that increased CO_2 enhances insect mortality and that there are synergistic effects of the two gases (high CO_2, low O_2).

Other workers (Jay, 1971; Jay and Rearman, Jr., 1973; Kashi, 1981; U.S.D.A., 1982; Paster and Chet, 1983; and Annis et al., 1984) have investigated the use of high concentrations of CO_2 in air and 100% CO_2 for the control of stored grain insects and fungi in hermetically sealed structures and containers, including pits. Kashi (1981) reported that this chemically residue-free technique has been "commercially used in China for treatment of grain placed under gas-proof sheets" and that it "is of considerable interest in the less developed countries because it requires only a low capital investment and can be adapted to suit local practices of storing grain in bags or small containers."

Economics of Underground Pit Storage. Some estimates of the cost of a 6,000-ton underground airtight silo were made in Argentina by Lopez (1973). His estimates of the equipment costs for the three 2000-ton celled structure were; a

swivel loader for $2,000, a telescopic unloader for $10,000, and ancillary equipment for $1,000. He further included the following breakdown for storing 6000 tons of grain:

Civil engineering works	$12-16 per ton
Loading/unloading equipment	$2.2 " "
Total average cost	$16.2 " " or $13.0/$m^3$.
Total storage costs for 2 yr	$14,500 or $2.40 per ton

All values are in U.S.$ and at that time, 1 U.S.$ was equivalent to Arg. $5.0. Lopez stated that "The total cost of $97,000 is estimated to be about one-third the cost of conventional vertical silo (country elevator) of the same capacity." According to the above estimates underground pit storage is economical if properly carried out.

EXPERIMENT I

LABORATORY TEST OF HERMETIC STORAGE OF PEARL MILLET, PENNISETUM AMERICANUM(L.) LEEKE.

Objectives

The objectives of the experiment were:

1. to determine the changes in the concentrations of the respiratory gases (CO_2 and O_2), temperature and RH in the intergranular atmosphere of pearl millet of three moisture levels in hermetically sealed 5-gallon cans infested with rice weevils or non-infested; and
2. to determine the effect of hermetic storage on rice weevils and on grain quality.

Materials and Methods

Grain. Pearl millet, (Pennisetum americanum (L.) Leeke, harvested in Fall, 1982 at Fort Hays Agricultural Experiment Station, Hays, Kansas, was used. The grain had previously been used briefly for experiments on trapping of stored-product insects, but was only slightly damaged and was fumigated about a month before it was used in this study.

About 100 kg of grain was placed in a freezer for two weeks to kill any insects that may have been present. The grain was then removed and cleaned using a Bates Laboratory Aspirator (Model 359BG608V) and mixed in a 200-liter drum mixer (Fig. 1.1A).

Moisture Adjustment of Grain. Using a Motomco Moisture Meter (Model 919), the moisture content (mc) of the mixed grain was found to be 12.6%. To prepare grain of 10, 13, or 16% mc, the grain was divided into three equal parts. One part was spread in the laboratory to be air dried, then the appropriate amount of water was added to each lot, which was rolled in the 50-gal drum mixer (Fig. 1.1A and B). Each lot was placed in a plastic-lined burlap bag and stored

Figure 1.1 (a) The 200-liter drum mixer on an electric roller; the Bates Laboratory Aspirator (Model 359BG608V) is mounted on a table near the drum.

(b) The empty drum mixer showing 3-inch wide metal strips welded on the inside wall.

A

B

in a coldroom. Using an air oven and aluminum drying dishes, three 10-g samples for each moisture level were dried at 120°C for 18 hr; final mc were 9.9, 12.8, and 15.6% (wet wt. basis).

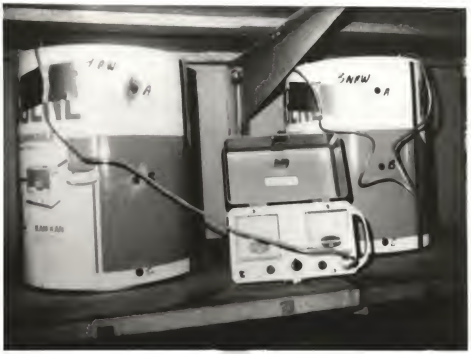
Airtight Containers. Six new 5-gal, 18.9 l, (27-cm in diameter X 33cm deep) cylindrical metal kerosene cans were used in the experiment. Three 6.5-mm holes spaced at 2, 15, and 28 cm from the bottom were drilled in the side of each can, and each fitted with a tight rubber septum for later gas sampling (Fig. 1.2A). Due to time involved in gas sampling and analysis, samples were taken only through the middle port. The metal screw cap over the 3.5 cm top opening of each can was replaced with a rubber stopper having a 4.8-mm diameter hole in its center through which a cable was passed connecting a sensor in the grain with the meter of a Delmhorst Electronic Hygrometer/Thermometer. A silicone rubber bathroom caulking compound was used to seal the cable in the hole.

Introduction of Insects and Grain. Each can was randomly assigned to a treatment; temperature/relative humidity sensors were randomly assigned to the cans, and the cans were randomly placed on the shelf space available in the insect rearing room (27$\pm$ 1°C and 67$\pm$ 3% RH). The temp/RH sensor was installed in the center of each can when half-filled with millet and the sensor cable was passed through the stopper to the outside for later attachment to the meter. The Model SN-1 sensors were each wrapped in 60-mesh brass screen to protect it from the grain and invasion of insects (Fig. 1.2B).

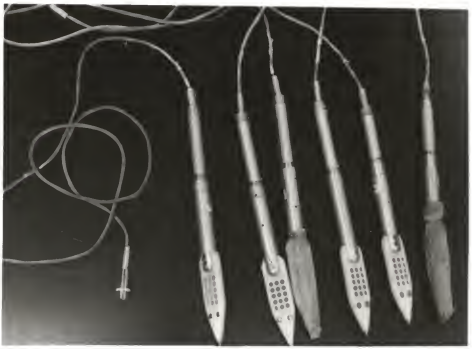
The rice weevils, Sitophilus oryzae (L.), used were from a strain maintained in the Stored-Product Insect Laboratory, KSU, for several years. Three to four-weeks-old adults reared in millet were used. One can for each mc was infested with 150 weevils, half introduced when the cans were half-filled and the remainder after all the millet was introduced. Samples were collected during the filling, to be used for the final moisture determination, a germination test, and

Figure 1.2 (A) Hermetically sealed test cans showing the three holes fitted with rubber septa and the temp/RH sensor cables, one of which is connected to the Model HT-1 Delmhorst Electronic Hygrometer/Thermometer.

(B) The Model SN-1 Temp/RH sensors, two of which are still wrapped with the 60-mesh brass screen.



A



B

determination of percentage of mold-infected kernels. Fifteen kg of millet were placed in each can.

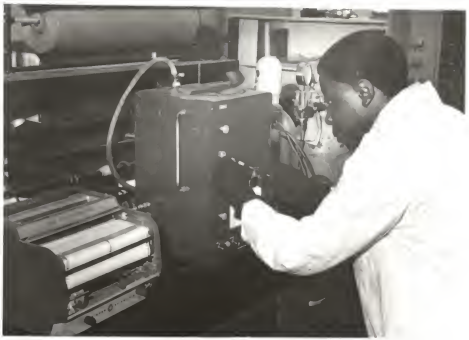
Germination Test. One hundred kernels from each treatment were placed on wet paper towels, wrapped with aluminum foil, and placed in the insect rearing room. The percentages of germinated seeds were determined after 7 days. Germination tests were also done at the end of the experiment.

Determination of Percent Mold-infected Kernels. At the beginning and at the end of the experiment 50 kernels from each treatment were surface-sterilized in 2% sodium hypochlorite for 1 minute, and rinsed with sterile distilled water, and plated on a sterilized malt-agar medium. The medium was a mixture of 30g malt extract, 40g sodium chloride, 15g purified agar, 1 liter distilled water and 0.2 ml Tergitol NPX. After 7 days incubation at 23-25^{o}C the numbers and types of fungal colonies were determined.

Gas Sampling and Analysis. Gas samples were withdrawn from the middle port of each can, using a Series A, 1-ml Pressure-Lok Gas Sampling Syringe with a stop in the cylinder to allow only a 0.25-ml sample to be introduced. Sampling began 24 hr after sealing the cans and was done daily for the first week, every other day for the next 4 weeks, and then at 4 day intervals until the end. The gas samples were introduced into a Model 29 Fisher-Hamilton Gas Partitioner (Fig. 1.3). Attached to it were a Model PWS S/N 3870 Fisher laboratory recorder, and an Autolab Digital 6300 Integrator. A linearity test using 4 standard gas mixtures established the accuracy of the equipment. The reading for the carbon dioxide and oxygen peaks for each test sample were compared with those obtained soon afterward from a sample of the appropriate standard gas mixture. The standard mixtures were as follows:

	Carbon dioxide	Oxygen	Nitrogen
1.	0.51%	20.64%	78.63%
2.	5.0	5.0	90.0
3.	15.0	10.0	75.0

Figure 1.3 Introducing a gas sample into a Model 29 Fisher-Hamilton Gas Partitior using a 1-ml Pressure-Lok Gas Sampling Syringe; the Model PWS S/N 38 Fisher Laboratory recorder is on the left.



A

B

The standard gas tanks were kept in the rearing room with the experimental cans. To obtain syringe samples 125-ml Fisher Pyrex gas sampling tubes with a rubber septum in the side were filled from the cylinder using a rubber tube. The stopcocks were closed and the test sample withdrawn through the septum.

The following formula was used for calculations of CO_2 or O_2 concentrations:

$$\% CO_2 \text{ (in sample)} = \frac{\% CO_2 \text{ in standard} \times \text{reading of } CO_2 \text{ peak for sample}}{\text{Reading of } CO_2 \text{ peak in standard}}$$

The same formula was used for O_2.

Temperature and Relative Humidity. Using the Delmhorst Electronic Hygrometer/Thermometer (Model HT-1) the temperature and RH within each can was observed at the same times the gas samplings were done. The sensors were earlier checked under known temp/RH conditions and were found to be fairly accurate for use.

Termination of Experiment. The experiment was terminated after 76 days. The rubber stoppers were quickly removed and the cans were closed with their original screw caps. Each can and contents were weighed. Three observers checked the odor in each can by smelling the air inside the newly-opened can. Five probe samples were taken from each can using a 2-compartmented probe (1.8 cm I.D.), which collected a sample between 5.5 and 12.7 cm from the bottom and another 19.5 to 26.5 cm from the bottom; the latter was quite near the top of the grain. The five lower level samples from each can were mixed together and placed in airtight plastic bags; the upper level samples from each can were similarly handled. Subsamples of these were used for determination of viability, moisture content, and mold infection. The grain from each can was observed for flowability and grain color. Samples of about 300 g were taken periodically as the grain was emptied and sieved to determine whether there were live insects, frass, or dust.

Replication. The experiment was replicated using the same equipment and methods, but different grain from the same original lot. Dates for each replication were Mar. 9 to May 24, 1984 and Nov. 12, 1984 to Jan. 27, 1985.

Data Analysis. To determine significant differences between the treatments, the data were analyzed in the KSU Computer Center using Proc ANOVA and Proc GLM.

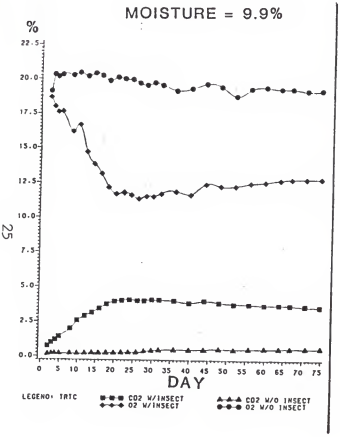
RESULTS

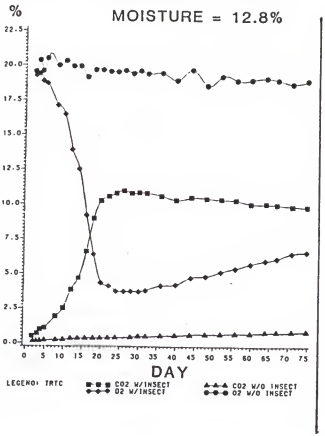
Data collected for the following six variables were analyzed: respiratory gas concentrations (CO_2 and O_2), seed viability, fungi-infected kernels, relative humidity, and temperature.

Carbon dioxide and oxygen. The mean CO_2 and O_2 concentrations in each of the six cans over the storage period are given in Fig. 1.4 and Appendix Tables 1 and 2, respectively. Moisture X insect interaction significantly influenced the CO_2 and O_2 concentrations which were significantly different in all six cans. Results for the two replicates were very similar, and averages for the two are given. The concentrations of CO_2 and O_2 in grain of 9.9 and 12.8% mc remained essentially constant in the non-infested treatments with final means of 0.36% and 19.70%, respectively for 9.9% mc, and 0.46% and 19.44%, respectively for the 13% mc, these were similar to the concentrations in the laboratory atmosphere (Fig 1.4 and Table 1.1). The changes in gas concentrations that occurred in the 15.6% mc grain without insects were nearly as great as those in the 15.6% mc with insects; microbial activity and perhaps some grain respiration was no doubt responsible. The 12.8% mc was too low to support significant microbial activity so the greater changes in gas concentrations in the insect-infested can were caused by insect metabolism. This was also true in the 9.9% mc treatments.

Figure 1.4 SAS graph plots, by moisure level, of the respiratory gas concentrations at the center of the grain bulk during the 76-day hermetic storage period.

RESPIRATORY GASES





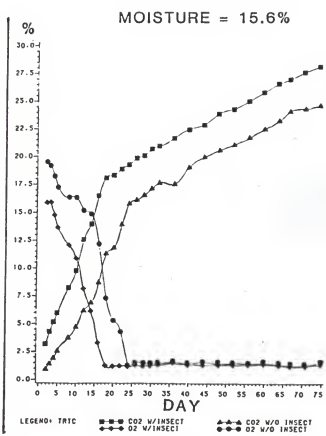


Table 1.1. Mean[1] CO_2 and O_2 concentrations in six hermetically sealed cans of millet grain after 76 days of storage at 27±1°C.

Grain Moisture (%)	Insects[2]	CO_2 %	O_2 %
9.9	Infested	3.30 a	13.44 a
9.9	Not Infested	0.36 b	19.70 b
12.8	Infested	7.82 c	8.50 c
12.8	Not Infested	0.46 d	19.44 d
15.6	Infested	18.30 e	4.46 e
15.6	Not Infested	14.16 f	6.74 f

[1]Means of 2 reps with 28 observations each.

[2]Infested cans contained 150 RW=10 insects/kg.

Means followed by the same letter are not significantly differently by Duncan's multiple range test (P<.05).

For the 9.9% and 12.8% mc grain, the changes in gas concentrations more or less stabilized after 18 and 22 days, respectively, but continued to change in the two cans containing grain of 15.6% mc, though more slowly after days 16 and 24 in the infested and non-infested can, respectively. There was, however, a slow increase in the O_2 level from 4.19% in day 40 to 6.56% at the end and a slow reduction in the CO_2 level from 9.98% in day 67 to 9.82% at the end in the infested can of 12.8% mc grain.

Fungi Infection. Although microbial activity in the 15.6 % mc grain was indicated by the large changes in gas concentrations, there were no significant increases in the percentage of mold-infected kernels. The percentage of kernels infected with field fungi, mainly Alternaria spp., significantly reduced from 3.5% at the beginning to 1.7% by the end of the storage period (Table 1.2). No storage fungi were observed at the beginning but a mean of .05% of the kernels were infected at the end, comprising mainly Aspergillus gluacus and Penicillium spp.

Seed Viability. Seed viability was not significantly different between infested and non-infested cans containing grain of the same moisture content (Table 1.2). The mean percent germination at the start was not significantly different between treatments and had not significantly changed at the end for grain of 9.9 and 12.8% mc but was much reduced (from about 90% to <60%) for the 15.6% mc grain. Moisture X insect interaction did not affect seed viability.

Temperature and Relative Humidity. The temperatures and relative humidities at the center of the cans did not change significantly over the storage period. The temperatures in all the cans equilibrated to the room temperature of 27± 1°C within five days and remained constant. The relative humidity in each can equilibrated to a value corresponding to the grain moisture content within five days and remained constant (Table 1.3). The means of all treatments were significantly different thus indicating moisture X insect interaction.

General Grain Condition. At the end of the storage period, the grain from all the cans was free-flowing, of normal color, dust free, clean, and contained no live insects. The grain of 15.6% mc had a sweetish odor but the rest had no peculiar odors. The weight and moisture content of the grain did not change.

Table 1.2. Percent grain germination and percent fungi infected kernels at the beginning and end of the 76-day experiment.

Treatment		Germination %		Fungi-infected Kernels %					
				Field Fungi		Storage Fungi		Total Fungi	
Moisture Content %	Insects[2] (RW)	Start	End	Start	End	Start	End	Start	End
9.9	RW	90.25	92.00 a	3.5	3.5	0	0	3.5	3.5 b
9.9	No RW	90.25	92.25 a	3.5	2	0	1	3.5	3.0 b
12.8	RW	92.25	92.00 a	3.5	1.5	0	0.5	3.5	2.0 b
12.8	No RW	92.25	92.25 a	3.5	0	0	0.5	3.5	0.5 b
15.6	RW	89.75	53.50 b	3.5	0.5	0	1	3.5	1.5 b
15.6	No RW	89.75	57.00 b	3.5	2.5	0	0	3.5	2.5 b

[1]Values followed by the same letters are not significantly different (P<0.05) by Duncan's multiple range test. Values are means of 2 replications.

[2]RW = Rice weevils at the rate of 10/kg of grain (150/can).

Table 1.3. The mean temperature and relative humidity in pearl millet bulk during hermetic storage for 76 days in the laboratory at 27±1°C (means of 2 replications).

Treatment		Mean Temperature[1] °C	Mean relative humidity[1] %
Moisture Content %	Insect		
9.9	RW	25.87 a	36.15 a
9.9	No RW	25.83 ab	37.28 b
12.8	RW	25.83 ab	69.15 c
12.8	No RW	25.74 b	67.64 d
15.6	RW	25.79 ab	83.88 e
15.6	No RW	25.79 ab	85.29 f

[1]Values followed by the same letter are not significantly different (P<0.05) by Duncan's multiple range test.

Carbon Dioxide and Oxygen. Even though no live insects were found in any of the containers, results showed that they significantly reduced O_2 and increased CO_2 in the infested cans. The gas concentrations in the uninfested cans having grains of 9.9 or 12.8% mc did not change significantly. The respiration of microorganisms and grain is negligible at this moisture level (Pomeranz, 1982).

In the infested cans, all the insects must have died by the 18th and 22nd day when the gas concentrations stabilized in the 9.9% and 12.8% mc grain, respectively. Calderon and Navarro (1980) showed that the addition of CO_2 to low concentrations of O_2 had synergistic effects on adult mortality of red flour beetles and lesser grain borers in controlled atmospheres at 26°C and 55% RH. The cumulative mixture of 10.3% CO_2 and 4.3% O_2 on the 20th day produced by the respiratory activities of the insects probably killed, or at least inactivated the insects in the 12.8% mc grain. Bailey (1956) achieved 100% mortality of RW exposed in an atmosphere containing a mixture of 13.2% CO_2 and 5.0% O_2. The mixture of 4.0% CO_2 and 11.7% O_2 in the grain of 9.9% mc was effective in killing the insects probably because of a combination of unsuitable atmosphere and dry grain. In 12.8% mc grain, a concentration of 11.7% O_2 will require more than 28% CO_2 dilution to become lethal; Bailey (1956) achieved only 10% mortality when he exposed rice weevils for 14 days in a mixture containing 11.6% O_2 and 27.6% CO_2. The temperature and RH in Bailey's experimental chamber were 29°C and 72% respectively.

The respiration of storage fungi, grain and insects was responsible for the early reduction of O_2 to 1.25% and increase of CO_2 to 18.14% by day 18 in the infested can containing grain of 15.6% mc. The reduction in O_2 to about the same level (1.32%) and the corresponding increase in CO_2 concentration to 15.78% was also achieved in the uninfested can containing grain of 15.6% mc but almost one week later (day 24) because there were no insects to contribute to the

respiratory products. All insects must have died or were inactivated by the time the O_2 level reached 1.25%. The continuous increase in the CO_2 concentrations in both cans of 15.6% mc grain probably was due to microbial and/or grain respiration while the stability of the O_2 at the low level of between 1.2 and 1.5% was perhaps due to either the inability of the gas chromatograph to detect lower O_2 levels or a slow leak. Anaerobic microorganisms might have been suspected if the grain mc had been high enough to provide an atmosphere near 100% RH (Christensen and Sauer, 1982). Some molds are known to grow in atmospheres of very little O_2 (about 0.2%) but the seed will maintain viability according to Peterson et al. (1956). Of course, this assumes a suitable mc. However CO_2 has long been reported to retard the germination and growth of fungi (Brown, 1922). The insignificant percent mold-infected kernels and the retention of the grain viability at the end of the storage period are in agreement with the findings of the above earlier workers (i.e. Brown, 1922 and Peterson et al., 1956). The slight reduction in the CO_2 and corresponding increase in the O_2 in the infested 12.8% mc grain was probably caused by a very slow leak. A similar observation was reported by Hyde and Oxley (1960) and Hyde and Burrell (1982), who also attributed it to a slow leak in the container.

Fungi Infection. The major field grain fungi (Alternaria spp and Fusarium spp) and storage fungi (Aspergillus spp and Penicillium spp) observed are the same genera of fungi reported by earlier researchers (Christensen and Kaufmann, 1969) to be the major molds that invade grain in the field and during storage, respectively. According to Christensen and Sauer (1982), all field fungi require very high moisture (in equilibrium with 95-100% RH) to grow, while the storage species have a wide range of moisture requirements and commonly grow in stored grain with moisture contents in equilibrium with 65-90% RH. The storage fungi must have been largely responsible for the high CO_2 accumulation and O_2 reduction in the cans containing the 15.6% mc grain, but most of them could not survive when the CO_2 increased and the O_2 decreased to inhibitory levels. Conditions

were not suitable for field fungi to grow, thus, most of them remained dormant or died during the storage period.

Seed Viability. The insects did not have time to cause much damage before they died, thus, seed viability was not affected in the low moisture grain (of 9.9 and 12.8% mc) which remained almost dormant. In the 15.6% mc grain, microbial activities reduced the kernel viability, but due to the high concentration of CO_2 and low concentration of O_2 their growth was inhibited (Brown, 1922) and a fair percent viability was retained. Seed viability is known to decrease when grain of more than 14% mc is stored even in air-tight containers (Hyde and Burrell, 1982).

Temperature and Relative Humidity. It is not common for grain temperatures in hermetically-sealed containers to be much different from ambient temperatures or for the mc/RH equilibrium to change during storage. The early creation of the high CO_2 and low O_2 atmosphere prevented the insects and molds from causing significant heating and moisture migration.

General Conclusions. (1) The hermetic sealing of the experimental cans was effective and the benefits expected of hermetic storage were achieved, since no live insects were found and the quality of the grain at the end of the 76 days storage period was comparatively good, even that of the 15.6% mc grain.

(2) The low viability and a slight sour odor in the 15.6% mc grain was not surprising since this moisture level is above the safe limits of grain intended to be preserved for human consumption (Hyde and Burrell, 1982). However, if it had not been in airtight storage there would have been much more deterioration from mold.

(3) Five of the most commonly-used quality assessment criteria are kernel viability, percent kernels invaded by storage fungi, grain appearance, color and odor.According to all these criteria the 9.9 and 12.8%-mc grains were in good condition.

(4) Hermetic storage is a method to be recommended to small scale farmers for dry grain storage if they have access to appropriate containers, as well as to commercial farmers who can afford hermetic structures.

(5) The method may also be used for the storage of damp grain as recommended by several earlier workers including Hyde and Oxley (1960), Hall and Hyde (1954), Hyde (1970, 1973a), and Wills et al. (1983), provided great care is taken in the management because any development of leaks is hazardous (Hyde, 1969b).

(6) If mc is high enough for anaerobic respiration, the grain will develop odors and flavors unsuitable for human consumption.

EXPERIMENT II

UNDERGROUND PIT STORAGE OF PEARL MILLET, PENNISETUM AMERICANUM(L.) LEEKE.

Objectives

The objectives of the experiment were to compare two types of millet storage pits (having straw or plastic linings) as regards to:

1. carbon dioxide and oxygen concentrations, temperature and relative humidity in the intergranular atmosphere,
2. growth of insect populations,
3. terminal percent grain mc, mold infection, and viability,
4. volumetric water canges in the soil around the pits.

Materials and Methods

Experimental Pits. Six pits were dug on May 9, 1984 using a 2-ft (60 cm) diameter auger mounted on a tractor. They were located on the Food and Feed Grain Institute storage site on Kimball Avenue, KSU campus. The pits were spaced 6 ft (1.8 m) apart, center to center (Fig. 2.1A). They were manually cleaned using a shovel, and the three that were to have straw linings were widened to a diameter of 80 cm to allow for a 10 cm-thick layer of straw between the grain and the soil. The depths were 85 cm for the pits to be plastic lined and 95 cm for those to be straw lined (Fig. 2.2 shows the layout). The treatments were randomly assigned to the pits.

Shelter for the Pits. In order to protect the pits from rain and to ensure dry working conditions, a pole building with closed sides on the west and south was constructed over them in June 1984 (Fig. 2.1B).

Figure 2.1 (A) The newly dug pits. The soil was later removed and the straw-lined pits were enlarged to 80 cm diameter X 95 cm deep.

(B) The pole building over the pits; the two closed sides of the building (West and South sides) are in the background.

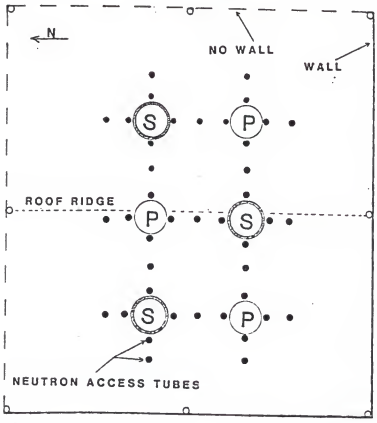
A

B

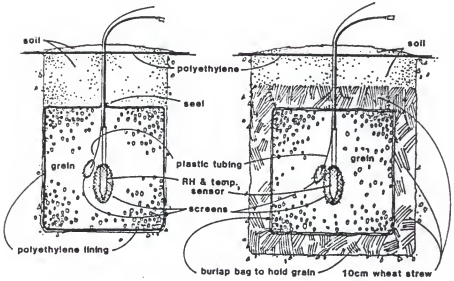
Figure 2.2 (A) Location of the pits under the pole building.

(B) Vertical sections of the two types of pits after they were filled and covered.

ARRANGEMENT OF PITS UNDER BUILDING



A



B

Monitoring Soil Moisture Changes. It is useful to study the moisture changes in the soil around experimental storage pits in order to account for the rate and amount of moisture changes within the grain and thus assess the effectiveness of pit wall lining meterials. A neutron moisture meter gives good estimates of soil H_2O content. The scientific theory for the use of a neutron moisture meter to estimate the soil H_2O content has been explained by Goodspeed (1981).

Forty-one aluminum neutron access tubes of 38 mm I.D. were inserted 100 cm deep between and around the pits and projected 5 cm above soil level to receive the neutron probe used for monitoring the soil moisture at 5 depths (20 cm, 30 cm, 50 cm, 80 cm and 90 cm) during the experiment (Fig. 2.3A). A Model 503 Hydroprobe Nuclear Depth Moisture Gauge, which measures the moisture content of materials at depths of 6" to 500' (15.24 cm to 152.4 m) using a radioactive source and internal electronics, was used (Fig 2.3B). The neutron counts recorded were later converted to volumetric water content figures using a calibration equation appropriate for the type of soil monitored (Wymore silty clay loam, 1-4% slope). The conversion equation was:

$\emptyset = 0.0494 + (0.0000222)$ (probe reading) where $\emptyset$ = volumetric water content.

The tubes were installed using a screw auger rotated by hand inside the access tube. The soil was removed about 15 cm at a time and then the tube was pounded in. Eight sets of obversations were made, one on each of the following dates: July 13 and 25; August 3, 17 and 31; September 14 and 26; and October 24, 1984.

Figure 2.3 (A) The 38-mm (ID) aluminum neutron access tubes (installed 100 cm deep) between and around the filled and covered pits; the ends of the tubes are closed with cork stoppers to prevent the entry of crawling animals.

(B) The Model 503 Hydroprobe Nuclear Depth Moisture Gauge attached on a neutron tube, and the cable fitted with neutron detector balls spaced at 10 cm intervals ready to be lowered to the required depths to obtain readings.

A

B

Grain. The pearl millet used, Pennisetum americanum (L.) Leeke, was harvested at Fort Hays Agricultural Experiment Station in Fall, 1983 and stored in 35 paper bags each holding 50 lb (22.7 kg) stacked on pallets in a metal building which was not heated or cooled.

Insects. Two species of insects—rice weevils [Sitophilus oryzae (L.)] and red flour beetles [Tribolium castaneum (Herbst)] reared in millet cultures in the Stored-Product Insects Laboratory were used to infest all of the pits at the rate of 5 insects of each species per kg of grain. The insects were 4-6 weeks old.

Filling Pits. The order of filling the pits (on July 10, 1984) was randomized. The bags of millet were numbered and then randomly selected for each pit. The weighed grain for each pit (127.5 kg) was placed in a 200-liter metal mixing drum, covered tightly, and rolled forward and backward over a distance of about 15 meters to mix the grain. After about half the grain was put into the pit, a temperature/relative humidity sensor wrapped in 60-mesh wire screen was placed in the grain. The ends of two 150-cm long small plastic tubing (0.020" or 5.08 mm I.D.) were also placed at this level after they were wrapped in a similar screen. The tubes extended to the outside of the pit so gas samples could later be withdrawn through them. Half of the insects, 325 rice weevils and 325 red flour beetles (counted earlier and placed into babyfood jars) were poured evenly over the grain at this time. The rest of the grain was then poured in while the sensor cable and tubings were held upright. The remainder of the insects were introduced just before the last 10% of the grain was poured in. The temperature/relative humidity apparatus used was a Model SN-1 Delmhorst Electronic Hygrometer/Thermometer with Model SN-1 sensors. The sensors were assigned randomly to the pits. The gas sampling tubing was type S-54-HL flexible crystal clear plastic tubing of 0.060" (15.2 mm) O.D. and 0.020" (5.08 mm) I.D.

For the plastic-lined pits, a 4-mil low-density polyethylene bag, 27" x 20" x 56.5" (68.6 cm x 50.8 cm x 143.5 cm), was placed in each pit and the grain was poured directly into the bag (Fig. 2.4A). The gas permeability information of the

material (personal communication from Joe Rothstein) for 100 cc/in^2 of material/1 mil/24 hr/25^{o}C are as follows:

Oxygen (O_2) 500 cc ÷4 = 125 cc/in^2 (19.4 cc/cm^2/24 hrs at 25^{o}C.

Carbon dioxide (CO_2) 2700 cc ÷4 = 675 cc/in^2 (104.6 cc/cm^2)/24 hrs at 25^{o}C.

Water Vapor (H_2O) 1950 cc ÷4 = 487.5 cc/in^2 (75.6 cc/cm^2)/24 hrs at 25^{o}C

Nitrogen (N_2) 180 cc ÷4 = 45 cc/in^2 (7.0 cc/cm^2)/24 hrs at 25^{o}C.

The excess top of the bag was folded over the grain and a hole cut through to allow passage of the sensor cable and plactic tubing to the outside. The hole was then sealed around the cable and tubing using plastic tape and a silicone caulking material. The pit was then covered with soil and gently compacted to soil surface level. It was then covered with a plastic sheet of the same material as the bag and a hole was also cut to pass the cable and tubings. A layer of 8-10 cm of soil was heaped over the plastic and gently compacted.

For the straw-lined pits, a uniform thickness of the wheat straw around the millet was acheived by using a sheet metal cylinder of 60-cm diameter and packing the straw between it and the soil and raising the cylinder as grain was poured into it (Fig. 2.4B). A large burlap bag sewn to size was used between the metal cylinder and straw during pit filling to hold the grain after removal of the metal cylinder, thus preventing the loss of grain into the straw. The sensors and tubings were installed in the same manner as for the plastic-lined pits, as well as the introduction of the insects. The remaining top of the burlap bag was folded over the grain and a layer of straw about the same thickness as along the walls was placed on top and covered with soil to ground level, after allowing the sensor cable and tubings to pass through to the outside. Sheet plastic was used to cover the pit and a layer of 8-10 cm of soil heaped over it as for the plastic-lined pits. Using pint jars, small samples were taken at intervals during the pouring of the grain into each pit. The samples from each pit were

Figure 2.4 (A) A plastic-lined pit filled with millet ready to be sealed and covered; the cable of the temp/RH sensor and the gas sampling plastic tubing are shown at the center.

(B) A straw-lined pit partly filled with millet and the temp/RH sensor placed at the center. The metal cylinder (50 cm high X 60 cm diameter) used to aid in filling the grain and placing the straw lining is inside the large burlap bag and 10-cm thick straw lining is between the burlap and pit wall.

A

B

mixed and sub-samples taken for determination of percentages of mold-infected kernels, germination, and moisture content using the same techniques described for the laboratory experiment.

Gas Sampling. For taking gas samples from the pits, six Series A2 1-ml Pressure-Lok Gas Sampling Syringes were used, each of which had a stop installed in the cylinder to allow only a 0.25 ml sample to be withdrawn from the pit through the plastic tubing. They were calibrated using standard gas mixtures to check for uniformity and were randomly assigned to the pits. The 125-ml Fisher Pyrex gas sampling tubes containing the standard gas mixtures used for comparison were taken to the pit site where the temperatures of the gases equilibrated with ambient. It was assumed that the temperature of the small gas sample (0.25 ml) withdrawn from the pit also equilibrated with ambient as it passed through the tubing and into the syringe. After withdrawing the sample, 15 seconds were allowed for pressure in the syringe to equilibrate before closing the pressure lock and withdrawing the needle from the tube. The sampling tubes and the syringes were then brought back to the laboratory where the samples were analyzed. The pressure of the standard mixtures in each cylinder was equilibrated by opening the cock for an instant and closing. This was done after the Pyrex sampling tubes were left on the covered pits for at least 30 minutes to allow the temperature to equilibrate. The analysis of the standards in the glass cylinders were compared with corresponding standards in tanks in the laboratory to ensure that there was no outside air mixture. Gas sampling was done at 4-day intervals during the first month and thereafter weekly until the end of the experiment. (Fig. 2.5). However, analyses for 8 sampling days were rejected because of poor performance of the gas partitioner. The chromatographic equipment used was the same as that used for the laboratory experiment.

Temperature and Relative Humidity. The temperature and relative humidity in the center of each pit were recorded when the gas samples were withdrawn. The

Figure 2.5 Withdrawing a gas sample from the center of the pit via the end of the type S-54-HL flexible crystal clear plastic tubing (of 15.2 mm OD * 5.1 mm ID) using the Series A2 1-ml Pressure-Lok Gas Sampling Syringe (left); temp and RH readings are being observed (right) on the Delmhorst Model HT-1 Electronic Hygrometer/Thermometer attached to the end of the cable of the Model SN-1 Temp/RH Sensor installed at the center of the grain bulk.

Delmhorst Model HT-1 Electronic Hygrometer/Thermometer was attached to the end of the sensor cable leading from each pit to obtain the readings.

Termination Procedures. On October 30, 1984, the pits were opened and samples of approximately 350 g were collected from three levels using pint jars. Nine samples were collected from each level (Fig. 2.6) and each sample was placed into a Ziploc plastic bag and closed. Each sample was sieved in the laboratory to separate live insects.

For grain moisture content calculation, 10- to 12-g samples were collected from the same locations described above and put into small aluminum drying dishes having tight-fitting covers and weighed soon afterward in the laboratory before moisture changes could occur.

Using thermocouples on a probe, terminal temperatures of the grain bulk were recorded at three depths as the pits were opened.

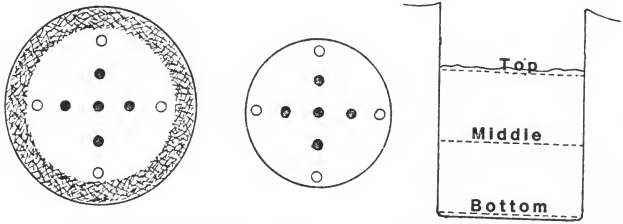
For summarizing, the data for the 5 central samples were composited as were the data for the 4 samples near the walls for each level.

After removal of the insects from all the samples, the 5 central samples for each level were combined, and the 4 wall samples were also combined. The composited samples were each mixed and sub-sampled to determine the percentages of kernels infected with storage molds and of viable kernels (Fig. 2.6). The methods for these determinations were the same as for the laboratory experiment.

Data Analysis. To determine significant differences between the treatments, the data were analyzed in the KSU Computer Center using Proc ANOVA and Proc GLM.

Figure 2.6 The locations from which the 27 samples of about 350 g each were taken from each pit when the pits were opened; the 10-12-g samples for mc determination were also taken from the same locations. The sites for samples composited (center and wall) for mold and viability tests are indicated.

LOCATION OF GRAIN SAMPLES



Samples per Level

- Center Samples
- Wall Samples

Levels Sampled

RESULTS

The seven variables analyzed to determine significant differences between treatments were the concentration of the respiratory gases (CO_2 and O_2), pit temperatures and relative humidities, live insects, types and extent of fungi infection of the grain, and kernel viability.

On termination, the plastic linings were still in good condition, but the straw was a bit matted due to molding. The grain from the plastic-lined pits was clean and uniform in all parts of the pit, but grain from the straw-lined pits looked moldy and dusty (but not caked) especially at the top and walls. Live insects were found in all pits, but significantly more in the straw-lined pits (Table 2.4).

Carbon Dioxide and Oxygen. In the straw-lined pits the CO_2 concentrations increased more and the O_2 decreased more than in the plastic-lined pits (Fig. 2.7A). The differences for both gases were significant. The CO_2 concentrations were significantly different between replications but not the O_2 concentrations (Table 2.1).

The final CO_2 and O_2 concentrations averaged 3.1% and 15.7% in the plastic-lined pits and 7.1% and 11.7% in the straw-lined pits, respectively. The mean changes in gas concentrations did not follow a smooth curve as in the laboratory hermetic storage experiment (Fig. 2.7A). The differences between the means of the two types of linings became significant only from day 89 for O_2 and day 96 for CO_2 concentrations.

Table 2.1. Respiratory gas concentrations in the center of 2 types of pearl millet storage pits (means of 3 replications).

Time (Days)	Oxygen %			Carbon dioxide %		
	Plastic[1]		Straw[1]	Plastic		Straw
2	18.96		19.25	0.40		0.43
6	20.01		18.55	1.16		1.02
10	16.63		14.96	1.37		1.62
14	16.11		15.31	2.01		2.03
61	14.30		15.63	3.49		2.19
68	14.39		14.59	3.01		2.84
89	16.56	*	12.26	3.31		4.14
96	15.56		13.79	3.75	*	5.68
103	15.71	*	11.96	4.07		5.63
110	15.72	*	11.68	3.10	*	7.09
Mean	16.40	*	14.80	2.57	*	3.27

[1]Pit wall lining material.

*Indicates significant difference between two adjacent values by T-test with $P<0.05$.

Temperature and Relative Humidity. The temperatures and relative humidities were significantly higher in the straw-lined pits than in the plastic-lined pits (Table 2.2). The temperature at the center of the grain was about 27.2°C in all pits at the start, but averaged 15.6°C in plastic-lined pits and 25.2°C in straw-lined pits at the end (Fig. 2.7B). The relative humidity reduced from an average of 68.1% to 66.3% in plastic-lined pits, but increased from 67.3% to 72.2% in straw-lined pits. The mean terminal temperatures at five locations each at the top, middle and bottom of the grain in each pit showed clearer details of the treatment differences and similarities; they were significantly higher at all locations and levels in straw-lined pits (Table 2.3). The ambient temperature and relative humidity was 8.2°C and 62%, respectively, during the opening of the pits. The temperature in pit No. 6 (straw-lined) was higher than that of the rest of the pits including the other two straw-lined pits, but the difference was not significant.

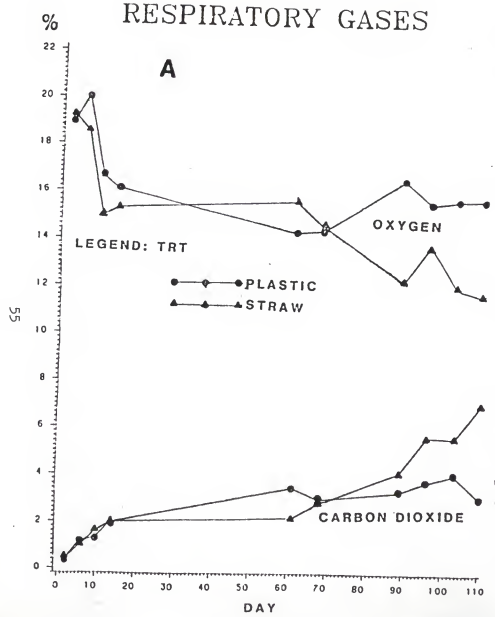
Grain Moisture Content (mc). The grain moisture content at the end of the storage period was much more uniform and significantly lower in the plastic-lined pits than in the straw-lined pits (Table 2.5). The mean grain mc in the plastic-lined pits at the end (13.4%) was not significantly different from the mc at the start (13.3%) while in the straw-lined pits the mc was significantly higher at the end (15.1%).

Insects. The numbers of rice weevils (RW) in all levels and locations were more for the straw-lined pits than for the plastic-lined pits (averaging 162.92/kg and 26.83/kg, respectively). Most of the differences were significant at the 5% level and the overall treatment means differed significantly at the 10% level (Table 2.4). There were more RW in the top level samples of both types of pits, followed by middle samples.

There was a reduction of the red flour beetle (RFB) populations from the original 5/kg in the plastic-lined pits to 1.18/kg, but there was an increase in the straw-lined pits to 16.34/kg (Table 2.4). Similar to the RW, there were more RFB in the surface grain. Some mites, psocids and sawtoothed grain beetles were found in samples from the straw-lined pits, but not in plastic-lined pit samples.

Figure 2.7 (A) SAS graph plot of the respiratory gas concentrations at the center of the grain bulk during the 112 day pit storage period (means of the 3 reps). Six data points are missing between days 14 and 61 and two between days 68 and 89 due to failure of the gas analyzer.

(B) SAS graph plot of the temperature (^{o}C) at the center of the grain bulk (means of the 3 reps).


%
RESPIRATORY GASES
A
LEGEND: TRT
PLASTIC
STRAW
OXYGEN
CARBON DIOXIDE
DAY

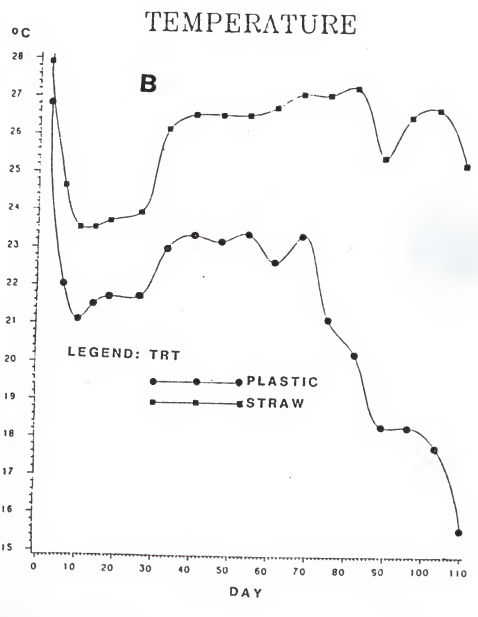

°C
TEMPERATURE
B
LEGEND: TRT
PLASTIC
STRAW
DAY

Table 2.2. Temperature and relative humidity in the centers of 2 types of pearl milet storage pits (means of 3 reps.).

Time (Days)	Temperature °C Plastic		Straw	Relative humidity % Plastic		Straw
2	26.83		27.90	68.07		67.33
6	22.03	*	24.63	67.33		66.90
10	21.10	*	23.53	66.83		66.63
14	21.50		23.53	67.03		66.47
18	21.70		23.70	67.13		67.07
26	21.70	*	23.90	67.13		66.67
33	22.97	*	26.10	66.67		66.53
40	23.30	*	26.50	66.87		66.73
47	23.13	*	26.50	66.93		67.07
54	23.33	*	26.50	67.20		67.40
61	22.60	*	26.70	67.47		68.00
68	23.30	*	27.07	67.20		68.60
75	21.10	*	27.03	67.00	*	69.53
82	20.20	*	27.23	67.00	*	69.47
89	18.30	*	25.37	67.33	*	71.13
96	18.30	*	26.47	66.67	*	70.73
103	17.77	*	26.67	67.20	*	72.00
110	15.60	*	25.20	66.33	*	72.20

* Indicates that the adjacent means are significantly different by T-test with $P<0.05$. The rest are not significantly different.

Fungi Infection. At the end of the storage period, the percent kernels infected by storage fungi was very significantly higher in samples from the straw-lined pits at all levels and locations than in samples from the plastic-lined pits, while the percentage of field fungi was correspondingly much lower in the straw-lined pits (Table 2.5). There were no significant differences among the pits of the same lining. The main species of fungi found are reported in Table 2.6.

Seed Viability. The percent germination of kernels decreased in both treatments, but the decrease was quite dramatic for grain in the straw-lined pits (from 82% to 16.9%) and much less (from 84.3% to 74.0%) for grain in the plastic-lined pits (Table 2.5). The reduction in seed viability was no doubt caused by storage fungi infection which were observed at the end of the germination test growing on the ungerminated kernels. As observed with grain moisture content, there was more uniformity in percent viable kernels at the different parts of the plastic-lined pits (with a range of 70.7 - 78%) than in straw-lined pits (with a range of 5.0 to 52.3%).

Soil Moisture Changes. The volumetric water content of the soil was not uniform by location, treatment or depth at the beginning. It was higher in the outer locations than adjacent to the pits for both treatments at start (3 days after pits were filled and covered), but the means for plastic-lined pits were higher than for straw-lined pits, though not significant. The differences continued to the end and the overall mean for plastic-lined pits was significantly greater than for the straw-lined pits (Table 2.7 and Appendix Table 3). It was shown that $B \neq 0$ but that $B_1 = B_2$ (Fig. 2.8) which means that there was a significant change in the volumetric water content of the soil during the period, but the rate of change was not significantly different between the two treatments.

Table 2.3. Temperatures of pearl millet at 5 locations at each of 3 levels taken immediately after pits were opened at the end of the storage experiment on October 30, 1984.

Level	Location	Temperature °C Plastic	Straw
Top	Center	14.47	19.07
	East	14.67	21.07
	North	14.60	20.53
	South	14.60	21.27
	West	14.73	21.07
Middle	Center	13.80	20.00
	East	14.20	23.20
	North	14.00	21.47
	South	14.07	23.27
	West	14.33	22.47
Bottom	Center	14.00	16.73
	East	13.67	19.33
	North	13.53	17.93
	South	13.40	19.80
	West	13.67	20.40
Mean	Overall	14.12	20.51

All corresponding means are significantly different between the 2 treatments by T-test with $P<0.05$.

Note. The maximum and minimum soil temperatures at 4" (5.16 cm) on the same day were 10°C and 7.8°C, respectively.

Table 2.4. Numbers of live red flour beetles (RFB) or rice weevils (RW) per kg in pearl millet stored in plastic-lined or straw-lined pits after 112 days (means of 3 reps).

Level	Location	RW/kg Plastic	Straw	RFB/kg Plastic	Straw	Total/kg Plastic	Straw
Top	Center	43.12	* 259.91	3.97	* 45.36	47.08	* 305.27
	Wall	113.61	* 294.06	2.59	* 43.33	116.20	* 337.39
Middle	Center	1.04	53.64	0.34	0.86	1.38	54.50
	Wall	3.23	* 184.32	0.00	7.11	3.23	* 191.44
Bottom	Center	0.00	30.35	0.17	0.52	0.17	* 30.87
	Wall	0.00	* 155.22	0.00	0.86	0.00	* 156.08
Mean		26.83	+ 162.92	1.18	* 16.34	28.01	* 179.26

* Indicates that the adjacent means are significantly different at 5% level while + indicates means significantly different at 10% level by T-test.

Table 2.5. Percent germination, moisture content, and fungi-infected pearl millet kernels at the beginning and end of 112-day pit storage in two types of pits.

Time	Trt.[1]	Level	Loc.	Fungi Field	Fungi Storage	Germ.	Moisture Content
Start	PL	Overall mean		56.0	4.0	84.3	13.3
	SL	Overall mean		52.7	5.3	82.0	13.3
End	PL	Top	Center	22.7	19.3	73.3	13.4
	SL	"	"	0.7	92.0	5.7	14.7
	PL	"	Wall	24.0	12.0	73.0	13.6
	SL	"	"	0.0	95.3	10.3	14.8
	PL	Middle	Center	23.3	6.7	70.7	13.2
	SL	"	"	12.0	26.7	52.3	14.1
	PL	"	Wall	25.3	14.0	72.7	13.4
	SL	"	"	6.7	84.0	14.7	14.7
	PL	Bottom	Center	32.0	3.3	78.0	13.3
	SL	"	"	6.7	78.0	13.7	16.0
	PL	"	Wall	26.0	6.0	76.3	13.4
	SL	"	"	12.7	88.0	5.0	16.1

All differences between the trts. at all levels and locations were significantly different at the end for all three variables at 5% level by the T-test. The overall means at the start were not analyzed but were very nearly the same for all three variables.

[1]PL = plastic-lined pits and SL = straw-lined pits.

Table 2.6. Principal species of fungi found in millet kernels from the two types of pits at the end of 112 days storage.

Species of fungi	Percent kernels infected PL[1] Pits	SL[2] Pits
Field Fungi		
Alternaria spp	17.4	3.4
Fusarium spp	8.0	3.2
Storage Fungi		
Aspergillus glaucus	5.2	71.6
Aspergillus orchraceous	1.0	1.8
Aspergillus niger	1.4	0.2
Penicillium spp	3.1	5.8

[1]Plastic-lined

[2]Straw-lined

Figure 2.8 SAS graph plot of the treatment means of volumetric water changes in the soil around the pits (cm^3/cm^3 of soil).

VOLUMETRIC WATER CHANGES

IN THE SOIL AROUND PITS

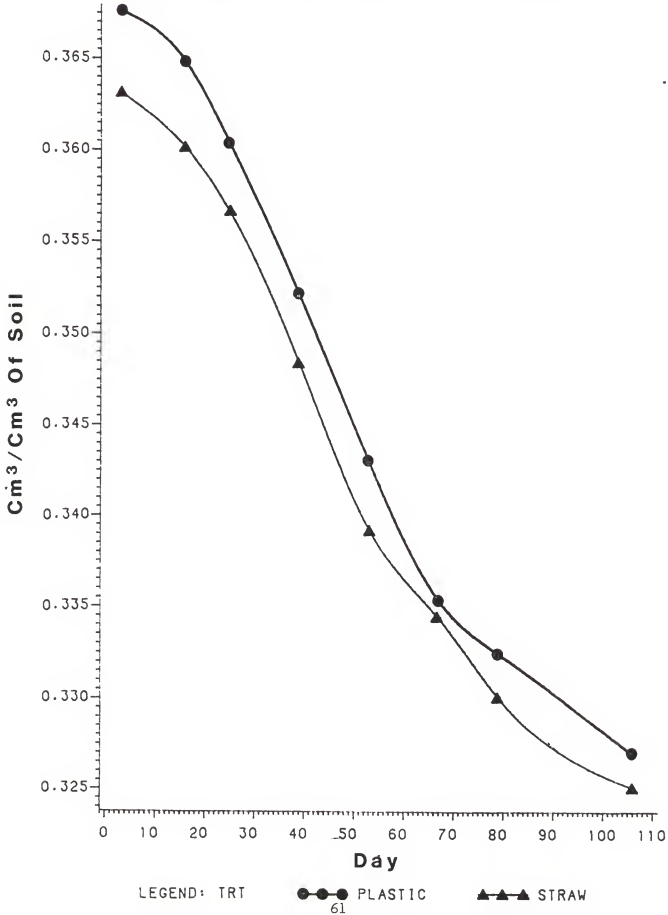


Table 2.7. The mean volumetric water content (cm^3/cm^3 soil) in the soil around the pits at 5 depths during the millet grain storage period.

Time	Depth (cm)	Inner[1] PL		SL	Outer[1] PL	SL	Treatment mean[2] PL		SL
At the start of storage	20	0.3723		0.3509	0.3765	0.3709	0.3744		0.3609
	30	0.3935		0.3891	0.3999	0.3966	0.3967		0.3929
	50	0.3827		0.3827	0.3854	0.3835	0.3840		0.3830
	80	0.3431		0.3410	0.3440	0.3417	0.3436		0.3413
	90	0.3400		0.3387	0.3389	0.3365	0.3394		0.3376
At the end of storage	20	0.2969		0.2823	0.2868	0.2946	0.2918		0.2884
	30	0.3386		0.3287	0.3383	0.3454	0.3385		0.3371
	50	0.3574		0.3557	0.3592	0.3604	0.3583		0.3581
	80	0.3249		0.3217	0.3274	0.3269	0.3262		0.3243
	90	0.3198		0.3185	0.3204	0.3164	0.3201		0.3174
mean for the whole storage period[3]	20	0.3315	*	0.3174	0.3287	0.3297	0.3301	*	0.3236
	30	0.3657	*	0.3567	0.3700	0.3707	0.3678		0.3637
	50	0.3725		0.3706	0.3748	0.3740	0.3737		0.3723
	80	0.3351		0.3334	0.3366	0.3339	0.3359		0.3336
	90	0.3316		0.3307	0.3319	0.3288	0.3318		0.3298

[1]Means of 4 tubes per pit x 3 pits per treatment i.e. 12 tubes.

[2]Means of 24 tubes (i.e. 8 tubes/pit x 3 pits/treatment.)

[3]Means of the 8 observations.

*Indicates significant difference between the adjacent means by T-test ($P<0.05$). Only overall means tested.

Discussion and Conclusions

Carbon Dioxide and Oxygen. An effective hermetic seal was not achieved in either type of pit since the O_2 did not decrease to lethal concentrations and the CO_2 did not increase as much as it would have in hermetic containers. The type of soil (Wymore silty clay loam) might have enhanced gas exchange as cracks were seen in the walls when the pits were opened. A sandy loam soil usually remains compact allowing less free air flow. Donahaye et al. (1967) were able to create within 7 wk a low O_2 (1%) and a high CO_2 (15%) atmosphere in a 50-ton barley underground storage pit sealed with a polythylene liner at Kibbutz Lahav. The O_2 decreased more and the CO_2 increased more in the straw-lined pits than in the

plastic-lined pits because of the higher biological activities in the former, particularly the respiration of the molds in the grain and straw as well as the respiration of the insects and perhaps grain. The pits were filled and covered in the summer when it was hot. The soil temp at 4" (10.16cm) at the agronomy farm meteorological station about 200m NW of the experimental site was 35.6 ^{o}C maximum and 25 ^{o}C minimum on July 10, 1984 when the pits were filled. Air temperature on the same day was 35 ^{o}C max and 23.3 ^{o}C min and RH was 50%.

The monthly mean weather data during the storage period are given in Appendix Table 4. Moisture migration from the soil increased the RH and grain mc in the straw-lined pits which enhanced mold growth in the straw and grain as well as the insect development and reproduction. The cumulative respiration of these organisms kept the temperatures in the straw-lined pits higher than the soil temperature when the soil cooled down in the fall (Sept. and Oct.) Increase of CO_2 was greater and decrease of O_2 was greater in the straw-lined pits than in the plastic-lined pits in which biological activities were slower. Due to the gas exchange between the pits and the surrounding soil, the combination of CO_2 increase and O_2 decrease did not result in an atmosphere lethal to the organisms present. The CO_2 and O_2 concentrations fluctuated in both pits over the period thus indicating that there was some gas exchange in both types of pits. The atmospheric changes were greater in the straw-lined pits due to the factors explained above, in spite of a lack of wall seals. A similar situation was also reported by Reynolds (1967) when he monitored CO_2 concentrations in pits lined with basketry over a 6-month period and the concentration never increased above 7%. He didn't monitor O_2. Anon (1960) monitored O_2 concentrations in a Guinea corn underground storage pit in Northern Nigeria and observed fluctuations between 7 and 14% from July 1958 to March 1959; but when a leak was repaired in March 1959 the fluctuations reduced and by August 1959 the mean O_2 concentration was about 10%. CO_2 was not monitored.

Temperature and Relative Humidity. Moisture migration from the surrounding soil increased the relative humidity (RH) in the straw-lined pits while the plastic provided an effective moisture barrier at least for the storage period used. The increased biological activities in the straw-lined pits (particularly the respiration of molds, insects and grain), enhanced by moisture migration from the soil, raised the temperatures (Table 2.2). As the soil temperatures reduced in the fall, those in the plastic-lined pits gradually reached near equilibrium with soil temperatures but those in the straw-lined pits remained higher. The terminal temperatures at 15 points in each pit (Table 2.3) reflected the same average pattern over the storage period. They were lower and more uniform in plastic-lined than in straw-lined pits, and were lowest in the bottom level of both pits where the mc was highest. This was a reversed pattern to what was reported earlier by Swaine (1957) who in Tanganyika (now Tanzania), recorded increasing temperatures with increasing grain mc in the same pit over a period of 118 days. The difference was probably due to the differences in soil temperatures in the two areas. In Tanzania as in other parts of the tropics soil temperatures remain fairly high and biological activities increase with increase in grain mc, and temperatures also increase with increase in biological activities. In Kansas as in other parts of the temperate zone, the soil was cool in October and influenced the temperature of the grain near it.

Grain Moisture Content. Moisture migration from the soil increased the grain moisture content in the straw-lined pits from a mean of 13.3% to 15.1% at the end of the storage period while there was no change in the mc of the grain in the plastic-lined pits. Within the straw-lined pits, there was greater variation in grain mc than within the plastic-lined pits. In one of the straw-lined pits (#4), the range was from 13.53% in the middle center location to 17.26% in the bottom south location between the center and wall and in another (#2), the range was from 13.72% in the middle center location to 16.92% in the bottom north wall location (differences of 3.73% and 3.2%, respectively). There was no range of

more than 1% in any of the plastic-lined pits. Girish et al. (1972) reported similar results with grain in two types of pits (the "kaccha khatties" and the "pucca khatties") in India. The "kaccha khatties" which remained cooler during the grain storage period also had less variation in grain mc among various locations in the pit than in the grain in the "pucca khatties" which were warmer. Also, Donahaye et al. (1967) observed very small changes in the mc of barley stored "in an underground pit sealed with a polyethylene liner."

Insects. More insects were found in the straw-lined pits than in the plastic-lined pits because of more favorable conditions in the former i.e., higher temp, RH, and grain mc. Rice weevil (RW) populations increased in both types of pits but much faster in the straw-lined pits (a mean of about 27 RW/kg in plastic-lined pits and a mean of about 163 RW/kg in straw-lined pits at the end of the 112 days storage period). The red flour beetle (RFB) populations decreased in the plastic-lined pits but increased slightly in the straw-lined pits. The relatively slow population increase may have been influenced by the lack of enough damaged grain, unfavorable atmospheric conditions, and below optimal temperatures. Cotton and Wilbur (1982) reported that Howe (1956) found the optimum conditions for the growth and development of RFB to be between 35-37.5°C and >70% RH where they took only 20 days to develop from egg to adult but may take about 75 days at 22°C and 70% RH. Howe's tests were probably not in whole grain, which is less suitable for RFB. The temperatures in the plastic-lined pits were usually below 22°C and the RH never reached 70%. Some early workers (Prevett, 1963 and Surtees, 1963b) consider the RFB to be a secondary pest which is not able to develop successfully in whole grain. The sawtoothed grain beetles (STGB) found in the straw-lined pits probably came from the straw. The mites and psocids found in these same pits probably also came from the straw since none were found in the plastic-lined pits, and high moisture in the straw-lined pits favored their development. Concerning the distribution of insects in grain, there are conflicting reports on the subject. Girish et al. (1972)

reported that insects were found only on the top layers of grain in the two types of pits he studied in India, but Swaine (1957) reported that the few insects found at the end of his underground maize storage trials in Tanzania were "evenly distributed in the consignment" and comprised of RW, RFB and STGB. Surtees (1963a, 1963b) reported "that disturbance typically results in upward dispersal of stored-product beetles." As there were more insects in the top layers of both types of pits, it might be assumed, considering Surtees' findings, that some of the insects moved upward during the opening and emptying operations of the pits. However, this is unlikely since the intergranular spaces are too small for rapid insect movements, especially insects the size of RFB and RW. The almost complete absence of insects in the bottom of the plastic-lined pits (0.0 RW/kg and only 0.2 RFB/kg) may have been due to the lower temp there (i.e. 13.7°C compared to 14.6°C at the top).

Fungi Infection. Moisture migration from the surrounding soil into the straw and outer grain in the straw-lined pits encouraged more mold growth in both straw and grain than in the plastic-lined pits in which the grain remained too dry for any significant storage fungi activity. Hyde (1969b) reported that there is little change in the properties of cereal grains in airtight storage if the moisture content is 12-13% or lower. Williams and McDonald (1983) postulated that the main requirements of preventing grain from storage fungi attack include the maintenance of low moisture and/or low temperature, and protection from insect infestation. Since the temperature range of storage fungi development is fairly wide, grain mc is much more the controlling factor. The minimum, optimum and maximum temperature ranges for growth of the common grain storage fungi have been reported by Busta et al. (1980).

The temperature ranges given for two fungi were:

Fungi	Temperature Range (°C)		
	Minimum	Optimum	Maximum
A. glaucus	0-5	30-35	40-45
Penicillium spp	-5-0	20-25	35-40

Therefore, temperatures were optimum for Penicillium spp and near optimum for A. glaucus in the straw-lined pits. These higher temp were caused by the respiration of the fungi themselves and insects. Since insects are known to spread fungal spores (Christensen and Kaufmann, 1969), insects could have been a factor in the greater mold activity in the straw-lined pits. Conditions in the plastic-lined pits were not conducive to mold activity, particularly the low grain mc (13.3%). The major field and storage fungi species found (Table 2.6) are the same as reported by Christensen and Kaufmann (1969) to be the common grain-infecting species.

Seed Viability. The percent germination was no doubt reduced by the storage fungi infection in both types of pits. Many workers have confirmed the fact that storage fungi infection reduces seed viability (Christensen and Kaufmann, 1969 and Singh et al., 1977). Singh et al. infested wheat with 2 levels of rice weevils and granary weevils (5 and 10% kernels infested) and studied their effect on fungi infection and on germination at the end of 49 days storage period. They reported among other things that the "fungi appear to be responsible for the loss of viability of seeds." The percent germination in the present study was negatively correlated to the percent of storage fungi infection with a correlation coefficient of -0.99.

Soil Moisture Changes. Initially the overall treatment mean volumetric water content of the soil was slightly more around the plastic-lined pits probably due to pit location, but the difference was not significant. The value was lower for the inner locations adjacent to the pit walls than for the outer

locations further away from the walls of both types of pits because of the diffusion of soil moisture into the empty atmosphere from the time pits were dug on May 9, 1984 until they were filled and covered on July 10, 1984 (61 days). The replacement from the outer locations was slower than the loss into the dry air (with low relative humidity of <60% and high temperatures of > 30°C for most of the period) thus creating the difference between the two locations. The amounts of water that diffused out of the soil around the two types of pits were not significantly different, however the straw and grain in the straw-lined pits absorbed more water than the grain in the plastic-lined pits. The H_2O loss from the soil around the plastic-lined pits during the storage period must have been mainly through evaporation into the atmosphere rather than through the plastic lining into the grain since the RH and mc in the grain bulk did not change significantly, during the storage period.

General Conclusions. The plastic-lined pits were superior to the straw-lined pits for storage of pearl millet because:

1. there was less moisture migration from the soil into the grain;
2. insect populations remained smaller;
3. kernel infection by storage molds was less; and
4. viability of kernels decreased less.

Even though the straw lining was inferior to the plastic lining for the above reasons, it did absorb some moisture coming from the soil which enhanced mold activity in the straw which contributed to the decrease of O_2 and increase of CO_2 concentrations in the straw-lined pits.

Plastic, perhaps a type with less permeability to CO_2 and O_2, can be recommended for lining of pits used for millet storage. Perhaps a combination of straw next to the soil and plastic inside would be superior to plastic alone; the straw would absorb moisture and thus retard its flow toward the grain.

Ambler, J. R. 1977. The Anasazi, Prehistoric People of the Four Corners Region. Museum of Northern Arizona Publications, Arizona. 52 pp.

Annis, P. C., H. J. Banks, and Sukardi. 1984. Insect control in stacks of bagged rice using carbon dioxide treatment and an experitmental PVC-membrane enclosure. CSIRO Aust. Div. Entomol. Tech. Pap. No. 22, 1-38.

Anon. 1959. Underground pit. W. Afr. Stored Prod. Res. Unit A. Rep., 1958, Paras 189-191. WASPRU, Dept. of Marketing and Exports, Lagos, Nigeria.

_____. 1960. Underground grain storage pit. W. Afr. Stored Prod. Res. Unit A. Rep., 1959, paras 158-166. Dept. of Marketing and Exports, Lagos, Nigeria.

Bailey, S. W. 1955. Air-tight storage of grain; its effects on insect pests. I. Calandra granaria L. (Coleoptera, Curculionidae). Aust. J. Agric. Res. 6: 35-51.

_____. 1956. Air-tight storage of grain; its effects on insect pests. II. Calandra oryzae (small strain). Aust. J. Agric. Res. 7: 7-19.

_____. 1957. Airtight storage of grain; its effects on insect pests. III. Calandra oryzae (large strain). Aust. J. Agric. Res. 8: 595-603.

_____. 1965. Air-tight storage of grain; its effects on insect pests. IV. Rhyzopertha dominica (F.) and some other Coleoptera that infest stored grain. J. Stored Prod. Res. 36: 256-283.

Baker, A. A. 1973. Small scale structures. pp. 16-36. In: Airtight Grain Storage (with particular reference to hot climates and developing countries). FAO Agric. Service Bull. 17.

Banks, H. J. 1981. Effects of controlled atmosphere storage on grain quality: a review. Food Technology in Australia 33 (7): 335-340.

Banks, H. J., and P. C. Annis. 1977. Suggested procedures for controlled atmosphere storage of dry grain. CSIRO Aust. Div. Entomol. Tech. Pap. No. 13, 23 pp.

_____. 1980. Experimental and commercial modified atmosphere treatment of stored grain in Australia. pp. 207-224. In: J. Shejbal, Ed. Controlled Atmosphere Storage of Grains. Elsevier Scientific Publishing Co., Amsterdam.

Bechtel, H. E., F. W. Atkesen, F. C. Fenton, and W. M. Carleton. 1945. Pit silos for the storage of Atlas sorgo grain and soft corn. J. Anim. Sc. 4 (4): 438-452.

Bowen, H. C., and P. D. Wood. 1968. Experimental storage of corn underground and its implications for Iron Age settlements. Univ. Lond. Inst. Archaeol. Bull. 7.

Boxall, R. A. 1974. Underground storage of grain in Harar Province, Ethiopia. Trop. Stored Prod. Info. 28: 39-48.

Brown, W. 1922. On the germination and growth of fungi at various temperatures and in various concentrations of oxygen and of carbon dioxide. Ann. Bot., 36: 257-283.

Burrell, N. J. 1980. Effect of airtight storage on insect pests of stored products. pp. 55-62. In: J. Shejbal, Ed. Controlled Atmosphere Storage of Grains. Elsevier Scientific Publishing Co., Amsterdam.

Busta, F. F., L. B. Smith, and C. M. Christensen. 1980. Microbiology of controlled atmosphere storage of grains—an overview. pp. 121-132. In: J. Shejbal, Ed. Controlled Atmosphere Storage of Grains. Elsevier Scientific Publishing Co., Amsterdam.

Calderon, M. and S. Navarro. 1980. Synergistic effect of CO_2 and O_2 mixtures on two stored grain insect pests. pp. 79-84. In: J. Shejbal, Ed. Controlled Atmosphere Storage of Grains. Elsevier Scientific Publishing Co., Amsterdam.

Choyce, M. A. 1960. Review of work in agricultural entomology, Nigeria. Rep. 7th Commonw. Ent. Conf., pp. 326-327.

Christensen, C. M., and H. H. Kaufmann. 1969. Grain Storage: The Role of Fungi in Quality Loss. University of Minnesota Press. Minneapolis. U.S.A. 153 pp.

Christensen, C. M., and D. B. Sauer. 1982. Microflora. pp. 219-280. In: Christensen, C. M., Ed. Storage of Cereal Grains and Their Products. Amer. Assoc. of Cereal Chem. St. Paul, Minnesota. 544 pp.

Cole, F. J. 1906. The bionomics of grain weevils. J. Econ. Biol. 1 (2): 63-71.

Cotton, R. T. 1950. Insect Pests of Stored Grain and Grain Products. Burgess Publishing Co., Minneapolis, Minnesota.

Cotton, R. T., and D. A. Wilbur. 1982. Insects. In: C. M. Christensen, Ed. Storage of Cereal Grains and Their Products. Amer. Assoc. of Cereal Chem. St. Paul, Minnesota. 544 pp.

DeLima, C. P. F. 1978. A review of the use of physical storage procedures in East Africa: aspects for improvement and extension. Proceedings of the 2nd Intern. Working Conf. on Stored-Prod. Entom., Ibadan, Nigeria, 237-242.

_____. 1980. Field experience with hermetic storage of grain in Eastern Africa with emphasis on structures intended for famine reserves. pp. 39-53. In: J. Shejbal, Ed. Developments in Agricultural Engineering—1. Elsevier Scientific Publishing Co., Amsterdam.

Dendy, A. 1918. Report on the effect of air-tight storage upon grain insects. Part I. Rep. Grain Pests (War) Comm. No. 1, 6-24.

Donahaye, E., S. Navarro, and M. Calderon. 1967. Storage of barley in an underground pit sealed with a polyethylene liner. J. Stored Prod. Res., 3: 359-364.

FAO Production Yearbook 1983, Vol. 36. Food and Agricultural Organization, Rome, Italy. 1984.

Gilman, G. A. and R. A. Boxall. 1974. The storage of food grain in traditional underground pits. Trop. Stored Prod. Info. 28:19-38.

Girish, G. K. 1970. Respiration of grain under storage conditions. Bull. of Grain Tech. 8 (1 & 2): 22-29.

Girish, G. K., R. K. Goyal, R. P. S. Tomer, P. K. Srivastowa, and K. Krishnamurthy. 1972. Bull. of Grain Tech. 10 (1): 11-21.

Goodspeed, M. J. 1981. Neutron meter theory. pp. 16-23. In: E. L. Greacen, Ed. Soil Water Assessment by the Neutron Method. CSIRO Canberra, Australia. 140 pp.

Hall, D. W. 1970. Handling and Storage of Food Grains in Tropical and Subtropical Areas. Food and Agricultural Organization, Rome, Italy. 350 pp.

Hall, D. W., and M. B. Hyde. 1954. The modern method of hermetic storage. Trop. Agric., Trin., 31 (2): 149-160.

Hill, R. A., J. Lacey, and P. J. Reynolds. 1983. Storage of barley grain in iron type underground pits. J. Stored Prod. Res. 19 (4): 163-171.

Howe, R. W. 1956. The effect of temperature and humidity on the rate of development and mortality of Tribolium castaneum (Herbst) (Coleoptera, Tenebrionidae). Ann. Appl. Biol. 44 (2): 356-368.

Hyde, M. B. 1969a. New storage systems in relation to infestation problems. Chem. and Indust., 1448-1451.

_____. 1969b. Hazards of storing high moisture grain in airtight silos in tropical countries. Trop. Stored Prod. Inf. 18: 9-12.

_____. 1970. Storage trials with moist barley and field beans in polyvinyl chloride and butyl rubber silos. Proceedings 4th International Colloquium on Plastics and Agriculture, Paris, June 1970. 178-185.

_____. 1973a. Scientific principles of airtight storage. pp. 1-15. In: Airtight Grain Storage (with particular reference to hot climates and developing countries). FAO Agric. Service Bull. 17.

_____. 1973b. Storage of grain in airtight silos or under vacuum. Ann. Technol. Agric., 1973. 22 (4): 707-718.

Hyde, M. B., and N. J. Burrell. 1969. Control of infestation in stored grain by airtight storage or by cooling. Proc. 5th Insecticides and Fungicides Conference. Brighton, 17-20 Nov. 1969. Br. Crop Bot. Council, London, pp. 412-419.

Hyde, M. B., and N. J. Burrell. 1982. Controlled atmosphere storage. pp. 443-478. In: C. M. Christensen, Ed. Storage of Cereal Grains and Their Products. American Assoc. of Cereal Chem. St. Paul, Minnesota. 544 pp.

Hyde, M. B., and T. A. Oxley. 1960. Experiments on the airtight storage of damp grain. I. Introduction, effect on the grain and the intergranular atmosphere. Ann. Appl. Biol. 48: 687-710.

Jay, E. G. 1971. Suggested conditions and procedures for using carbon dioxide to control insects in grain storage facilities. U.S.D.A. Agricultural Research Service. ARS 51/46.

_____, and G. C. Pearman, Jr. 1973. Carbon dioxide for control of an insect infestation in stored corn (maize). J. Stored Prod. Res., 9: 25-29.

Kashi, K. P. 1981. Controlling Pests in stored grain with carbon dioxide. Span 24 (2): 69-70.

Khalifa, A. 1960. On open-air and underground grain storage in the Sudan. Bull. Soc. Entomol. Egypte 44: 129-142.

Lacey, J. 1972. The microbiology of grain stored underground in Iron Age type pits. J. Stored Prod. Res., 8: 151-154.

Lindgren, D. L. 1935. The respiration of insects in relation to the heating and the fumigation of grain. Tech. Bull. Minn. Agric. Exp. Stn. No. 109. 32 pp.

Lopez, C. O. 1973. Airtight underground silos (AUS) in Argentina. pp. 54-65. In: Air-tight Grain Storage (with particular reference to hot climates and developing countries). FAO Agric. Serv. Bull. 17.

Luders, D. J. 1970. Storage of grain in hermetically sealed storage, both above and below ground; a review. Farm Manag. (Australia) 6 (2): 1-5.

Martin, J. H., W. H. Leonard, and D. L. Stamp. 1976. Principles of Field Crop Production. 3rd ed. Macmillan, New York. 1118 pp.

McCabe, J. B. 1976. Storing wheat in underground pits. Bulk Wheat 10: 21-22.

Navarro, S. 1978. The effects of low oxygen tensions on three stored-product insect pests. Phytoparasitica 6 (2): 51-58.

O'Dowd, E. T. 1971. Hermetic storage of cowpea (Vigna unguiculata Walp.) in small granaries, silos and pits in Northern Nigeria. (Samaru Misc. Paper 31). Institute for Agric. Res., Samaru, Zaria, Nigeria.

Paster, N., and I. Chet. 1983. Influence of controlled Atmospheres on the formation of Aspergillus orchraceus Scleratia, p. XI (Summary only). In: Progress Report for the Year 1981/82 of the Stored Products Division. Agric. Res. Org., Bet Dagan, Israel.

Peterson, A., V. Schlegel, B. Hummel, L. S. Cuendet, W. F. Geddes, and C. M. Christensen. 1956. Grain storage studies. XXII. Influence of oxygen and carbon dioxide concentrations on mold growth and grain deterioration. Cereal Chem. 33 (1): 53-66.

Pomeranz, Y. 1982. Biochemical, functional, and nutritive changes during storage. pp. 145-217. In: C. M. Christensen, Ed. Storage of Cereal Grains and Their Products. Am. Assoc. Cereal Chem. St. Paul, MN.

Prevett, P. F. 1963. Underground pit storage of sorghum. W. Afr. Stored Prod. Res. Unit A Rep., 1962, pp. 79-81. WASPRU, Fed. Min. Commerce and Industry, Lagos, Nigeria.

Pruthi, H. S., and M. Singh. 1948. Pests of Stored Grain and Their Control. Gov't of India Press, Calcutta, India.

Purseglove, J. W. 1968. Tropical Crops: Dicotyledons, 2 Vols. Longmans, London. 719 pp.

_____. 1972. Tropical Crops: Monocotyledons, 2 Vols. Longmans, London. 607 pp.

Pushpamma, P., and R. K. Chittemma. 1981. Varietal Preference, Marketing, Storage, Processing and Utilization of Sorghum and Millets in Andhra Pradesh. Andhra Pradesh Agricultural University, Hyderabad, India. 81 pp.

Ramasivan, T., K. Krishnamurthy, and S. V. Pingale. 1966. Studies on preservation of food grains in rural storage, Part I: Rural storage of food grains. Bull. Grain Tech. 4 (4): 177-194.

_____. 1968. Studies on preservation of food grains in rural storage, Part II: storage of grain in villages near Hapur. Bull. Grain Tech. 6 (2): 69-75.

Reynolds, P. J. 1967. Experiment in Iron Age agriculture. Trans. Bristol Gloucestershire Archaeol. Soc. 86: 60-73.

_____. 1969. Experiment in Iron Age agriculture. Trans. Bristol Gloucestershire Archaeol. Soc. 88: 28-33.

Shellenberger, J. A. and F. C. Fenton. 1952. Underground grain storage. Milling Production 17 (7): 5, 12-16.

Sigaut, F. 1980. Significance of underground storage in traditional systems of grain production. pp. 3-13. In: J. Shejbal, Ed. Controlled Atmosphere Storage of Grains. Elsevier Scientific Publishing Co., Amsterdam.

Singh, N. B., R. N. Sinha, and H. A. Wallace. 1977. Changes in O_2, CO_2 and microflora of stored wheat induced by weevils. Environ. Entomol. 6 (1): 111-117.

Sterling, R. L., G. D. Meixel, F. Dunkel, and C. Fairhurst. 1983. Underground storage of food. Underground Space 7: 257-262.

Surtees, G. 1963a. Laboratory studies on dispersion behavior of adult beetles in grain I—The grain weevil, Sitophilus granarius (L.) (Coleoptera, Curculionidae). Bull. of Entomol. Res. 54 (1): 147-159.

_____. 1963b. Laboratory studies on dispersion behavior of adult beetles in grain, III—Tribolium castaneum (Herbst) (Coleoptera, Tenebrionidae) and Cryptolestes ferrugineus (Steph.) (Coleoptera, Cucujidae). Bull. of Entomol. Res., 54 (2): 297-306.

Swaine, G. 1954. Underground storage of maize in Tanganyika. E. Afr. Agric. J. 20: 122-128.

_____. 1957. Trials on the underground storage of maize of high moisture content in Tanganyika. Bull. of Entomol. Res. 48 (2): 397-406.

USDA. 1982. Carbon dioxide used for insect control. Milling and Baking News, August 10, 1982. pp. 36-38.

Wendorf, F., A. E. Close, and R. Schild. 1985. Prehistoric settlements in the Nubian Desert. Amer. Sc. 73 (2): 132-141.

White, N. D. G., V. F. Wright, F. L. Watters, and R. B. Mills. 1983. Future directions and current problems for stored product entomology. Bull. Entomol. Soc. Amer. Summer 1983. pp. 35-37.

Williams, R. J., and D. McDonald. 1983. Grain molds in the tropics: problems and importance. Ann. Rev. Phytopathol. 21: 153-178.

Will, G. F., and G. E. Hyde. 1917. Corn Among the Indians of the Upper Missouri. University of Nebraska Press, Lincoln, Nebraska. 323 pp.

Wills, R. B. H., S. Moeljopawiro, L. Moore, and K. J. Scott. 1983. Short-term storage of high-moisture rice in sealed containers. Trop. Agric. (Trinidad) 60 (1): 36-40.

Wright, F. N., and B. J. Southgate. 1962. The potential uses of plastics for storage with particular reference to rural Africa. Trop. Sc. 4 (2): 74-81.

ACKNOWLEDGEMENTS

My sincere appreciation is extended to Dr. Robert B. Mills, my major advisor, who proposed this challenging research project and provided assistance throughout, not only counselling, but considerable physical "labor" on parts of it.

Mr. John Krchma is acknowledged for his technical expertise and ever-willingness to keep a 20-year-old gas analyzer operating; this was important equipment for the study.

I am indebted to Mrs. Rosemary Burroughs for the generosity of her time and expertise in teaching and helping me in the preparation of mold tests and mold identification.

I am grateful to Dr. Ahmed M. Kadoum for loaning me his two digital integrators for the gas analyzer; this eliminated the laborious measurement and calculation of gas peak areas on the recorder papers.

I thank all the rest of my committee members for their professional advise whenever contacted, and for the time they spent on committee meetings and reviewing the thesis——Dr. T. L. Hopkins, Professor of entomology; Dr. G. E. Wilde, Professor of entomology; Dr. J. R. Pedersen, Associate Professor of Grain Science and Industry; and Dr. J. B. Sisson, Professor of Agronomy, who also provided counseling and equipment for monitoring the soil moisture changes.

I express sincere appreciation to Dr. Robert G. Helgesen, Head, and the Department of Entomology staff in general, for the use of facilities, equipment, and other assistance during the conduct of my research.

The following persons who offered assistance in a variety of ways to enhance the study also need special recognition. They are:

Dr. L. Pinkerton, who supplied the tractor with a post-hole digger to dig the pits;

Mr. Joe Wilson, who assisted in several operations especially in shed construction and neutron pipe installation;

Mr. Dale Reed, who supplied the pipe installation equipment;

Mrs. Shenck-Hamlin, Head, and the staff of Post Harvest Documentation Service in general, who did the literature search and supplied the articles for review;

Dr. Alberto Broce, who advised on suitable airtight containers;

Dr. Kenneth E. Kemp, who advised on the appropriate statistical tests of the data;

Dr. Valerie F. Wright, who organized the recording of the pit terminal temperatures;

Dr. David Sauer, who advised on the activities dealing with grain microorganisms; other Stored-Product Insect Laboratory personnel who assisted in one way or the other especially in the terminal operations and final data collection of the pit experiment. I sincerely thank all of them for their help. I also wish to thank Mrs. Sandie Anderson for the personal interest and excellent work done in typing this thesis.

Finally, I wish to extend my sincere appreciation to my sponsors—The Ministry of Higher Education and Scientific Research, Cameroon, and the USAID Mission for providing me the opportunity and funds to pursue these studies.

VITA

Cletus Tangwe Asanga, son of Mr. Nicholas Asanga and Mama Catherine Abowmbia, was born on Jan. 4, 1943 in Bambili village, Bamenda, Cameroon. He attended primary school in St. Peters Catholic School, Bambui, 4 km away from his home from Jan. 1951 to Dec. 1958. From Jan. 1959 to Dec. 1963 he pursued secondary school education in St. Joseph's College, Sasse near Buea, Cameroon.

After working as a bank clerk for 6 months, he studied general agriculture in a Junior Agricultural College in his village from July 1964 to Dec. 1965 and was selected for further studies abroad. Before proceeding for further studies, he worked as a Gov't Agric Extension Assistant I/C of his council area (Bafut Area Council, Bamenda) from Jan. 1966 to Aug. 1967.

From Sept. 1967 to July 1969 he studied Horticulture at Hadlow College, Kent, England where he obtained the British National Certificate in Horticulture (NCH) and the Kent Advanced Certificate in Commercial Fruit Production at credit level.

From Aug. 1969 to April 1974, he served as a Gov't. Agric. Extension Technical Officer I/C of four administrative divisions in succession. During the same period he held other posts of responsibility including the post of Cameroonian Coordinator of two foreign sponsored agricultural projects (a French project in Ndop, Bamenda from Sept. 1969 - July 1970 and a German project in Wum, in 1970/71). He headed a High Altitude Arabica Coffee Research Station in Santa, Bamenda from May 1974 to May 1978 and then he was appointed to take charge of the Horticultural Program of Ekona Research Center near Buea where he worked from June 1978 to Dec. 1981.

He was awarded a scholarship under the joint Cameroon Gov't./USAID sponsored Cameroon National Cereal Research and Extension Project to study in the U.S. from Jan. 1982 to July 1983 where he completed the requirements for a B.S. degree in Agronomy and a B.S. degree in Horticulture at Oklahoma State University.

While at OSU, he was 4 times on the President's honor roll and once on the Dean's honor roll for academic excellence.

In Aug. 1983 he gained admission to Kansas State University to persue an M.S. in grain storage entomology. He is a member of the Entomological Society of America, the American Society of Agronomy, and the Association for International Agricultural Education.

Appendix Table 1. Carbon dioxide concentrations (%) in millet grain intergranular atmosphere during hermetic storage in the laboratory for 76 days.

Day	9.9% mc		12.8% mc		15.6% mc	
	W/ RW	W/O RW	W/ RW	W/O RW	W/ RW	W/O RW
2	0.75	0.16	0.50	0.12	3.16	0.87
3	1.00	0.18	0.68	0.17	4.29	1.42
4	1.20	0.22	0.98	0.17	5.17	1.92
5	1.41	0.18	1.12	0.18	5.98	2.56
8	2.00	0.18	1.92	0.22	8.24	3.77
10	2.56	0.18	2.53	0.26	9.77	4.74
12	2.91	0.20	3.82	0.30	12.60	6.16
14	3.18	0.22	4.68	0.30	14.03	6.87
16	3.46	0.22	6.54	0.34	16.52	8.67
18	3.78	0.22	9.00	0.32	18.14	11.32
20	3.98	0.24	10.28	0.36	18.39	11.84
22	4.06	0.25	10.57	0.38	18.96	13.86
24	4.11	0.29	10.82	0.40	19.32	15.78
26	4.02	0.27	10.99	0.38	19.90	16.13
28	4.07	0.34	10.76	0.42	20.13	16.56
30	4.07	0.43	10.83	0.47	20.76	17.16
32	4.06	0.46	10.79	0.46	20.97	17.69
36	4.01	0.48	10.62	0.52	21.72	17.56
40	3.86	0.48	10.30	0.54	22.53	19.10
44	4.02	0.50	10.48	0.62	22.94	19.99
48	3.90	0.54	10.44	0.64	23.96	20.58
52	3.80	0.51	10.33	0.64	24.38	21.08
56	3.77	0.54	10.29	0.69	25.08	21.74
60	3.72	0.54	10.06	0.72	25.86	22.50
64	3.74	0.58	10.03	0.78	26.66	23.29
67	3.70	0.60	9.98	0.79	27.06	24.18
71	3.62	0.58	9.88	0.80	27.72	24.40
75	3.58	0.60	9.82	0.85	28.24	24.72
Means[1]	3.30a	0.36b	7.82c	0.46d	18.30e	14.16f

[1]Means followed by different letters are significantly different ($P<0.05$) by Duncan's multiple range test.

Appendix Table 2. Oxygen concentrations (%) in millet grain intergranular atmosphere during hermetic storage in the laboratory.

Day	9.9% mc		12.8% mc		15.6% mc	
	W/ RW	W/O RW	W/ RW	W/O RW	W/ RW	W/O RW
2	18.66	19.12	19.22	19.42	15.88	19.50
3	18.00	20.29	19.38	20.34	15.92	19.15
4	17.60	20.08	18.89	19.52	14.72	18.18
5	17.61	20.26	18.70	20.45	13.66	17.22
8	16.12	20.24	17.12	19.90	12.05	16.32
10	16.64	20.40	16.42	20.28	10.82	16.31
12	14.67	20.14	13.89	19.86	8.11	15.17
14	13.82	20.40	12.47	19.86	6.14	14.83
16	13.12	20.20	9.20	19.10	3.28	12.18
18	12.18	19.84	6.40	19.69	1.25	7.29
20	11.66	20.10	4.33	19.65	1.18	5.31
22	11.80	19.96	4.12	19.54	1.22	4.26
24	11.65	19.94	3.73	19.50	1.20	1.32
26	11.31	19.68	3.70	19.60	1.27	1.45
28	11.54	19.54	3.69	19.38	1.21	1.44
30	11.52	19.75	3.72	19.54	1.24	1.43
32	11.75	19.59	3.80	19.39	1.28	1.42
36	11.90	19.20	4.12	19.43	1.44	1.56
40	11.69	19.34	4.19	18.92	1.29	1.42
44	12.43	19.68	4.72	19.66	1.34	1.58
48	12.26	18.48	4.80	18.52	1.28	1.42
52	12.29	19.77	5.13	19.22	1.33	1.50
56	12.49	19.32	5.39	18.90	1.30	1.44
60	12.58	19.42	5.72	18.96	1.35	1.47
64	12.74	19.32	5.96	19.08	1.25	1.33
67	12.82	19.32	6.10	18.94	1.15	1.24
71	12.82	19.16	6.48	18.69	1.22	1.28
75	12.82	19.20	6.56	18.91	1.38	1.58
Means[1]	13.44a	19.70b	8.50c	19.44d	4.46e	6.74f

[1] Means followed by different letters are significantly different ($P<0.05$) by Duncan's multiple range test.

Appendix Table 3. The mean volumetric water content of the soil around the pits at 5 depths during the period of pearl millet grain storage.

Day	Depth (cm)	Inner		Outer		Treatment mean	
		PL	SL	PL	SL	PL	SL
3	20	0.3723	0.3509	0.3765	0.3709	0.3744	0.3609
	30	0.3935	0.3891	0.3999	0.3966	0.3967	0.3929
	50	0.3827	0.3824	0.3854	0.3835	0.3841	0.3830
	80	0.3431	0.3410	0.3440	0.3417	0.3436	0.3413
	90	0.3400	0.3387	0.3389	0.3365	0.3394	0.3376
16	20	0.3636	0.3533	0.3672	0.3612	0.3654	0.3572
	30	0.3899	0.3838	0.3974	0.3937	0.3936	0.3838
	50	0.3808	0.3810	0.3851	0.3829	0.3829	0.3820
	80	0.3431	0.3397	0.3442	0.3409	0.3437	0.3403
	90	0.3396	0.3382	0.3377	0.3363	0.3386	0.3372
25	20	0.3517	0.3420	0.3549	0.3486	0.3533	0.3453
	30	0.3831	0.3778	0.3924	0.3879	0.3878	0.3829
	50	0.3809	0.3789	0.3842	0.3822	0.3825	0.3806
	80	0.3408	0.3398	0.3421	0.3387	0.3414	0.3392
	90	0.3373	0.3353	0.3363	0.3342	0.3368	0.3348
39	20	0.3343	0.3234	0.3323	0.3299	0.3333	0.3267
	30	0.3715	0.3619	0.3761	0.3722	0.3738	0.3671
	50	0.3781	0.3747	0.3798	0.3775	0.3790	0.3761
	80	0.3385	0.3378	0.3396	0.3372	0.3390	0.3375
	90	0.3366	0.3352	0.3346	0.3332	0.3356	0.3342
53	20	0.3201	0.3053	0.3134	0.3154	0.3168	0.3104
	30	0.3582	0.3473	0.3610	0.3602	0.3596	0.3538
	50	0.3716	0.3675	0.3748	0.3716	0.3732	0.3695
	80	0.3323	0.3326	0.3350	0.3322	0.3336	0.3324
	90	0.3308	0.3304	0.3328	0.3294	0.3318	0.3299
67	20	0.3103	0.2940	0.3008	0.3127	0.3055	0.3034
	30	0.3462	0.3391	0.3503	0.3592	0.3483	0.3492
	50	0.3651	0.3637	0.3665	0.3696	0.3658	0.3667
	80	0.3292	0.3276	0.3317	0.3286	0.3305	0.3281
	90	0.3253	0.3253	0.3282	0.3233	0.3267	0.3243
79	20	0.3031	0.2881	0.2976	0.3044	0.3004	0.2963
	30	0.3444	0.3359	0.3443	0.3504	0.3444	0.3431
	50	0.3634	0.3604	0.3637	0.3641	0.3635	0.3623
	80	0.3287	0.3267	0.3292	0.3251	0.3290	0.3259
	90	0.3236	0.3237	0.3263	0.3213	0.3250	0.3226
106	20	0.2969	0.2823	0.2868	0.2946	0.2918	0.2884
	30	0.3386	0.3287	0.3383	0.3454	0.3385	0.3371
	50	0.3574	0.3557	0.3592	0.3604	0.3583	0.3581
	80	0.3249	0.3217	0.3274	0.3269	0.3262	0.3243
	90	0.3198	0.3185	0.3204	0.3164	0.3201	0.3174

Appendix Table 4. Weather data obtained from an automatic recording[a] station located on the KSU North Agronomy Farm about 200 m from the experimental pits site.

Month	Total Precip-itation (mm)[1]	Avg. RH %	Air Temperatures °C[2] Max	Air Temperatures °C[2] Min	Soil Temperatures °C[2] At 2 in (5.08 cm) Max	At 2 in (5.08 cm) Min	At 4 in (10.16 cm) Max	At 4 in (10.16 cm) Min
July	32.00							
Range		34-69	26.67-38.89	13.89-28.33	30.56-41.67	17.78-25.56	27.22-35.56	18.33-25.00
Mean		52.30	32.76	18.96	38.15	21.44	33.46	21.94
August	20.07							
Range		40-82	27.78-40.56	12.22-24.44	25.56-44.44	16.11-25.56	23.81-37.22	17.22-26.67
Mean	20.07	59.22	34.78	19.52	39.34	21.93	33.49	22.53
Sept.	110.74							
Range		32-88	10.00-36.67	-0.56-23.89	15.56-36.11	5.56-24.44	14.44-31.67	7.22-24.44
Mean		64.39	26.02	12.43	26.94	16.33	24.15	16.96
Oct.	102.11							
Range		54-89	9.44-26.11	-0.56-15.56	11.11-25.00	3.33-17.22	10.00-21.67	4.44-16.67
Mean		79.03	18.62	7.33	17.88	10.06	15.84	10.45

[1]Converted from inches.

[2]Converted from °F.

[a]By courtesy of Dr. Dean Bark, KSU Climatologist.

CHANGES IN ENVIRONMENT, GRAIN QUALITY, AND INSECT POPULATIONS IN PEARL MILLET, *PENNISETUM AMERICANUM* (L.) LEEKE, STORED IN AIRTIGHT CONTAINERS OR UNDERGROUND PITS.

BY

CLETUS TANGWE ASANGA

B.S. AGRONOMY, OKLAHOMA STATE UNIVERSITY 1983

B.S. HORTICULTURE, OKLAHOMA STATE UNIVERSITY 1983

AN ABSTRACT OF A MASTER'S THESIS

Submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Entomology

KANSAS STATE UNIVERSITY

Manhattan, Kansas

1985

ABSTRACT

Two "airtight" methods of storing pearl millet, Pennisetum americanum (L.) Leeke, were compared for effects on intergranular atmosphere, insects, mold-infection, grain viability and moisture content (mc).

In the laboratory, six 5-gal (18.9 liters) cans were used to store millet of three mc (9.9, 12.8 and 15.6%, 2 cans for each) for 76 days. One can of grain of each mc was infested with 10 rice weevils/kg; the others remained uninfested. Carbon dioxide, oxygen, temp and RH were monitored throughout the storage period, and the percentages of mold-infected kernels, grain mc, and kernel viability were determined at the start and at the end.

The CO_2 concentrations increased and O_2 concentrations decreased in all cans with insects, but this occurred in uninfested grain only in that having 15.6% mc, and then the changes were slower than in the infested 15.6% mc grain. Insects died in all treatments, percents of mold-infested kernels were not significantly different among treatments, and mc did not change. Kernel viability decreased significantly only in the 15.6% mc grain. All grain appeared normal; but the 15.6% mc grain had a slight sweetish odor.

In the field test, six pits were used for 112 days storage of pearl millet of 13.3% mc, 127.5 kg/pit. The effectiveness of two types of pit linings were compared: 3 pits (60 cm diam X 85 cm deep) were lined with plastic and 3 pits (80 cm X 95 cm) with 10 cm of wheat straw. All pits were infested with red flour beetles (RFB), Tribolium castaneum (Herbst) and rice weevils (RW), Sitophilus oryzae (L.), at the rate of 5 insects of each species/kg of grain. The pits were filled and covered on July 10, 1984, and opened and emptied on October 30, 1984. The same variables as for the laboratory test were measured and in addition, soil moisture changes around the pits were monitored throughout the storage period using neutron access tubes installed around each pit, and the numbers of each

species of insect/kg in samples from each pit were determined at the end of the storage period.

The CO_2 increased more and the O_2 decreased more in the straw-lined (SL) pits than in the plastic-lined (PL) pits (the final mean concentrations were 7.09 and 11.68%, respectively, for SL pits, and 3.10 and 15.72%, respectively, for PL pits). The temp and RH at the center of the pit were significantly higher in the SL pits. At the end, live insects were found in all pits but significantly more (at 10% level) in the SL pits (viz 162.9 RW + 16.3 RFB/kg compared to 26.8 RW + 1.2 RFB/kg in PL pits); the grain from the PL pits was cleaner and significantly more viable with significantly less mold-infected kernels, and drier than the grain from the SL pits. The amounts of water that diffused out of the soil around the two types of pits were not significantly different, however, the straw and grain in the SL pits absorbed more moisture than the grain in the PL pits which had essentially the same mc at the end as at the start of the storage period.