COMPARATIVE STUDIES OF THE EFFECTS OF DIFFERENT CONSTRUCTION MATERIALS ON THE PERFORMANCE OF GRAIN SILOS ERECTED IN MINNA

by

ALABI, J. B.

(MENG./SEET/89/97/98)

Submitted to the Department of Agricultural Engineering
School of Engineering and Engineering Technology of the
Federal University of Technology, Minna, Niger State

In Partial Fulfilment of the Requirements for the award of
the Degree of Master of Engineering (M.Eng.) in
Agricultural Engineering

October, 2001

CERTIFICATION

We certify that this work was carried out by John Bala Alabi of the Department of Agricultural Engineering, School of Engineering and Engineering Technology, Federal University of Technology, Minna, Niger State.

14 – 03 – 2002

Dr. E. S. A. Ajisegiri — Date
Supervisor

Dr. D. Adgidzi — Date
Supervisor

External Examiner — Date

Dr. D. Adgidzi — Date
Head of Department

DEDICATION

To the glory of God
&
To my wife and the twins

ACKNOWLEDGEMENT

This project was successfully completed under the leading of the holy spirit and I am grateful to God Almighty for His provision of life and sustenance.

I wish to thank my Supervisor Dr D. Adgidzi for his suggestions and guidance and his encouragement during the period of my coursework.

I am very grateful to the former Head of Department of Agricultural Engineering, Federal University of Technology, Minna, Dr M.G. Yisa and my initial supervisor, Dr E. S .A. Ajisegiri. Without all the support and encouragement that I received through them, this work would not have been possible.

I thank Dr A. Egharevba, Mr. T. Alabadan, Mrs. Z. D. Osunde and Mr. P. Idah, all of the Department of Agricultural Engineering of the Federal University of Technology, Minna, for their encouragement. I must mention Dr Adekola who did a marvellous job of thoroughly checking this thesis, in a very short time too. The comments and criticisms he made were so invaluable.

I wish to acknowledge the kind support of my employer, The Polytechnic, Birnin Kebbi. Alh. Bello Bagudu Ambursa, who is the Registrar of the institution and Engr. Garba Abdullai Kangiwa, the Director of my college were very understanding and supportive and I appreciate their patience. I thank my Head of department, Engr. Peter Oseghale who was very supportive of my M. Eng. pursuit.

On a personal note, I am greatly indebted to Engr Z.O. Ajani of the National Strategic Grains Reserve Silo Complex, Minna for granting me full access to the use of their laboratory and giving me most of the equipment I used. I also thank him for his moral and financial support. Only God Almighty can reward his kindness. The support of Mr. Bello, the Assistant Manager of the NSGRSC, is also hereby acknowledged.

I gratefully acknowledge the assistance received from Mr. Billy Graham of the Department of Agricultural Engineering, The Polytechnic, Birnin Kebbi and Mr Emmanuel Adoyi of the Complete Computers Limited. Their contributions to the success of this work were very immense.

I cannot thank Mr and Mrs Gbadebo (Daddy and Mummy) enough for their prayers and encouragement as well as their care of my family during so many absences from home. Dr. Jerry Ojediran, Mrs Ojediran and Toyin Ojediran gave me a boost when I needed it most. I thank them from the depth of my heart.

The following people: Ayo Fatogun, Mr and Mrs Razaq Adegboye, Jide Ibironke, Engrs. Abdulrazaq Abdulkadir and Mamaki Usman Peni, occupy special places in my heart and I thank them very much for always wishing mme well. In addition, I must not fail to mention special members of "under- the – tree" institute, particularly, Christopher, Mr. Dan, Emma and Chief Dioha.

My brother Deji, and my sisters Mrs F O. Arowolo, my children Oluwasegun and Ifeoluwa endured so much to enable me complete this course of study. I thank them all and may the Lord Almighty be with them. I thank my sister-in-law, Mrs. J. F. Olutimayin and her children especially Kayode who believes in my ability to forge ahead.

Finally I wish to thank my wife, Oyinlola Deborah, my jewel of inestimable value, for enduring so much of my absence even when she needed me most. May our Lord Jesus Christ continue to bless and guide her Amen.

TABLE OF CONTENT

CONTENTS **PAGE**

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

ABSTRACT

The performances of four 1.0 metric tonne grain silos erected in Minna were monitored and compared. They were built with mild steel, clay, sandcrete and wood. The steel silo is of 1.0mm mild steel sheet while the clay silo was built with a mixture of clay and straw has a thatched grass roof. The wooden silo has a 12mm thick plywood on a timber frame while the sandcrete silo is of 450mm x 225mm x 150 mm hollow block construction plastered inside and outside with cement. The objective was to compare their performances under the same exposure to weather. Average temperatures in the steel silo were highest at 43.7°C (maximum attained was 48 °C) followed by the sandcrete bin with 37.7 °C. Lower temperatures were recorded in the wooden silo (average of 36.5 °C and the clay silo with an average of 35.6 °C. Temperature gradients developed within the silos were however highest in the sandcrete silo with about 11.0 °C. Temperature gradients between the grain surface and the centre of the grain bulk during the 56 days of storage were highest in the steel silo (up to a maximum of 5.5 °C), while the lowest was obtained in the clay silo (as low as 0.2 °C). Moisture contents of the grains remained stable at an average of 14.0% in the silos, except in the sandcrete silo where it rose up to 24.7% in the 3rd week of storage. Condensation, with the attendant caking and mouldiness occurred in the sandcrete silo only. The stored maize was in good condition at end of the experiments as all the quality characteristics (moisture content, bulk density, insect infestation level, percent mould damaged kernels and discoloured grains) tested showed no significant changes between the initial and final conditions except in the sandcrete silo. The wooden and clay silos were adjudged the best in terms of moisture and temperature control within grain bulk. However, their durability reduces significantly with long exposure to sun and rain; and it is in this respect that the steel silo becomes superior.

CHAPTER ONE

INTRODUCTION

A silo is a structure that is designed and erected to store free-flowing solid materials (Gurfinkel, 1979). It is a tower or pit for storing grains, usually on a farm, so that the grains can be kept fresh (Oxford Advanced Learners Dictionary, 1989). Silos are particularly used for the bulk storage of corn, rice, sorghum, wheat and millet. However, while in use the internal conditions of a silo (temperature, relative humidity, gases etc.) must be properly managed to prevent the occurrence of conditions that favour the activities of deteriorative organisms such as moulds, insects and rodents. According to Okoye (1989), moulds, more than insects and rodents cause severe damages to stored produce in the humid South of Nigeria. On the other hand, it was noted that the risks of degradation come mainly from insects and rodents and to a lesser extent moulds in the less humid savannah zones of the North. These damages manifest as losses in quantity, quality and in the nutritional value of the stored produce The farmer that is therefore, able to store his grains properly would avoid or at least, minimise most of these losses. He would be able to meet his year-round domestic food demands. In addition, he would earn higher incomes since he would be in a position to sell high quality produce when prices are favourable.

Over the years farmers in Nigeria have not been able to effectively store their produce. More than 80% of grains storage is done at the farm level using traditional technologies. Storage in open air is still being practised by some farmers. This involves hanging crops, say maize cobs on tree branches or roof rafters directly over the household-cooking fireplace. In some areas grains are stored in baskets woven with grass, reeds and/or bamboo. In the humid south maize are mainly stored in cribs, which are simple rectangular structures with open sides. Grains meant for seeds are stored in small calabashes, gourds and earthen pots and jars. However, by far the most popular structure is the earthen granary known as the rumbu. It is built in many shapes and sizes ranging from tonnes to 10 tonnes. Storage in bags in homes and locally build stores is popular among grain merchants. The performances of these structures have been found to be poor. This is due to their inability, at varying levels, to control moisture, rain, heat, insects, rodents and fungi attacks (Igbeka and Ajisegiri, 1986; and Ivbijaro, 1989a.). In the rumbu, which is the predominant bulk grain storage structure (Ivbijaro, 1989b; Osunde *et al.*, 1996 and El-Okene *et al.*, 1996), losses of up to 50% have been recorded. Clearly, efforts must be made to reduce these losses during storage.

Two possible approaches have been advocated for lowering the losses from pest attacks in grain silos (Linbald and Druben, 1977). One of them is to make improvements to traditional storage structures. The other is to build new structures from non-traditional materials. The first approach has produced improvements in the construction of clay silos.. These improvements include building solid floors, and providing access for loading and unloading the silo, careful finishing or smoothing of silo walls, and mixing small quantities of cement with the clay. Other innovations include building small capacity (1 to 2 tonnes) silos with bricks or breeze blocks made of re-inforced earth, or with sun-dried bricks (Anon., 1988a; Olumeko, 1989; and Igbeka and Olumeko, 1993).

The second approach involves building new storage structures that generally require non-traditional materials and construction techniques (Igbeka and Ajisegiri, 1986; Anon., 1988a.; Anon., 1988b). These materials include concrete, metal and wood.

The challenge now for storage specialists is to come up with structures that would be small farmer-oriented and scale-neutral. Their adoption potential should cut across different agro-ecological zones of Nigeria.

1.2 IMPORTANCE OF MAIZE

1.2.1 Production Trend

Maize is widely grown in Nigeria. Figures on the total area cultivated for maize are not exact because a major part of the production is for the farmer's home consumption. In addition, published statistics of the area cultivated and planted with maize mostly ignore the fact that it is cultivated on small plots or even mixed with other backyard crops on the family compound. Nevertheless, there are some private and state owned farms of several hundred hectares where maize is grown as a single crop with highly mechanized technologies. The Federal Ministry of Agriculture estimated that about 10.48 million metric tonnes of maize were produced in 2000.

1.2.2 Consumption and Industrial Uses of Maize

Maize is used for three major purposes (IITA, 1982): (i) as a staple human food, (ii) as feed for livestock and (iii) as raw material for many industrial products.

1.2.2.1 Food for man

Maize is widely used as food in all parts of Nigeria. It is eaten in various forms and is loved for its high palatability. The fresh grains are eaten roasted or boiled on the cob. The grains can be dried and cooked in combination with some edible leguminous crops like cowpea. The grains can also be milled and boiled as porridge ("ogi" or "akamu") with or without fermentation. Maize can also be dry milled and used for "tuwo". It can be baked into a form of bread, or the dough cooked or fried in oil. Dry maize grains of certain variety can be popped and eaten as "popcorn".

1.2.2.2 Beverages and alcoholic drinks

According to IITA manual on maize (IITA, 1982), various beverages and alcoholic drinks can be obtained from maize locally and industrially. Maize grains are steeped in water for 2-3 days and then left to germinate. On germination, the seeds are exposed to sunlight, which stops the germination. The grains are then pounded and cooked for some hours. The liquid portion is drained off and cooled rapidly. This can be taken as a mild beverage. It can however, be left to ferment naturally from moulds present in the air to obtain "beer".

1.2.2.3 Livestock feeds

Maize forms the major part (around 40-75%) of the concentrate ration of farm animals. According to Agboola (1987), the livestock sub-sector of the Nigerian economy alone consumed up to 60% of total national production in the 1990's. To make the feed, the dry grains are milled and other ingredients added to make the marsh, which vary in composition for the different classes of livestock.

1.2.2.4 Industrial uses

The industrial uses of maize are divided into mixed feed manufacture; dry milling; wet milling, distillation and fermentation. Dry- milled maize products include maize meal, maize flour, grits and breakfast cereals. Maize grits consist of the coarsely ground endosperm of the kernel from which most of the bran and germ have been separated. Maize flakes and confectionery are made from these grits. Products of wet milling include starch, syrup, sugar, oil and dextrin. The syrup and sugar are used in the manufacture of some pharmaceutics. The starch is also used in the textile industry. Ethyl alcohol, whiskey e.t.c are products of fermentation and distillation.

1.3 IMPORTANCE OF CROP STORAGE

Grains are stored at the farmer, consumer, trader, retailer and government levels. They are stored in order to ensure year-round availability, to preserve surplus produce for transport to food deficit area and to serve as reserve during times of food scarcity. For small-scale farmers storing less than 10 tonnes the main purposes are to ensure steady household food supplies and seed for the next planting season. Apart from these, storage serves the purpose of generating income for the farmer who releases the stored produce into the market gradually depending upon his financial needs and the prevailing market prices. Farmers also use storage as insurance against possible low yield or low quality of subsequent harvests.

Traders buy grains at harvest time when the prices are generally low, store and later sell them when prices are high. Thus their aim is mainly to make and maximise profits. On the other hand, certain companies such as flour millers, breweries and certain food processing industries hold stocks to cover their raw materials requirements.

Governments embark on large-scale storage projects for national food security purposes i.e. to ensure availability of food at all times. To this end, they buy up surplus grains after harvest and store in large silo complexes. These serve as insurance against general shortages and famines or the sudden outbreak of war (Hindmarsh and Trotter, 1989). Another reason for government's involvement in storage is to even out the fluctuations in supply and demand. By so doing prices are stabilised. Government also acts as "buyer of last resort" thereby stabilising farmers' income.

Apart from reasons of national interest, governments are also known to be concerned with catering to certain sectional interests. Several studies, including FAO (1994), have revealed that governments in many developing countries give priority to the interests of the civil service and ruling party. These studies further showed that large national food reserves tend to be supported by the civil servants whose job it is to manage them; and by politicians who sometimes use their procurement and distribution as a means of dispensing patronage (Hindmarsh and Trotter, 1989). This is typical of the present Nigerian situation. Most grains stored by the National Strategic Grains Reserve department and State agencies are firstly released to civil servants at subsidised prices and the grain contractors are mostly politicians.

1.4 GRAIN STORAGE SITUATION IN NIGERIA

Over the years successive Nigerian governments concentrated their agricultural policies on increased production, believing, erroneously, that increasing overall output would mean regular food supply. Fetuga (1987), cited in Ogunfowora (1989), debunked this when he said that "production *per se* cannot provide the answer to the quest for self sufficiency since sudden increases in food production exert strains on existing methods of harvesting, handling and storage and could lead to larger food losses''. The conclusion is that unless effort is made to provide adequate and efficient storage facilities much of the touted increased production will continue to be lost. It is in the realisation of this that the Federal Government of Nigeria incorporated a national Food Storage Programme in its 5th National Development Plan. The Programme was intended to achieve two major objectives. These are to provide food security for the nation and to minimise intra-and inter-seasonal variations in the supply of agricultural products and, as a result, stabilise prices within the limits of market forces (Philips, 1989). Under the programme, the Federal Government is supposed to hold 5% of the nation's total grain output in strategic grain reserve. The State Governments are to hold 10% of the total output as buffer stock. The balance of 85% is thus left for the private sector (small-scale farmers, farmers' co-operatives, grain merchants and corporate firms) to cater for. By the time the programme was launched, the total storage capacity available to the Federal Government (consisting of facilities of the defunct Nigerian Grains Board and the National Grains Production Company) was 80,000 tonnes (Olumeko, 1989). The whole States of the Federation as at then had a combined grain storage capacity of 129,000 tonnes (Phillips, 1989). The combined government capacity of 209,000 tonnes was capable of holding about 1.7% of the total national output. This fell short of the 15% target of the programme. It should be noted however, that the capacity situation has improved since the implementation of the first phase of the National Strategic Grains Reserve Scheme, which has added over 125,000 tonnes to the scheme.

The situation with the private sector, which is expected to hold 85%, is even more worrisome. Here, the small-scale farmers who produce over 90% of the total output (Igbeka, 1983) still store all their grains in traditional storage structures. Results of various studies support this claim. Ivbijaro (1989a) found that in the Sudan and Guinea Savannah areas, between 40 and 85% of grains are stored after harvest and the structures most commonly used was the rumbu. More than 90% of the farmers sampled used it. In the same study it was found that while in store, the grains suffered severe damages mainly from insects. He revealed that an amount between 40 and 60% of cowpea was lost in storage within 5 - 11 months. Similarly, 36-58% of rice and 45 - 58% of unthreshed millet were lost during storage. Osunde *et al.*,(1996) found that grain losses in Niger State could be as high as 43%.

1.5 PROJECT JUSTIFICATION

It has been said that to obtain effective storage of grains and minimise losses, appropriate structures must be provided that will be suitable for a given area. This is supported by the result of studies (Sinha, 1973) which showed that the structural requirements for grain storage usually vary according to the climate, crop type and dominant pest species of a country or geographical area. In Nigeria, bulk storage structures have been built based purely on imported designs: without any serious considerations for climatic differences. Many of these structures have proved to be too expensive to run and at times too complex for our level of technical know-how. Apart from these, there is also the problem of inadequacy and inefficiency of the traditional structures which record losses of up to 65% (Ivbijaro, 1989b). Research efforts have still not yielded the desired "best" storage structures (in terms of materials, methods and cost) to suit the needs of grain growers and others involved in grain storage in Nigeria. Many workers in the field of grain storage (Igbeka, 1983, Olumeko, 1989, etc. have advocated that structural improvements on the existing traditional storage structures would go a long way in improving the entire storage system in Nigeria. El-Okene et al. (1996) made a case for further studies aimed at adapting mud silos for storing threshed grains. Others (notably, Igbeka and Ajisegiri, 1986; Aboaba, 1989; Mijinyawa, 1989) advocated the use of readily available, relatively low cost materials adaptable for creating suitable storage environments for silo construction.

This study was carried out to complement efforts of other researchers in the search for an appropriate storage structure: in terms of structural design, materials used and construction methods. The work was aimed at evaluating the performance of grain silos built with different materials (clay, sandcrete, sheet metal and wood) with a view to making functional comparisons between them. The design and construction of the silos incorporated some of the improvements recommended by various investigators. In doing this however, effort was made to balance these improvements with the desire to maintain low costs. The justification for selecting these materials and the methods of construction are stated in the following paragraphs.

Clay silos (rumbu) are the main storage structures used for storing grains in Nigeria especially in the northern parts. In a survey of storage methods in Sudan and Guinea Savannah areas of Nigeria, Ivbijaro (1989a) found that over 90% of the farmers sampled used the rumbu for storing grains. Osunde *et al.* (1996) also reported that the rumbu is the most predominant storage structure used in Niger State. It has, however, been reported (El-Okene *et al.*, 1996) that these structures are basically used for storing unthreshed grains (corn on the cob, sorghum and millet in their panicles tied in bundles, etc.). Apart from this, technical appraisals of the rumbu (Anon., 1988b; Arinze and Abdullahi, 1989; Igbeka and Olumeko, 1989; etc.) revealed several deficiencies in them that make improvements a necessity. These deficiencies they noted, include inadequate protection against moisture, and rodents, lack of airtightness (leading to low fumigability) and inadequate strength which is the reason for early failure of many of these structures.

The use of wood for constructing grain silos, is a recent development in Nigeria (Aboaba, 1989) and it is still in the experimental stage. Igbeka and Ajisegiri (1986) noted that wooden silos were not common in Nigeria. Rather it was noted that it use is limited to building frames of maize cribs. Although it is generally recognised that wooden silos would have advantages for storing products especially in the hot dry conditions as found in northern Nigeria, evidence has shown that most experimental studies have been carried out in the wet humid conditions of the south (Mijinyawa, 1989 and Aboaba, 1989). It is therefore necessary to carry out tests with wooden structures to evaluate the various claims. Tests have been started on performance evaluation of wooden silo in the Federal University of Technology, Minna (Tolufase, 1998). The inclusion of wooden silos in this study is part of the on-going tests.

Metal silos, though generally used for large-scale storage, are now being tried for small-scale use. However, the silos being tried are built of low cost sheet metal, rather than the expensive prefabricated, corrugated, galvanised sheet or the "aluzinc" panels being imported and assembled in Nigeria. Although trials on sheet metal silos have been on for long, only one set of studies (carried out at NCAM in Ilorin and documented in Olumeko, 1989) was done in the Savannah region in recent years and that was in1989. No tests on metal silos have been carried out anywhere in Niger State.

Concrete silos have been tested (Osobu, 1971; Ajayi, 1986; Olumeko, 1989 etc.), and only a few are in use in different parts of Nigeria today. They are generally expensive and require some measure of skill, which most local builders in the rural areas do not have. It is envisaged that sandcrete hollow-block structures should be cheaper and easier to put up for the local builders who already have some measure of skill in putting up brick masonry buildings. It is with these in mind that a sandcrete silo was included in this work. Maize was chosen for this study mainly because it is the grain used in other studies on metal and wooden silos and this is necessary for uniformity and to facilitate standardisation and comparisons of results.

1.6 OBJECTIVES OF THE PROJECT

The main objective of this project was to carry out comparative studies of the performance of four silos built from different materials. The specific objectives were,

1. To design and construct four different grain silos i.e. wooden, clay, sandcrete and sheet metal silos.
2. To carry out comparative studies of temperature and relative humidity fluctuations within the silos
3. To determine the storage effectiveness through grain quality tests.

1.7 SCOPE OF THE STUDY

Apart from designing and constructing the four silos required for this study, each will also be stocked with 400 kg of maize grain. During the period of storage the following shall be monitored in order to evaluate the performance of the structures:

- The heat and moisture transfer characteristics exhibited by measuring the following:
  - i. Atmospheric air and silo head-space (air above the grain surface) temperatures, monitored three times daily
  - ii. silo wall temperatures (internal and external surfaces)
  - iii. grain temperatures at different points in the bulk
  - iv. grain moisture contents at different zones in the bulk
  - v. relative humidity of outside air and silo head-space

- The extent of protection these silos provide against insects, rodents and microorganisms. This will be determined from possible occurrence of hot spots, grain caking, discolouration, sprouting, and foul odour.

- The integrity of the silo materials in terms of weather resistance and resistance to attacks by insects, rodents and fungi.

At the end of the studies, the data gathered would be analysed and carefully studied. Comparisons would be made among the four silo materials. Conclusions would be drawn and recommendations made.

1.8 BACKGROUND OF STUDY AREA

A good understanding of the climate of an area is necessary for any successful storage project (Sinha, 1973). This is because climate plays a major role in the storage stability of agricultural products. Among several climatic variables, those of interest in storage technology are, primarily, solar radiation, temperature, humidity, precipitation and wind. The amount of solar radiation received on an area will determine the air temperature. It will also affect the amount of heat that will flow across the storage structure.

The temperature of the air outside the silo is very important because the amount of the daily variations will determine the temperature gradient across the wall and within the storage environment. High temperature gradients result in moisture condensation on the walls and roofs of storage structures especially the metal ones.

Variations in humidity with time and space are known to affect the physiological responses of stored grain and other organisms in the storage bin (Potter, 1980). The probability of condensation occurring on the surfaces or grains depends also on the amount of fluctuation of relative humidity.

Wind speed and direction will, according to Markus and Morris (1980), affect the thermal regime of a building. The resistance of the external surface of the silo depends on wind speed and direction; so also does the air-change rate due to air infiltration through openings. Thus the wind condition will affect the total heat balance of the storage system. Furthermore, winds affect the stability of a structure.

The pattern of rainfall in a geographical zone plays a vital role in the stability of a silo and affects the relative humidity of the ambient air. This causes relative humidity gradients across the walls and if the wall material is porous, moisture will be transmitted into the silo and subsequently into the grain mass.

This study was carried out in Minna, Niger State. Located in the guinea savannah climatic zone of Nigeria, average daily temperatures range from about 18 °C to 38 °C. The highest temperatures occur between February and April, while the lowest are recorded in November to January. Variations in diurnal temperatures can be as high as 16.5 °C during the hot dry season. Yearly variations in temperatures between the harmattan season and the hot season is up to 20 °C. The average annual rainfall is about 1250 mm and most of it falls between April and October. The dry season varies from 120 to 140 days. The average solar radiation received on a typical day ranges between about 2 ly/hr at sunrise (05.00hrs – 06.00hrs) and 60ly/hr in the afternoon (between 12.00 and 14.00hrs). The average sunshine hours in a day are 9 hours. Mean daily relative humidity ranges between 29% in January and about 85% in August (Ojo, 1977). These conditions (adequate rainfall, temperature and sunshine) are very favourable for growing grains. The grains grown are sorghum, rice, maize, millet, groundnut and cowpea.

High diurnal and yearly temperature variations are expected to impose limitations on the adoption of outdoors metal silos for storage in Niger State. However, this has never been tested so that no proof exists. Although prolonged dry season should ensure that grains are kept at safe moisture content level, the methods of storage generally used result in severe losses. These methods, according to Osunde et al. (1996), comprise of hanging, storage in pots, rumbu, pits, , silos, baskets and warehouses.

CHAPTER TWO

LITERATURE REVIEW

2.1 GRAIN STORAGE STRUCTURES USED IN NIGERIA

Grain storage in Nigeria largely involves traditional technologies and the availability of local building materials determines the types of structures used in a particular area. Generally, the structures are classified as traditional structures and improved/modern structures (FAO, 1994).

2.1.1 Traditional Structures

Traditional structures are further grouped into three (FAO, 1994): open-air storage (e.g. storage on trees), semi-open storage (e.g. crib storage) and storage in enclosed containers (e.g. mud silo).

2.1.1.1 Open-air storage

i) Aerial Storage

Aerial storage is a method used by many farmers in Nigeria for storing grains. In this method, maize cobs, sorghum or millet panicles are tied in bundles, which are then suspended from tree branches, posts or even tight lines inside the house. It is a very precarious method of grain storage as it does not provide any protection against the weather (if outside), insects, rodents, birds and thieves. A modification of this method is that which is popular in the humid zone of Nigeria. It involves the suspension of the crops on roof rafters directly above the household-cooking fireplace. While the crop is hanging, the heat and the smoke from the fire will further dry the produce and deter insects and other pests from attacking it. Mould growth will also be controlled as a result of heat and the low moisture content resulting from drying. Consequently the storage is much more effective (FAO, 1994).

ii) Storage on the ground or on drying floor

This is a provisional method of storage. It is a fairly common sight on Nigerian farms where farmers are compelled to stack their grains (mainly unthreshed) on the ground in bundles to await transportation to the homestead or market. The grains are exposed to weather and pests, including domestic animals.

2.1.1.2 Semi-enclosed storage

i) Storage in Baskets

Grain has been stored in basket - like containers made of grass, reeds, bamboo strips or small tree branches for thousands of years (Bodholt and Diop, 1987); they are therefore very traditional and used widely. According to Linbald and Druben (1977), there are almost as many different kinds of basket granaries as there are available villages making them. They are popular in the humid areas of the South mainly because of the recognised need to ventilate crops during the period of storage. These structures are employed because of local availability of construction materials at low costs and the ease of construction.

ii) The Maize Crib

The maize crib is very common grain storage structure in the rain forest zone of Nigeria (Okoye, 1989). A typical crib consists of a rectangular platform raised above the ground, a framework, roof and walls all built from bamboo, thatched grass and wood. The walls of a crib are made of open construction so as to permit free circulation of air in order to dry the grain at the same time because of this ventilation requirement maize cribs are normally placed outside in a N-S orientation. Care is taken in orienting the crib in order to provide equal exposure of both sides to the sun and airflow.

Several studies have been carried out at the National Stored Product Research Institute (NSPRI), Crop Storage Unit, Ilorin of the Federal Ministry of Agriculture (FMA) to assess the suitability of the crib for storing maize. Results of some of these studies have been reported in Bodholt and Diop (1987), Anon. (1988) and Okoye (1989). They showed that most cribs are actually too poorly ventilated to afford continuous drying, and too open to prevent attacks by pests. They also noted that protection from rains was not adequate enough.

2.1.1.3 Enclosed storage structures

i) Calabashes and gourds

These are low capacity containers mainly used to store grains intended for use as seeds and for pulse grains (especially cowpea). They are the hard dried outside cases of certain *cucurbitaceae* plant. The mouth is closed as tightly as possible (after filling with grains) using corncob sometimes wrapped round with cloth material. Several studies, including Mcfarlane (1970) and Hyde *et al.*(1973) have revealed the ineffectiveness of these structures. The major problems are that the skin is permeable to gases and the mouth is difficult to seal completely. Certain insects attack these structures and make them ineffective. Treating the surface of containers with certain oils (linseed oil, pitch, bitumen etc.) has been advocated as a possible solution to the problem of incomplete airtightness.

ii) Earthenware Pots and Jars

These are large clay containers of various shapes and sizes. Jars differ from the earthenware pots in the sense that they can be used for grains meant to serve as buffer stock. Unlike the earthenware pots, jars are not gourd-shaped. However, their necks and mouth are narrower than the main body. The mouths are closed with flat stones, or clay lid, and sealed into position with clay. They are normally kept indoors, not exposed to the sun at all. The main problem identified with the use of these containers is their porous nature and the ease with which they crack (O'Dowd, 1971).

iii) Storage in Sacks

This involves bagging of the grains in sacks made of plant fibre material (jute and cotton) and plastics for subsequent stacking in a storehouse, or hut. It is a very common method of storage in Nigeria (Linbald and Druben, 1977). Experience has shown that sacks do not afford adequate protection against moisture. This, according to Bodholt and Diop (1987), is why they are stacked off the ground; to prevent spoilage by translocating moisture. Sacks are highly vulnerable to tear and rodent and termite activity and are also easily penetrated by insects (Cruz and Diop, 1989). Often, the sacks are either stacked on platforms raised off the ground or placed on tarpaulin or plastic sheeting. Stacks of bagged grains are normally covered with waterproof material to protect them from rainwater.

iv) Pit or Underground Storage

Storage in underground pits is specifically used for long - term storage of large quantities of threshed grain. According to FAO (1994), this method of storage is mainly practised in dry regions where the water table does not endanger the stored product. It is widely used in Nigeria for storing various products. In the humid zones of the country it is used for storing tubers only. Its use for storing grain is restricted to the North Eastern parts (Borno, Yobe and Jigawa States). A typical underground store is a hole dug in the ground in any of three main shapes (cylindrical, square, and amphoric shapes). The inner walls of the pit are usually lined with straw and reed mats and grasses to protect the grain from ground moisture and heat. After lining the walls the pit is filled with the grains and covered with layers of timber and reed mat. The earth or sand dug out is then heaped back onto the mat. Benefits derivable from pit storage (FAO, 1994) include, relatively low and constant ambient temperatures (thus keeping the grains cool); few problems with rodents and insects and low cost of construction. There is currently, a dearth of useful data on the performance of underground pits in Nigeria, perhaps because it is not extensively used. Nevertheless, it is recognised (Olumeko, 1989) that digging the pit is laborious and after a long period op storage the grains acquire fermented smell. It goes to reason too, that removal of grain from the pit will not be easy.

v). Mud Silos (Rumbu).

The rumbu is a farm and village level storage structure built with clay. It is popularly used across Nigeria for storing crops meant for reserve or as buffer stock. In a survey of storage methods in Sudan and Guinea Savannah

Areas of Nigeria (Ivbijaro, 1989) it was found that over 90% of the farmers sampled used the rumbu for storing grains. Furthermore, the survey confirmed that the mud silo is used in all grain- growing zones of Nigeria; variations existing in size, shape and other structural details. For example, Arinze and Abdullahi (1989) found that smaller sized silos are predominant in the southern part of Nigeria. They opined that the reason might be because the period of dry season in the south is very short and farmers generally do not harbour any fears of famine. Generally, the range of sizes is between 0.5 and 10 tonnes (FAO, 1994).

The wall of the rumbu is either made from clay (clay silo) or thatched grasses-thatched silo (Igbeka and Olumeko, 1993). The roof can be the clay dome type or thatched type. Rumbus are usually made in round or cylindrical shape; rectangular-shaped bins being less common probably because of cracking that may occur at the corners due to the uneven pressure of the grain inside. Clay is the basic material for the construction of Rumbus. It can be used alone or mixed with some straw material (e.g. rice straw) to give it added strength. The straw may be chopped and thoroughly worked into the clay mud and allowed to decompose, or cut into 20-30cm length and mixed with the mud. In some areas the practice is to soak bundles of the straw in the mud and then weave them together to form layers of the wall. When only clay is used, the walls are 15-20cm thick (Bodholt and Diop, 1987) and the construction is similar to the walls of a house. But when the clay is mixed with straw the wall thickness may be less, but very strong, so that it is possible to climb it in order to unload the grains. The interior is sometimes compartmentalised, for storing different grains. Vertical walls are built to join the centre on a central column that serves to support the foot when one enters the silo. The walls are rendered as smooth as possible, inside and outside, in such a way as not to offer refuge for insects and their larvae; fissures are sealed with liquid clay before each loading.

Similarly, the angles formed by partition walls and external wall are rounded for the same reasons.

In a thatched rumbu the walls are made of thatched grass only. Local rope materials are woven round it to serve as tension rings. They are not as durable as the clay types since the thatched grass are liable to rot within 2-3 years. The clay type can last up to 15 years (even up to 50 years, according to FAO (1994)) as long as there is regular maintenance. As stated earlier the roof of the rumbu is usually made in two distinct shapes. One type is conical in shape and consists of thatched grass normally built on the ground and then raised into position on top of the bin. Thatched roofs are built to have generous overhang in order to protect the mud walls from splash erosion. Side doors or detachable 'caps' provide access into the silo. When these are not provided the practice is to lift the entire roof away and then enter the silo. The clay dome roof is usually more difficult to construct and requires skilled workmanship.

Technical appraisals of the rumbu in Nigeria (Olumeko and Fashakin, 1989; Anon., 1988b, Arinze and Abdullahi; 1989; Olumeko, 1989 etc) revealed the following deficiencies. Firstly it is believed that rodents are able to burrow into the structure and gain access to the grain. There is also the problem of wooden platforms (floors) and supports being attacked by termites and rodents despite the mud plastering. Most rumbu are neither moisture-proof nor airtight. Therefore, pest control by fumigation is not effective. Finally, it was revealed that loading and unloading these bins are generally very arduous. It is therefore necessary to make improvements on these structures bearing in mind the foregoing problems.

2.1.2 Improved/Modern Storage Structures

The search for alternatives and /or improvements to traditional grain storage techniques has been of major concern to researchers in Nigeria for a long time now. Hyde *et al.* (1973) reported that studies into the use of alternative containers (metal and plastic drums, sacks, polythene bags etc.) were first carried out in the period 1957-1960. Today there is a wide range of structures that are suitable for different levels of storage.

2.1.2.1 Farm/Urban Storage Structures

a) Metal structures

Storage structures made from metal are innovations to grain storage technology in Nigeria. Metal structures such as steel drums and sheet metal bins are low capacity containers for on-farm grain storage.

i) Metal drums

These are steel drums designed for the transport of liquids such as petroleum products. They are effectively airtight (McFarlane, 1970) which makes them very suitable for storing seeds or grains that are normally difficult to store. They are available in various sizes ranging from 20 litres to 200 litres meant to hold about 150 kg of grain. Two main designs have been described (Caswell, 1968; McFarlane, 1970 and O'Dowd, 1971). Because of the problem encountered in filling drums through the original small opening, it has been modified to take in more grains at a time. This modification involves cutting the drum around its circumference just about 75mm below the top. This creates a press-on lid, which if properly sealed with a gasket can be made airtight. This would facilitate effective pest control by fumigation. Another design involves the removal of the drum lid, welding half of it to the rim, and providing a riveted joint to the other half of the lid so that it alone can be opened. To secure the contents a padlock can be fitted on to it. Temperature and moisture control are easy in drums because they are stored indoors. As long as the grains stored are adequately dried they remain safe in drums for as long as 10 years (Mcfarlane, 1982).

ii) Circular metal bins

These bins are of higher capacity than metal drums and can be made adequately airtight and moisture-proof. They are specifically built for grain storage. The basic designs have been described (Hall, 1975; Pingal, 1976 and Olumeko, 1989). They are made of welded sheets of mild steel (MS) which may be plain or corrugated. The bin has an opening at the top for filling and a spout at the bottom for removing grains. Two designs are common. In one, the bottom is flat the roof is sloping and the wall is made of pieces of curved sheets bolted and assembled on site. When not in use, it can be taken apart and reassembled whenever required. This type also has a built-in arrangement for aeration to prevent the development of temperature gradients that lead to moisture migration and deterioration of grain. The bin is made airtight by the provision of neoprene washers with the bolts. The other type of bin has a flat roof and base, and the sheet metal used is welded in whole. Both designs have provision for locking the openings to ensure the security of the grain. These bins are generally recommended for indoor storage.

iii). Prefabricated steel bin with hopper bottom

This is an outdoor structure with a sloping roof, manhole for filling, a hopper bottom with a sliding door for discharging grains. A natural aeration arrangement is provided in the bin to prevent the build up of uneven temperatures that lead to moisture-related problems. The bin stands on firm support, with a clearance of about 60cm at the bottom below the hopper. It is built of 16-gauge curved MS sheets and can easily be erected and dismantled. Both manhole and hopper gates have locking arrangements. A metallic ladder and pulley are provided to facilitate filling of the bin.

iv). Aluminium bins

Salunkhe *et al.* (1985) observed that Aluminium bins are used outdoors. These bins are built with several corrugated aluminium sheets and conical roofs with flat aluminium sheets. They are constructed on a 60cm high platform into which a spout is embedded for unloading the grain. A manhole is provided in the roof and locking arrangements made for security.

c). Plastic Bin

Plastic containers have been found suitable for indoor and outdoor storage of grains. Small plastic containers (called "Jerry cans"), originally meant for the storage of liquids, are finding popular applications in Nigeria for the storage of grains. Apart from these containers, there are other bigger low cost bins that are described also in Salunkhe *et al.* (1985). These bins have tube-shaped metal base with a provision for placing bamboo sticks vertically around the inside of the metal drum. A cylindrical rubberised fabric is hung inside, into which the grain is loaded. Grains can be taken out from the top or through a sliding door at the bottom of the metal base. Plastic bins are stable and compact structures and can be dismantled when not in use.

d). Cement/Concrete bin

Concrete bins have been built in several locations in Nigeria (Anon., 1988b). They are circular, sturdy and weatherproof structures that can be built for surface or underground grain storage. They can also be built according to the requirements for both outdoor and indoor storage. There are two main types of these structures - the plain concrete type and the reinforced concrete (RCC) type. The former consists of 30cm high concrete rings that are assembled on a precast bottom slab. The top slab is also precast on the ground and later raised into position. In RCC bins the structure is cast at the site on prepared steel rods that provide the reinforcement. The joints of all concrete structures are sealed with cement mortar. Provision is also made for filling and removing grains from these silos. These consist of a manhole at the top and a sliding door/spout near the bottom.

(e) Masonry Bins

This bin is weatherproof and easy to construct. The walls are built with either sun-dried bricks or burnt bricks, which are stronger and more durable

(Okoye, 1989). The brick wall sides are more than 10 cm thick and cement mortar is used to bind the bricks in place. Both surfaces are plastered with cement mortar. A spout at the bottom and a slanting floor makes for easy discharge of grain. In this type of bin, locking arrangements are available for securing the manhole and the spout. Another design being tried in Nigeria is the "USAID" silo. The design is based on the traditional dome-shaped rumbu. It is constructed with stabilised earth bricks. The silo is built on concrete pillars supporting a reinforced concrete slab 1.5m in diameter. The walls are made of stabilised earth bricks and are plastered inside and outside with cement reinforced with chicken wire mesh.

(f) Wooden Bins

The wooden bin is a structure that is not common in Nigeria though several trials have been carried out to test its suitability for storing grains (Mijinyawa, 1989; Lucas and Mijinyawa, 1996 and Tolufase, 1998). It consists of a hexagonal body built with several panels of plywood sheets (of African Mahogany face and core veneers) around a solid wood (Mansonia altissima) frame. It has a sloping roof with an opening for filling and a door near the bottom for removing the grain. The entire structure is mounted on wooden supports that are firmly embedded in the ground with concrete.

2.1.2.2 Commercial Large-Scale Storage Structures

Large-scale storage facilities provide a combination of strategic, commercial and buffer storage. According to FAO (1994), their essential purpose is to facilitate long-term operational storage of grain and thereby provide a buffer between harvest receivals and the markets or consumers of grain. Large-scale storage of grain is done in bags stacked in a warehouse or in silos.

a). Bulk or Silo storage

Bulk storage consists of storing unpackaged grain in structures built for this purpose (de Lucia and Assennato, 1994). The main structure for storing bulk grain is the silo. The most common types are the "conventional or proprietary" silos. These are built from prefabricated corrugated galvanised steel or "aluzinc" panels imported, and later assembled/erected on reinforced concrete platforms (Hindmarsh and Trotter, 1989). They are usually cylindrical in shape with sloping roofs. A typical silo has a manhole at the top for loading the grains and an opening at the bottom for emptying the silo. Mechanical conveyors do all movements of grain in and out of the silos. Special aeration fans are provided for the control of temperature and relative humidity within the silo enclosure. Storage conditions are monitored with electronic sensors with automatic controls. A group of silos built in rows makes up what is called a Silo complex (Ajani, 2000). They are very expensive structures to construct. Most of the components are imported and they require some expertise to put together. In addition, management of silo complexes is very expensive.

Concrete may also be used in building large silos. Techniques of constructing concrete silos require specialised and experienced builders. The more common of these structures are built in the fixed-form method, which is done right there on site. The other method, known as 'tilt - up' technique, involves casting of wall panels on the ground and lifting them into position later. According to de Lucia and Assennato (1994), post-tensioned cables are required to resist the grain loads imposed on them.

b). <u>Warehouse storage</u>

A warehouse is a rectangular building intended for the storage and protection of bagged grains (Cruz and Diop, 1989). According to Salunkhe *et al.* (1985), the buildings used for bag storage in the tropics and subtropics have generally not been designed for grain storage. Many of them are old structures erected for general purpose and have corrugated metal or concrete roofs and mud or brick walls. The floors are often made of earth or masonry and have inefficient waterproofing. Basically, a good warehouse consists of a floor, walls, a roof and one or more entrances. It has a sealable opening for controlled ventilation and complete building fumigation. The opening can be used for both natural and fan-controlled aeration. The bags are placed on raised wooden planks placed on the floor. These planks keep the bags away from direct contact with the floor heat and moisture.

Part of a warehouse's major functions is also to prevent attacks by insects, rodents and birds.

2.2 REVIEW OF OPERATIVE FACTORS IN GRAIN STORAGE

A grain bulk is a man-made ecological system in which living organisms and their non-living environment interact on each other (Sinha, 1973). Deterioration of stored grain results from interactions among physical, biological, chemical variables. These variables seldom act alone; they interact with the grain and with each other to affect the quality of the grain. A good understanding of these variables and those of the grain itself and their interrelationships is important for any successful storage.

2.2.1 The grain and the grain bulk

The grain and the grain bulk have several biological, and physical attributes whose condition mainly depend on the surrounding physio-chemical environment.

2.2.1.1 Biochemical Composition of Grains

All grains are made up of living cells that are basically carbohydrates, fats, protein materials, vitamins, fibre and water (Potter, 1987). The relative proportions of these components differ from one type of grain to another and from one farming system to another. These constituents of grains are broadly grouped into two: dry matter and water.

(i) Dry matter

The dry matter (or water-free portion) of maize kernel contains about 77% starch, 2% sugar, 9% protein, 5% fat, 2% ash and 5% pentosan. More than 70%

of the maize kernel is carbohydrates, which are present as starch, sugar and fibre (cellulose). They are broken down during respiration to obtain energy. The starch is found mainly in the endosperm (Cruz and Diop, 1989), the sugar in the germ and the fibre in the bran.. The fibrous framework of the kernel is composed of cellulose. In the maize kernel about 80% of the protein is found in the endosperm. The remainder is contained in the germ. There are however, variations in the protein contents of different varieties. The quality of protein in maize is poor due to the low content of 2 essential amino acids (lysine and tryptophan. It is also known that maize is contains oil, 65% of which is concentrated in the endosperm. The rest of the oil is found in the endosperm. When storage conditions (temperature, moisture and microorganisms) are favourable, lipids are known to oxidise and produce rancid odour and odd flavour in the grain. Vitamins are found in minute quantities in maize and are chiefly located in the outermost layer of the endosperm. High storage temperatures and insect infestation destroy the vitamins in maize and so maize in storage must guarded from these conditions.

Carbohydrates or sugars are found mainly in the endosperm of starch granules (Cruz and Diop, 1989). Lipids or fats are said to be generally concentrated within the germ and are also sources of energy.

Proteins are mainly found in the germ and aleurone layer of the grain. Cereal grains do not contain as much protein in them as legumes. Vitamins are found in minute quantities in the germ and pericarp of the grain. High storage temperature and insect infestation destroy the vitamin s in the grain.

(ii) Water

Water is an important constituent of grains. The amount and state of moisture in agricultural products determine the rate and occurrence of chemical reactions, enzyme activity and microbial growth (Labuza and Lewicki, 1978). Moisture is present in grains in different forms. According to Ajisegiri (1987), moisture in stored produce can be "free water", "bound" or cytoplasmic water,

water of constitution, colloidal water and water of hydration. "Free" water is most readily available to micro-organisms for their development and so it affects the storability of the grain. Stored produce does not ordinarily contain "free" water; but due to its hygroscopic nature, it can absorb free moisture from the environment. This is why control of moisture in a grain store is of immense importance.

The amount of water or moisture contained in a product is expressed in terms of its moisture content. Moisture content is the ratio (in percent) of the moisture contained in a given sample of material to either the initial (total) weight or the dry weight of the material. When it is considered relative to the total weight, the moisture content is said to be on wet basis. If the basis is the dry weight of the material then it will be referred to as moisture content dry basis. Brooker et al. (1978) explained that the wet basis index is used in commercial applications while the dry basis index is more useful for research purposes.

2.2.1.2 PROPERTIES OF GRAIN BULK

According to Sinha (1973), every grain bulk has five properties that determine the effectiveness of a storage system. These properties are porosity, flow, segregation, sorption and thermal conductivity.

(i) Porosity

The porosity of grain kernel and grain mass is due both to the colloidal nature of the kernel itself and the presence of inter-granular spaces within the grain mass. The porosity of a grain mass will depend on the size and shape of the kernels, dockage level bulk weight, compaction and the distribution of moisture in the bulk. Cruz and Diop (1989) revealed that 30-40 % of the volume of bulk maize consists of inter-granular air. Porosity is important in that it affects the movement of air, heat and moisture within the grain mass.

(ii) Flow

Grains flow whenever they are poured from a container and the ease with which they flow is affected by the grains' coefficient of friction, the angle of repose and the internal angle of friction. These parameters are therefore important in the design of any grain handling and storage system. Table 2.1 shows these parameters for some common grains. The internal angle of friction is the angle between grain particles within the grain bulk. According to Sinha (1973), the angle of internal friction is usually greater than the angle of repose.

(iii) Hygroscopicity This is the ability of a material to gain or lose moisture from the air. All grains are hygroscopic (Sinha, 1973) and so have the propensity to exchange moisture with ambient air. This property of the grain is what is called sorption and it consists of two processes: absorption, and adsorption. Absorption takes place when moisture is held, loosely by capillary forces within the grain kernels. On the other hand, Crosby (1985) defined adsorption as a type of adhesion which occurs at the surface of a solid (grain) in contact with another medium (in this case moisture) resulting in an increased concentration of molecules in the immediate vicinity of the surface.

(iv) Thermo-physical mass exchange properties

These include thermal conductivity, capacity and "thermal moisture conductivity". The phenomenon of transfer and exchange of heat and moisture is dependent on the processes of conduction, convection, radiation, evaporation, condensation and absorption. Conduction is transfer of heat from grain to grain in bulk. Convection in grain bulk is the heat transfer by inter-granular air. The thermal conductivity of bulk grain determines the rate of change of temperature in a grain bulk. Consequently, it has been a subject of serious study by investigators. Results of these studies generally agree that bulk grain has low conductivity. Maize for instance has a thermal conductivity of about 0.0004 cal $cm^{-1}sec^{-1}{}^{o}C^{-1}$ .The thermal diffusivity (the rate at which temperature changes are transmitted through the grain bulk) is regulated by the thermal capacity of the grain bulk. Thermal diffusivities of grain are (Sinha, 1973) in the order of $0.00115cm^2\ sec^{-1}$. Sinha also defined thermal moisture conductivity to be the movement of moisture within the grain bulk owing to a temperature gradient. He went on to note that thermal moisture conductivity is responsible for the transfer of moisture from warmer to cooler parts of a grain bulk.

Table 2.1 Angle and coefficient of friction at 12-16 % moisture content

Grain	Angle of repose+/- 5°	Coefficient of friction between grain and wall		
		Steel	Concrete	plywood
Maize	27	0.25-0.50	0.30-0.60	0.28-0.42
Rice	36	0.40-0.50	0.45-0.60	0.40-0.45
Wheat	31	0.22-0.44	0.45-0.55	0.30-0.45
Sorghum	33	0.29-0.32	0.41-0.58	-

Source: Brooker et al. (1978)

2.2.1.2 Intrinsic factors of the Grain

Agricultural crops at harvest are living organisms in which physiological and pathological processes associated with life continue to take place (Linbald and Brumen, 1977). Intrinsic factors are those based on these processes; they include respiration, biochemical reactions in the crop and the condition of the crop such as maturity.

(i) Respiration

Respiration is an important physiological process that takes place in all living things. It is a physio-chemical reaction that involves the decomposition of organic matter to produce energy. It can either take place in the presence of oxygen (aerobic respiration) or in the absence of oxygen (anaerobic respiration). Aerobic respiration involves the complete breakdown (oxidation) of the carbohydrates, usually in the form of sugars, to generate carbon dioxide, water and energy, in the form of heat. On the other hand, in anaerobic respiration the carbohydrates are not completely decomposed so that ethyl alcohol is formed instead of water.

The heat liberated during respiration raises the grain temperature and generally contributes to the heating of the grain bulk. It is this heat of respiration that marks insect activities in the grain bulk. The carbon dioxide remains within the inter-granular air and eventually changes the composition of such air. As more oxygen is consumed, the amount in the air will continuously reduce while the concentration of carbon dioxide will increase. The degree of intensity of the respiration of the grain and the organisms living in it determines, in part, the rate and extent of deterioration in the grain bulk.

(ii) Biological reactions in the crop

All grains contain natural enzymes that control their life processes (Onayemi, 1986). The activities of these enzymes do not, however, cease with the harvest of the crop. Rather, evidence has shown that they are often intensified. Citing possible reasons for this, Potter (1987) said that before harvest the enzymatic reactions are controlled and delicately balanced whereas after harvest this balance is upset. Studies by various investigators have shown that some chemical reactions may initially lead to improvement in quality after harvest. Nevertheless with time all the chemical and biological reactions in the stored produce eventually lead to deterioration in quality (Oyeniran, 1990).

In stored grain changes in carbohydrates are known to be very slight and these are usually in the form of loss of dry matter. Grain legumes, especially oil seeds are said to be more vulnerable to enzymatic spoilage of hydrolysis and oxidation. Lipids present in grains contain natural enzymes called lipase and these, according to Potter (1987), catalyse the hydrolytic breakdown of fats in grains. This reaction, known as lipolysis, produces free fatty acid and glycerol and is positively affected by temperature and mould activity. On the other hand, the oxygen present in the storage atmosphere may oxidise the fats and lead to rancidity and foul odour. This spoilage is slower in whole kernels than in broken kernels because unbroken kernels are said to contain certain antioxidants.

2.2.2 Environmental factors

The condition of the physical and chemical environment within the storage system is very crucial for safe storage of grains (Sinha, 1973). Although the state of the environment may not directly cause grains to deteriorate, its effect on promoting or checking the activities of spoilage organisms is profound. For instance, in an atmosphere of low oxygen insects will not thrive and most fungi will cease to develop (Rulon, 1996). Environmental factors to be considered include temperature, moisture air relative humidity and pressure as well as the composition of the storage gases.

2.2.2.1 Temperature

The temperatures of stored grains and that of the ambient air are considered to be crucial variables for safe and prolonged storage of grains. They are significant in the sense that they regulate moisture movement within the grain bulk and also control insect and mould infestation. Moisture migration and condensation can only occur when temperature gradients exist in the storage system (FAO, 1994). The temperature gradient might exist either within the grain bulk or between the internal and external surfaces of the storage structure. The reasons for the occurrence of temperature gradients in storage bins were given in Oxley (1969) as prevalence of large diurnal fluctuations in temperature, localised heating due to insect activities and faults in the structure. The significance of temperature on the rate of respiration of grain and its contents (insects and microorganisms) has been reviewed earlier.

The effects of temperature on insects and microorganisms in stored grains have been widely studied. Temperature affects the growth and development of insects and moulds (Rulon, 1996). The optimum temperature for the development of most fungi is less than 40°C (Cruz and Diop, 1989) except for the so-called thermophilic fungi that grow best at about 50 °C. On the other hand, the activities of stored product insects are said to be at peak within temperature range of about 30-35 °C. Above this range insect activities are known to decrease rapidly. However, the insects can raise the temperature of a grain mass to around 42 °C by their activities. When this happens, a "hot spot" develops and the spot becomes uncomfortable or even lethal to the insects. According to Oxley (1969), the insects would thereafter either move to a cooler part of the grain bulk or remain in the spot and die.

2.2.2.2 Moisture

Moisture is a key part of most processes of deterioration that occur in stored grain (Okoye, 1993). It is required for chemical reactions, enzyme activities and microbial growth. Moisture increases the rate of respiration of grains and hastens internal breakdown of grains (Potter, 1987). Studies have shown that the amount of heat released within a grain mass doubles for each additional 1.5 % increase in grain moisture content. Subsequently (Cruz and Diop, 1989), for a given temperature, it can be considered that grain stored at 15 % moisture content deteriorates twice as fast as grain stored at 13.5 % moisture content. Even slight changes in moisture content can cause severe problems during storage. For instance, Potter (1987) revealed that slight changes in relative humidity of storage air could lead to caking and lumping of the grain. In addition, the slightest amount of condensation on the grain surface can lead to an environment that is conducive for the growth of microorganisms and insects.

Moisture in foods has been extensively studied. Results of some of these studies have shown that absolute moisture content is not as critical as water activity when considering the storage system. According to Young (1985), two materials with the same moisture content can have very different water activity values, depending upon the degree to which the water is "free" or bound to the material. Labuza (1968), observed that it is the water activity of a food material that influences the activities of microorganisms, enzymes and chemical reactants at the micro-environmental level in food materials and not the absolute moisture content. Water activity of a material can be defined either qualitatively or quantitatively. Qualitatively, Potter (1987) defined it as a measure of the unbound, free water in a food system, available to support biological and chemical reactions. In quantitative terms, Labuza (1968) defined water activity as the ratio of the vapour pressure of water in the material divided by the vapour pressure of pure water at the same temperature.

As it is with most storage parameters, moisture content has its own limits for the development of insects and microorganisms. Below 13 % moisture content for instance, the growth of most microorganisms will be arrested (Karmas, 1973). Insects survive in a little drier condition but below 10 % moisture content most of those associated with stored grains cease to grow. Generally, all grains have specified moisture content at which they can be safely stored. This moisture content is known as the "safe moisture content" or "permissible moisture content". This permissible moisture content is defined in the Agricultural Compendium (1989) as the moisture content low enough to prevent growth of micro-organisms in the grain and is based on the grain's water activity. According to Cruz and Diop (1989), this moisture content must not be higher than that which would be in equilibrium with a relative humidity of 70 %. Table 2.1 shows the maximum permissible moisture contents for some grains at 27 °C.

2.2.2.3 <u>Relative humidity</u>

The relative humidity of air has been described as a percentage measurement of the amount of moisture contained in the air as compared to the maximum amount it can hold at the same temperature. This means air at any temperature is capable of holding more air than it holds but when it holds the maximum amount it is capable of, the air is said to be saturated and the relative humidity at that point is 100%.

Table 2.2Safe moisture content for storage of selected grains in Nigeria

Crop	Safe moisture content (%)
Maize: yellow	13.0
White	13.5
Paddy	14.0
Milled rice	12.0
Sorghum	13.5
Millet	15.0
Wheat	13.5
Groundnut: unshelled	9.0
Shelled	7.0
Cowpea	15.0
Soybean	11.0

Source: Agricultural Compendium (1989)

2.2.2.4 Equilibrium relative humidity:

Relative humidity has also been defined as the ratio of the vapour pressure of air to the vapour pressure of saturated air at the same temperature and atmospheric pressure (Brooker *et al.*, 1978). This explains the phenomenon of sorption in grains discussed earlier i.e. the constant exchange of moisture between grains and the surrounding air. It is only natural that moisture should move from a region of higher pressure to that of lower pressure until the two surfaces reach equilibrium. As the condition of the ambient air changes, the two surfaces will shift again until another equilibrium is attained. Thus for a grain at any moisture content, and for a given temperature, there is a corresponding equilibrium relative humidity. A plot of relative humidity against grain moisture content for a given temperature is called a moisture sorption isotherm or equilibrium relative humidity curve. Linbald and Druben (1977), gives the air-maize equilibrium curves at three temperatures (15°C, 20 °C, and 35 °C). It can be seen that at 20 °C, for a relative humidity of 70%, equilibrium is reached when the moisture content of the grains of maize is 14%. When the grain is ventilated with air at 55% relative humidity, the grains lose moisture, and reach equilibrium when their moisture content is 12%. On the other hand ventilating the grain with air at 80% relative humidity, the grains are rehumidified, and reach equilibrium when their moisture content is 16%.

2.2.3 Biological factors of grain deterioration

It is common knowledge that grains are the major source of nutrients for microorganisms, insects, rodents and birds. For this reason, grain whether on the field or in storage are ever prone to attacks from them. But an attack by any of these organisms, in whatever peculiar way it comes, usually leaves the grain in a condition that is most unsuitable for usage. Apart from the differences in how they attack grains, these pests also have specific conditions under which they thrive. It is therefore very important to discuss the individual pest and how they affect stored grains.

2.2.3.1 Micro-organisms

Bacteria, fungi and yeast are said to be the common microorganisms associated with the deterioration of stored produce. Bacteria are by far the smallest of these organisms. They usually grow at the expense of the material on which they live by secreting substances which dissolve the material into simple forms required by them FAO (1994). Whereas some bacteria are useful in certain processes, others are pathogenic i.e. their secretions are toxic to man and /or animals. Oyeniran (1990) noted however, that bacterial activities are more common in highly perishable high moisture crops. The lower limit of development of bacteria corresponds to an air relative humidity of 90 % (Cruz and Diop, 1989).

2.2.3.2 Fungi

Fungi are multi-cellular plants consisting of branching intertwined filaments called hyphae. A mass of these hyphae is known as the mycelium; and mycelium present on cereal grain is termed mould growth (Hartman *et al*., 1984). Moulds are always present on grain surface in form of spores and as soon as conditions of temperature, moisture and oxygen are favourable, the spores develop and grow gradually spreading into the stored grain. This way it causes the grain mass to become mouldy. Christensen and Kaufinann investigated the activities of moulds on grains and determined that the conditions favourable for their development in a grain mass include grain temperature, its moisture content, presence and amount of foreign material in the grain (Brooker *et al*, 1978). Moulds can grow over a wide range of temperatures (Hayes, 1966) from below freezing to temperatures in excess of 50 °C. It is believed that for a given substrate, the rate of mould growth will decrease with decreasing temperature and water availability (Hartman *et al*., 1984).

The presence of moisture within the inter-granular air in the grain mass is sometimes adequate enough to meet the demands of moulds. The amount of water present is however, determined by the state of equilibrium between the free water within the grain (as expressed by its moisture content) and waters in the vapour phase immediately surrounding the grain particle. This equilibrium is known as equilibrium relative humidity or water activity (FAO, 1994). According to Brooker *et al*. (1978), no fungus species develop below 60 % equilibrium relative humidity. In fact, Various studies have shown that, for given moisture content, different grains exhibit a variety of water activities and therefore differing rates and type of mould growth. Chirife and Iglesias (1978) particularly noted that moulds actually grow in range of 0.70-0.90 water activities.

Apart from their individual effects, the interaction between grain temperature and moisture content also affects the extent of mould colonisation (Labuza, 1968). The vaporisation of water is temperature-dependent so that, for a particular moisture content, the water activity and the propensity for mould growth will increase with temperature. For example, FAO (1994) noted that maize that could be relatively safely stored for one year at a moisture content of 15 % and a temperature of 15 °C, if stored at 30 °C would be substantially damaged by moulds within three months. The interaction between moulds and insects also influences mould growth in stored grain (Hartman *et al.*, 1984). It is generally accepted that grain is not infested below a temperature of 17 °C.

Another factor that can affect mould growth is the proportion of broken kernels in a grain mass. When grain kernels are broken their endosperm is exposed to invasion by moulds. FAO (1994) estimated that a 5 % increase in the amount of broken kernels would reduce the storage life of that batch of grains by approximately one order of magnitude i.e. from say, 150 to 15 days. In addition, as was noted earlier, mould growth is regulated by the gaseous environment i.e. the proportion of oxygen and carbon dioxide in the inter-granular atmosphere.

The effects of mould colonisation on grains and the consumers have been given adequate attention. Some moulds are said to be capable of producing chemical substances that are toxic to man and/or animals. According to FAO (1994), these substances are basically metabolites and are called mycotoxins. Aflatoxin caused by the fungi Aspergillus spp. is the most commonly known mycotoxin. Brooker *et al.* (1978) noted that even minute amounts of Aflatoxin in grain could cause serious illness and sometimes death in animals.

2.2.3.3 Insects

Insects are the most common of stored grain pests. Most of them feed on the soft nutritious germ of the grain kernel. Some have jaws strong enough to penetrate the pericarp of the grain kernel (Linbald and Druben, 1977). For most insects the life cycle is approximately three weeks to one month under favourable conditions. These conditions are temperature, moisture content of the grain and oxygen supply, as explained in earlier sections.

The optimum temperature for insect development is generally accepted to be between 25 °C and 30 °C (Rulon, 1996). The upper limits for their development and survival vary, to some extent, between species (Evans, 1987), but temperatures above 45 °C are usually fatal to all stored product insects. At 50 °C most species would die quickly within a matter of hours. Experiments with infested wheat (Evans, 1987) even showed that complete disinfestation could be achieved with a very short exposure to air heated to 60 °C. At 17 °C or less insect development is said to be relatively negligible. However, even at 15 °C some species are able to continue feeding, to some extent, so that grain damage may very slowly increase. It has also been known that certain insects survive longer than a year in cold stores having temperatures of 6-9 °C (Donahue, 1990).

The moisture content of grain is an important parameter in the survival of insects. Sadly, it has been realised that no amount of manipulation of moisture content can sufficiently control insect activities. This fact is attributed to insects' ability to obtain water from other sources apart from the free water in the grains. The water of metabolism resulting from respiration of the grain and its micro-flora, and water vapour from the air are important alternative sources for insects. Generally though, insect activity is said to be very minimal in grains with moisture content below 10 % (Brooker *et al.*, 1978).

A third and very important factor that influences insect development is oxygen supply. All insects require oxygen for respiration and without it they will die. This basic need of insects is used as the basis for the technique of sealed (hermetic) storage. In this method the oxygen within the storage container is reduced to the barest minimum and as insect respiration continues, the oxygen supply is further depleted. This process continues until a stage is reached when the oxygen supply is no longer able to sustain the insects. Hayes et al. (1989) observed that this happens when oxygen level gets to about 2 % by volume. Donahue (1990) later showed that some insects are capable of adapting to low oxygen tensions and may eventually evolve strains that will have considerable resistance to sub-optimal levels of oxygen, even down to 1 %. Cruz and Diop

(1989) noted however, that it might not be possible for any storage insect to multiply rapidly in a condition of about 1.0 % oxygen.

The main insect pests found in stored grains belong to the orders Coleoptera and Lepidoptera (Cruz and Diop, 1989). In the order Coleoptera the grain weevils are the most common. They are primary pests in that they attack whole, undamaged grains. Prostephanus truncatus, a large grain borer is the most destructive of these insect pests of maize, especially those stored on the cobs (Mejule, 1990). These insects differ in their timing of attacking crops and it is important to know this in order to effectively combat them. Many insects commence their attack right in the field before harvest, and can initiate major damage to the grain. Others can only attack grains that have previously been damaged either mechanically, or by other insects. This second group of insects is known as secondary pests. Nevertheless, whether infestation starts from the field or right in the store, one fact is that insects cause considerable losses to farmers.

Losses due to insect activities consist of the damage done by the insects chewing on the germ and endosperm of the grains thereby constituting losses in weight and nutrients. Other aspects of grain damage by insects include various types of contamination, heating, translocation of moisture, dissemination of moulds and other microorganisms including disease organisms and customer resistance.

2.2.3.4 Rodents

Rodents, especially rats and mice cause high losses in stored products. They cause direct losses in quantity of the stored product by consuming it. In addition, while feeding on the grains rodents leave their droppings, urine and hair on the product thus contaminating it and reducing its sale value. Through their habits of gnawing and burrowing, rodents cause severe damage to storage structures (floors, walls etc.) and packaging materials (e.g. storage sacks). Rodents have also been known (FAO, 1994) to transmit diseases to man and animals (e.g. rabies, plagues, cattle plague and swine fever). Several studies have been carried out on the damage done to stored products and structures by rodents. According to Gratz (1988), the actual value of the losses caused by rats vary with crops, variety, tear, geographical location, pest species involved, length and method of storage and climate. This has therefore made it difficult to assess exact losses and so recourse is being made to estimates. According to Cruz and Diop (1989), a granivorous rodent can consume 10 % of its own weight per day. FAO (1994) estimated that a rat could destroy about 50 g of grain in one night and that losses of 40-210 kg of grain were recorded in some storehouses in the Philippines. Mian *et al.* (1984) noted that on the average, each household in Bangladesh was infested with about eight mice and two rats. It is even feared that the situation is worse in Nigeria (Oyeniran, 1990).

2.2.3.5 Birds

Birds, especially the granivorous types, are always attracted to grains either on the field or in storehouses. These birds feed on the grains and in the process contaminate the rest with their droppings and feathers. Birds are relatively easy to control in stored products. The essential thing is to prevent them from reaching the grains and this can be achieved by closing all openings and using wire mesh to protect ventilation openings.

2.2.4 Technical factors of grain deterioration

These factors include the grain condition before storage, length of storage and the condition of the storage structure.

2.2.4.1 Grain condition

The condition of the grain to be stored is very vital to safe storage. It is widely accepted that for grain to be stored safely, it must be clean, i.e. free from dust, broken kernels, straws, husks, insect wastes etc. These materials are collectively known as foreign matter, and they contaminate good grains thereby constituting themselves into centres of infestation.

2.2.4.2 Length of storage

It is obvious that the longer a batch of grains stays in storage, the higher the losses of dry matter. This is because even when the grain is uninfected, as long as respiration continues, there will be loss of weight. Prolonged storage also increases the risk of attack by pests because as time progresses there is always a possibility (Ajisegiri, 1986) of storage conditions changing in favour of pests.

2.2.4.3 Structural factors

The design and construction of proper granary structures are important factors in maintaining and improving storage stability of grains. They are the easiest to control of all factors. The choice of the site for the structure or facility, its design and the materials used in its construction to a large extent determine whether certain harmful organisms, including birds and rodents will be significant pests. Generally, according to Sinha (1973), structural requirements for grain storage should vary according to the climate, crop type, and dominant pest species of a country or geographical area. Smith (1985) noted that most building structures are likely to reduce pest infestation if they minimise heat uptake from the environment and maximise heat and moisture loss from the granary to the environment. Thus a good grain store should have adequate control over the thermal and moisture conditions in the internal environment.

2.3 A REVIEW OF MATERIALS USED FOR SILO CONSTRUCTION

2.3.1 Properties of silo materials

Various materials have been used in building grain silos in Nigeria. Whereas some are readily available locally (e.g. clay and wood), others are manufactured products requiring some capital outlay to obtain. However the cost of the latter types discourage small-scale farmers from using them. While in service, the materials and the silos built from them are generally exposed to the environment and their performance under these conditions are dependent on their functional properties. In a storage structure, these properties are those that affect the structure's ability to protect the grain from the external environment (moisture, temperature, wind, insects, rodents, fungi etc.). The functional properties of a silo material are categorised into physical, mechanical, chemical and biological. Physical properties are those structural and mass characteristics that describe the response of a material to water vapours and gases, heat, cold, radiation etc (e.g. porosity, water absorptivity, and thermal transmission properties). Mechanical properties describe the material's ability to resist deformation and failure under the action of external and internal forces. Biological properties describe a material's response to attacks by fungi, insects and their larvae, rodents and birds. Corrosion resistance is the major chemical property of a silo material.

2.3.2 Construction Materials

According to FAO (1994), the choice of construction materials for grain silos is usually between steel and concrete. However this holds true for only developed countries. In most parts of Africa and South East Asia, wood, masonry, clay, raffia and thatched grass are popular.

2.3.2.1 Steel

Steel is widely believed to be the most common among building materials used for the construction of bulk grain facilities (Stewart and Britton, 1973; FAO, 1994 and Igbeka and Ajisegiri, 1986). The reason for this, it is believed is that steel is easily adapted to high volume prefabrication manufacture. Used in thin sections, steel is also relatively light in weight. It has a good workability factor makes it easy to fabricate into different shapes. Its high strength makes it impossible to penetrate by rodents. Steel is impervious to moisture vapour and air and requires no special sealing except at joints. This makes steel structures most suitable for sealed (airtight) storage that would effectively control insects. Steel however, exhibits extremely high heat absorptivity and conductivity characteristics (coefficient of thermal conductivity is greater than 53 W/mK and specific heat of 460 – 480 J/kg K). This is why very high temperature gradients and the resulting moisture migration and condensation are recorded in steel bins (FAO, 1994; Lucas and Mijinyawa, 1996 etc.). As a result steel bins generally require a lot of monitoring and this would involve high costs. Coupled with this is the issue of high initial cost of steel and maintenance (steel must be protected from corrosion).

2.3.2.2 Aluminium

Aluminium is another metal that is used in constructing large silos. But it is not used alone, rather it is alloyed with zinc to form what is termed "aluzinc" in silo manufacturer's parlance. Aluminium has very high coefficient of thermal conductivity (202 W/mK). Its density is 2700 kg/m^3 though it is made in thin lightweight sheets too. It offers adequate protection to stored grain against external sources of moisture, insects and rodents.

2.3.2.3 Concrete

Concrete is an artificial building material made from agglomerated and carefully proportioned mixture of a binder (cement), water, sand and gravel (Fowler, 1982). Concrete generally have relatively low thermal conductivity compared to steel (1.5 – 3.5 W/mK) and high specific heat (800 – 1200 J/kg K) The absorptivity of solar radiation of concrete is low too (0.65). These, according to Igbeka and Ajisegiri (1996), decrease the rate of temperature rise in concrete structures. Concrete has a high moisture absorptivity and permeability. The moisture permeability of well-compacted concrete with a water/cement ratio of 0.4 is put at 10^{-12} m/s (Mosley and Bungey, 1976). This explains why concrete structures in tropical area become damp easily. Concrete is a brittle material that has a low tensile strength (about 3.0 MN/m^2). This brittleness makes it fail catastrophically in tension (BRE, 1975). This of course, can be overcome by pouring the concrete around steel reinforcement rods. Stewart and Britton (1973) observed that concrete normally requires considerable forming and labour unless it is used in prefabricated or precast forms. Building with prefabricated and precast concrete requires specialised labour that is expensive and mainly not available to the farming community. The major advantage of concrete is its high compressive strength.

2.3.2.4 Wood

The use of wood for building storage structures has been restricted primarily to frame construction of maize cribs and rectangular bins (Stewart and Britton, 1973 and FAO, 1994). Wood, as a construction material is locally available and relatively cheap. Construction with wood is easy and the skill can be acquired quite easily within a short period. Other advantages of wood are its low thermal qualities. Thermal conductivity (0.094 – 0.42 W/m K) and absorptivity of wood are quite low compared to other materials. Plywood is normally used for silo walls as it is manufactured in large sections (2440 x 1220 x 250 or x 180 or x 120-mm sheets) that are relatively lightweight, as compared to timber. The major drawback of wood is its vulnerability to deterioration by weathering and biological agents like fungi and insects. Fungi attack wood and make it brittle and weak. Wood, ordinarily has poor vapour resistance (porosity is 50 – 75 %). When it decays it develops an abnormal capacity for absorbing water. Very often when damp it develops unnatural odour and colour. According to Mathur (1983), when this happens, the wood tissue is destroyed by the pressure exerted by growing mycelia (causing mechanical destruction). In addition, biochemical destruction takes place as a result of the action of solvent chemical enzymes that the mycelia secrete. However treating wood with certain substances and painting makes it less susceptible to effects of weather. Attacking insects and their larvae leave wormholes in wood. Another disadvantage of wood is that it burns quite easily. This imposes limitations on its use as silo material on farms where bush burning is very rampant.

2.3.2.5 Clay

Clays are secondary earths largely consisting of clay minerals such as illite, montmorilonite and kaolinite. According to Airapetov (1980), clay reinforced with straw, is one of the most ancient building materials in the world. Its use dates back from 5000 or 4000 BC. In Nigeria, adobe bricks still remain the most popular materials for building houses in rural areas. Clay has a very high capacity for moisture absorption and this makes it swell and shrink easily. Clay has low tensile strength (dried clay is very brittle), and depending upon the proportion of the clay in the soil material, it may also not be strongly bonded. Therefore, any clay-based wall subjected to repeated cycles of wetting and drying would develop cracks and eventually cave in unless it is reinforced. Certain substances (rice husk ash, lime, cement etc.) are mixed with clay in a process known as earth stabilisation (Mathur, 1983) in order to strengthen the bonds. In addition, chopped grass or straw is mixed with the clay to give it added strength. On the other hand, clay has a low thermal conductivity (0.2 – 0.65 W/mK) and so it would reduce the incidence of temperature gradients that cause moisture translocation and deterioration of stored grains.

2.3.2.6 Plastics

Plastic materials such as polyvinyl chloride (PVC), polypropylene and polyethylene are low-density materials whose main quality is their good moisture- proofing properties. PVC has very high puncture strength and drums made from it are now being used as grain tanks. Polypropylene materials have thickness in the range of 25 = 200μm for the low density types while the high density types are within the range of 350 - 1000μm. Butyl rubber is also a popular material for grain containers (Pingale, 1976). However, the more popular plastics used in grain storage are plastic sheets. They have low initial and maintenance costs. They are used as weatherproof covers for stacked bags of grain, as waterproofing material in bin walls and beneath bin floors, and as bags for grain storage. Their main drawback is that they have low tear resistance. Insects and rodents easily attack most plastic sheets. Prolonged exposure to weather causes these sheets to deteriorate.

2.3.3 Assessment of the Effects of Construction Materials on Silo Performance

2.3.3.1 Metal

The most important problem with metal silo, from a safe storage standpoint, is the possibility of moisture migration occurring due to the high coefficient of thermal conductivity of steel and aluminium (12 - 62 W/mK and 202 W/mK, respectively). Metal walls readily transfer heat inward or outward, depending upon the changes in air temperature. Furthermore metal absorbs radiation heat in varying degrees, depending upon the reflectivity of the exterior surface and its radiation capacity of long wavelength heat energy (Salunkhe et al., 1982). When metal silos are exposed to the high temperatures in the tropics with its attendant high diurnal temperatures, wide temperature gradients develop. This, in turn, can result in moisture condensation on the walls and roof. The condensed moisture would eventually migrate into the grain leading to dampness and eventually, deterioration of the grain. Bakshi and Bhatnagar (1973) reported the development of moisture gradients and grain spoilage in outdoor metal silos exposed to high temperatures. Onwuzulu (1986) reported incidences of caking of grains stored in metal containers. He also reported of the occurrence of "hot spots" in his study. A possible method of improving the thermal performance of metal silos is to paint them in bright colours. This will improve their solar radiation reflecting capabilities. According to Salunkhe *et al.*, (1982), white paint is a good reflector and even as good as aluminium and bright steel and is a better radiator of low temperature energy. The emissivity of low temperature radiation of aluminium is 0.05 and that of white paint is 0.9. Apart from improving heat reflectivity, painting also protects ungalvanised surfaces from corrosion. Such silos require regular maintenance to keep the paint coatings effective.

Metal silos are good for sealed storage of grains because they are impervious to water vapour and gases. This makes pest control by fumigation effective. However, some of them have been reported to be insufficiently airtight for effective fumigation. This is attributed to weakness in welded or bolted joints. FAO (1994) reported that proprietary silos are difficult to seal because of the large number of bolts used in assembling them; these range between 8,000 and 10,000 in a 1,000 tonne silo. Even this can easily be overcome by sealing the bolted joints with special impregnated-felt (neoprene) washers (Salunkhe *et al.*, 1985). Another problem, restricted to proprietary bins alone, is that of the possibility of distortion of bolt holes which may result in relative movement between panels when the silo is under load (FAO, 1994). This creates both structural and moisture infiltration problem.

Several studies have been carried out on the phenomenon of condensation, moisture migration and diffusion in metal silo (especially the sealed ones) and how to solve the problems arising from them. In one of such studies conducted with low capacity bins (Agboola, 1987), the internal surface was entirely insulated with some commercial insulators. It was reported that the cost of the project was so high that not even for a 100 % guarantee of safety would it be advised.

In the case of high capacity metal silos, recent revelations seem to discourage its use. For instance, the report of a technical review of Nigeria's Strategic Grain Reserve Scheme noted that the choice of metal silos for the hot and humid climatic conditions prevailing in much of Nigeria is not suitable from the point of view of moisture activities (FAO, 1994).

2.3.3.2 Concrete Silos

Concrete, according to FAO (1994), should be the preferred material for building silos in coastal areas and where high corrosion risk is severe. However, concrete silos are not common in Nigeria (Igbeka and Ajisegiri, 1986). Apart from those built for research purposes (NSPRI, CSU-FMA, IAR/ABU etc.) only a few are in use in Nigeria. These structures are built as either surface bin or underground silos. Research into the latter is intended to come up with a silo that can replace the traditional pit stores. Igbeka and Ajisegiri (1986) noted that concrete silos, unlike metal silos, have little temperature problems. In a comparative study of metal and concrete silos, Olumeko (1989) observed lower temperature fluctuations in the concrete silo. He also found that the concrete had less moisture condensation within it. The major drawback of concrete silos is that of moisture absorption. They easily absorb moisture from the ground thereby making their inner surfaces very damp. Cracking of walls is another problem encountered with concrete silos, especially in poorly designed or poorly constructed silos. These are the problems encountered with the underground structures built by CSU-FMA (Anon., 1988a.) at NCAM, Ilorin. A way around these problems is to take great care in applying a damp-proof course or any capillary breaking layer. It is advisable to use materials with good heat-insulating properties to build the floors in order to avoid moisture condensation on the floor of the silos Hyde *et al.* (1973)

2.3.3.3 Wooden Silos

As was observed earlier, the use of wood for building silos in Nigeria is still at the experimental stage. And it is being developed mainly for use in the dry regions of the country rather than the humid south. This is largely due to wood's high susceptibility to moisture absorption, fungal and insect attack that would limit its use in moisture-laden environments. Igbeka and Ajisegiri (1986) cited wood's low thermal conductivity, year-round availability and low cost as merits in its favour as silo material.

Wooden silos usually consist of a frame of solid wood and walls of plywood panels. Their performance under Ibadan condition has been evaluated (Mijinyawa, 1989; Lucas and Mijinyawa, 1996). Test results showed that temperature fluctuations are low compared with metal silos. During one of the tests (Lucas and Mijinyawa, 1996) it was discovered that while the interior of the wooden silo remained dry, moisture had condensed on the inner walls of the metal silo.

2.3.3.4 Plastic Silos

Various attempts have been made to develop small storage bins using synthetic materials. According to Okoye (1989), most of these (rubber silos) had very poor record of performance during tests. Tests conducted with butyl rubber inserted in a metal weld mesh for the storage of cowpea were largely unsuccessful (O'Dowd. 1971). It was observed that the materials were easily punctured by insects, eaten by termites, fractured by weathering and chewed by rodents.

2.3.3.5 Clay Silos

Much work have been done on evaluation of clay silos (Giles, 1965; O'Dowd, 1971; Hyde *et al.*, 1973; Arinze and Abdullahi, 1989; etc.). Some of the major weaknesses of these structures include high moisture absorptivity, inadequate sealing and low structural strength. In an attempt to make the rumbu airtight, Giles (1965) applied two thick coats of bitumen emulsion to the internal surface. Grain (sorghum and maize) stored in the rumbu did not fare better than those stored in the untreated bins even though insect numbers were reduced. O'Dowd (1971) lined the walls of the rumbu with polyethylene and obtained a fairly airtight condition within the silo. The use of stabilised soil technique was introduced in order to make up for clay silos' low resistance to weathering (Bengston and Whitaker, 1986). This technique consists of adding lime or cement to the mud to give a greater strength to the silo. The wall is rendered with lime too. Olumeko (1989) described the design of an improved mud silo using mud bricks. Two types of these structures (brick masonry structure and reinforced brick masonry structure) are being tried. So far tests results have been very positive in terms of strength, moisture proofing and airtightness.

2.4 Classification of silos

Grain silos are generally classified as either deep or shallow for the purpose of design. Several criteria have been used to distinguish between the two types. One of these criteria is the plane of rupture theory. Based on this criterion, a silo is said to be shallow bin if the relative dimensions are such that the plane of rupture meets the grain surface before it strikes the opposite wall. In contrast, when the plane of rupture strikes the opposite side before meeting the grain surface the silo is said to be a deep one. A second criterion is based on the relationship between the depth of the silo, H, its diameter d, the coefficient of friction of grain on wall μ', and the pressure ratio k to the extent that for a deep circular silo,

$$H/D > 0.75\ (1/\mu'k) \quad \text{- deep silo} \tag{2.1}$$

A third criterion is based on the ratio of the height of the silo to the least lateral dimension so that a silo is considered shallow when the height is less than or equal to the least lateral dimension. Thus for a circular bin whose lateral dimension is the diameter,

$$H \leq D \quad \text{for a shallow silo.} \tag{2.2}$$

The significance of whether a silo is deep or shallow, according to Barre and Sammet (1966), is that it determines the load distribution pattern within the structure. Subsequently, it was noted that when a silo is shallow the floor will bear the entire vertical load of the grains and the walls would bear only the lateral pressures. By contrast, in a deep silo the floor does not bear the vertical load alone. Instead, the load is shared with the walls.

2.5 Grain pressure theories

Several models have been developed over the years for predicting pressures induced by grains in silos. The more common ones are those of Janssen, Airy, Rankine and Coulomb.

2.5.1 Janssen's equation for pressures in deep bins

Janssen based his theories on the following assumptions (Michael and Ojha, 1987):

-Grain pressures are carried by a grain arch within the grain structure, which distributes a portion of the grain weight in the form of vertical weight.

-The intensity is constant at any horizontal section

-Silo wall is rough and friction exists between grain and wall surface, but the coefficient at the material-wall interface is constant

-The ratio of lateral to vertical pressure (k) is constant throughout the grain mass

-The stored material is uniform in shape and homogeneous

Based on these assumptions, Janssen presented the following equation for the lateral wall pressure,

$$L = (WR/\mu')\,(1 - e^{-k\mu' h/R}) \qquad (2.3)$$

Where,

W = Unit weight of grain ($N\ m^{-3}$)

R = hydraulic radius = area/ perimeter (m)

μ' = co-efficient of friction of grain on wall material

k = pressure ratio = $(1 - \sin\Phi)/(1 + \sin\Phi)$

The vertical pressure borne by the wall is given by,

$$V_T = \mu' L_T \qquad (2.4)$$

Total load on the floor of a deep bin is,

$$F_v = W - C\,V_T \qquad (2.5)$$

where,

C = circumference of the bin (m)

V_T = vertical pressure on wall $N\ m^{-1}$

2.5.2 Rankine equation for determining pressures in shallow bins

This equation was developed to determine the pressures induced by granular materials on retaining walls. It is most often used for the design of shallow silos. The theory is based on two assumptions that, (i) pressure is caused by sliding effects of grains and no surcharge exists and (ii) there is no active frictional force between the stored grain and the silo wall. Hence the total weight of the stored grain is transmitted unto the floor. Rankine presented the equation for the lateral pressure of the grain per unit area of wall as,

$$L = W\,y\,[(1 - \sin\Phi)/(1 + \sin\Phi)] \qquad (2.6)$$

where,

Φ = Angle of internal friction, usually taken as angle of repose

y = depth of grain to point of consideration (m)

k = $(1 - \sin\Phi)/(1 + \sin\Phi)$ = pressure ratio

The total lateral pressure per unit of wall perimeter can thus be found, for a silo whose depth is h, by integrating equation 2.4 to obtain,

$$L_T = (Wh^2/2)\tan^2(45 - \theta/2) \qquad (2.7)$$

However, working further on shallow silos, Mohsenin (1978) observed that the pressure distribution in shallow silos is triangular in nature.

2.5.3 Dynamic pressures due to loading and unloading

It has been noted that during loading and unloading, dynamic pressures are exerted on the wall, which were not considered in the equations put forward by Janssen and Rankine. Michael and Ojha, (1987) revealed that the additional pressures were in the order of 2 to 4 times the static loads. Other workers, including Reynolds (1980), found that dynamic pressures are not significant in shallow bins and should be ignored in calculations.

2.6 Heat and Moisture Flow Theories

Among a silo's major functions is the exclusion of the stored grains from the effects of the prevailing environmental conditions. In order to achieve this objective, the fabric or skin (roof, walls and floor) must act as a barrier between the external and internal environments. Of particular interest to safe storage is the behaviour of the fabric to the flow of heat and moisture.

Three main sources of heat in a storage bin have been identified. They are external and internal. According to Loudon (1971), solar radiation is the main source of heat and the amount of it received in an area affects the outside air temperature directly which in turn affects the internal temperature of the silo. However, Welty *et al.* (1982) noted that the rate of penetration of heat from external sources would depend on the ability of the fabric of the silo to transmit it. Internal sources of heat within a storage system include respiratory activities of the grain and metabolic activities of all the living organisms (insects, fungi etc.) in the system (Sinha, 1973).

2.6.3 Heat and moisture flow through silo walls

Generally heat flows only when there is a temperature gradient in a system (Welty *et al.*, 1982). Temperature gradients are mainly caused by large diurnal fluctuations of temperature. The behaviour of a particular silo wall to heat flow depends on some basic properties of the materials used in building it. These properties include thermal conductivity, thermal resistivity, thermal transmittance, emissivity and absorptivity. Most of the materials in this section are adopted from Markus and Morris (1980).

2.6.3.1 Thermal Conductivity

Under steady-state conditions, the rate of heat flow through an element whose surface temperatures are t_1, and t_2, area A m^2 and thickness, l is given by,

$$Q\ (\text{watt}) = (kA/l)(t_1 - t_2) \qquad (2.9)$$

where, k = coefficient of thermal conductivity (W/m^2K)

However, heat flow through a silo wall is not under steady state and so other parameters are considered.

2.6.3.2 Thermal Resistance

Thermal resistance is a more apt property since one's concern here is with the resistance of walls to heat flow. It is the reciprocal of thermal conductivity. Mathematically then, thermal resistivity is,

$$R = 1/k \qquad (m^2K/W) \qquad (2.10)$$

If the resistivity of an element is known it will be possible to compute the rate of heat flow per unit area thus,

$$Q/A \quad = (k/l)\,(t_1 - t_2) \qquad (2.11)$$

It has been observed however, that in storage bin problems the heat transfer is not by conduction only and the transfer too, between surfaces only. Instead there are heat exchanges between the external and internal surfaces of the silo, and also between the external and internal air. This then calls for consideration of heat transfer by radiation and convection. According to IHVE Guide (1970), the rate of heat flow per unit area by convection is approximately,

$$Qc\,/A \quad = h_c\ (t_{ai} - t_{si}) \qquad (2.12)$$

And, that flow due to radiation is also approximately,

$$Q_R/A \quad = E\ h_r\ (t_{ri} - t_{si}) \qquad (2.13)$$

Where, h_c = convection heat transfer coefficient (W/m^2K)

h_r = radiation heat transfer coefficient (W/m^2K)

t_{ai} = internal air temperature

t_{si} = internal surface temperature

E = emissivity factor, assumed to be = 0.9

Total heat flow due to convection and radiation is thus,

$$= Q_R/A + Q_c\,/A$$

$$= E\ h_r\ (t_{rmti} - t_{si}) + h_c\ (t_{ai} - t_{si}) \qquad (2.14)$$

The internal resistance to heat flow was computed from these formulae and the following values were obtained for use.

Heat flow upward, R_{si} = 0.106 m^2K/W

Heat flow downward, R_{si} = 0.15 m^2 K/W

Heat flow horizontally, R_{si} = 0.123 m^2 K/W

Similarly the external surface resistance can be obtained from,

$$R_{so} = 1/(E\ h_r + h_{co}) \qquad (2.15)$$

where, $E\ h_r = 4.14\ W/m^2K$

h_{co} = external convection coefficient, which depends on the external wind speed.

Since wind speed affects the rate of heat flow from a structure then the degree of the structure's exposure in relation to wind flow must be considered. Values of wind speed and corresponding h_{co} and R_{so} are given in Table 2.4

Table 2.4 Values of wind speed and corresponding h_{co} and R_{so}

Surface	Wind speed m/s	h_{co} W/m^2K	R_{so} m^2K
Roof	1.0	9.9	0.07
Walls	0.7	8.7	0.08

Source: Markus and Morris (1980)

2.6.3 Thermal Transmittance

This parameter facilitates the determination of the rate of heat transfer resulting from the difference between internal and external air temperatures through a composite element. If t_{ai} = internal air temperature and tao = outside air temperature, the rate of heat flow per unit area through an element is given by

$$Q/A = U\ (t_{ai} - t_{ao}) \qquad (2.16)$$

where,

U = thermal transmittance

$$= 1/\text{sum of thermal resistances} = 1/\Sigma R$$

If then one is to determine heat flow through a wall made, for instance, of hollow blocks, plastered both on the inside and outside, the following resistances must be considered: internal resistance Rsi, plaster resistance, the block leaves resistances, airspace resistance, external plaster resistance and the external resistance. The sum of these resistances will give the total resistance to be used in computing the thermal transmittance.

2.6.4 Temperature gradient across silo walls

Temperature gradients are obtained when there are differences between the internal and external air temperatures. According to Markus and Morris (1980), the temperature gradient in an element can be obtained once the air temperatures inside and outside the element are known. The method used is based on the relationship,

$$t_1 = t_{ai} - [R_{si}\, U\, (t_{ai} - t_{ao})] \qquad (2.17)$$

The average temperature for a sunny day in a particular month can be determined from the equation,

Average monthly temperature for sunny day = $0.3t_{max} + 0.7t_{mean}$

where; t_{max} = average monthly maximum temperature and

t_{mean} = average monthly mean daily temperature

2.6.5 Heat flow into the system due to solar radiation

When the surfaces of a building are exposed to solar radiation a rise in the internal temperature is produced (Markus and Morris, 1980). This is aside from that caused by an increase in the external temperature. According to the IHVE Guide (1970) the effect of these combined temperatures is termed sol-air temperature. Consequently, the rate of heat flow due to sol-air temperature is the sum of heat flow due to solar radiation and that due to actual external air temperature. In other words, rate of heat flow at surface per unit area is the sum of flow due to actual temperature difference and heat gain due to solar radiation. Mathematically, this is given by Markus and Morris (1980) as,

$$Q_{sa} = (1/R_{so})(t_{ao} - t_{so}) + aI_G \qquad 2.16$$

2.6.1 Temperature Distribution in a grain bulk

Temperature gradients result from differences between the temperatures of two regions, surfaces etc. In a grain store temperature gradients exist across the wall depending upon the thermal conductivity of the wall material.

Variations in diurnal temperatures existing outside the storage bin do not readily get transmitted to the grain centre. Muir (1973) noted that these variations affect grain temperatures only up to 15 cm from the bin wall. This is because of grains' low thermal conductivity. Nevertheless, solar radiation causes the temperature of the bin wall to rise well above atmospheric temperatures. The degree of the heating of the wall depends on the thermal absorptivity of the wall material (Markus and Morris,1980). When the wall becomes heated it causes a temperature gradient to exist between the atmospheric temperature and the wall and this leads to flow of heat. The effect of this difference will be conducted to the grain through the wall by conduction. On the other hand seasonal variations in atmospheric temperatures are known (Muir, 1973) to have a greater impact on the grain temperature. During winter the centre of a bin, below the upper surface of the grain remains warmer than the remainder of the bin as convective air currents flow upward through the centre of the bin. In contrast to this in summer the centre of the bin near the bottom remains coolest as the air currents move upward along the warm walls and downward through the centre of the bin.

2.6.2 Moisture condensation, migration and diffusion in bulk grain

The mechanisms for moisture movement in bulk grain have been studied. Generally three mechanisms have been identified (Chung and Pfost, 1967): moisture vapour diffusion through the intergranular air spaces, diffusion through the kernel solid matter and moisture carried by convection currents. These movements are initiated by the existence of either a temperature gradient or variable vapour pressure or both.

Differences between the temperature of the grain and the outside air can be transmitted to the grain bulk through the walls. However, because of the low thermal conductivity of grain, these temperature effects on the outside of the grain mass are only very slowly transmitted to the centre (Muir, 1973). Thus condensation due to this temperature variation is not a common occurrence. However problems occur mainly when insect infestation occurs. The metabolic activities of insects result in localised increase in temperature and moisture content. This has been known to be a common cause of thermal instability within a grain bulk. Although the temperature increase is transmitted slowly to the surface of the bulk, its magnitude is sometimes high enough to create convection currents. Thus warm air rises and carries along with it moisture from high temperature region to a low temperature region. When this air gets to a cool surface its relative humidity rises and may reach saturation point. At this point excess moisture will condense on the grain surface. This, according to de Lucia and Assenato (1994), is a chain reaction, which if left unchecked, can ultimately lead to massive spoilage with wetting and caking on the grain surface.

Moisture diffusion out of individual grains occurs when their vapour pressures exceed the vapour pressure in the surrounding air.

2.7 COST OF STORAGE STRUCTURES

The elements of costs of building storage structures comprise purchased materials and labour costs. The cost of materials (which includes the cost of transporting them to site) is the most tangible to the small-scale farmer especially when erecting modern structures. It is often the deciding factor in whether a farmer can afford a new improved structure.

Labour costs are important where artisans are required for their skills. Otherwise the farmer and his family supply the necessary labour and do not charge any costs (Ezedinma, 1993). It has been suggested that the farmer should actually charge for their own labour when adding costs of storage structures. This suggestion was set aside (de Lucia and Assenato, 1994) based on the fact that during the dry season, opportunities for alternative employment are generally limited in rural areas so that the farmer's time is of little value. This is however not always true for farmers near towns and cities; employment opportunities are greater and the farmer's time is of more value. For this reason a farmer would choose a particular structure because he can do much of the construction work himself without paying for it.

CHAPTER THREE

METHODOLOGY

3.1 DESIGN OF THE SILOS

The design of the silos was based on standard procedures. It involved considerations of grain pressures and other imposed loads and structural stability and strength characteristics.

3.1.1 Determination of dimensions

The silos are to be designed for a storage capacity of 1.0 metric tonne. The next step in designing the silo is to determine the volume required to store the desired quantity. Storage volume is obtained from:

$$\text{Volume of silo} = \frac{\text{Mass of grain to be stored}}{\text{Bulk density of the grain}}$$

Since maize is to be stored, its bulk density (720 kg/m^3) will be used. Thus,

$$\text{Volume} = \frac{1000}{720}$$

$$= 1.39\ m^3$$

$$= 1.4\ m^3 \text{ approx}$$

For ease of monitoring, height of 1.1 m was chosen.

For a circular bin, volume = area of base x height

A height of 1.1 m is also chosen for this design in order to facilitate easy access to the interior of the silos and also to facilitate economical use of metal sheet.

Area of base = volume of bin/ height

$$= 1.4/1.1 = 1.3\ m^2$$

But base area $= \pi D^2/4$

Diameter, $D = \sqrt{(4A/\pi)}$

$$= \sqrt{(4 \times 1.3)/\pi} \qquad = 1.3\ m$$

$$\text{Diameter} = \sqrt{(4A/\pi)}$$
$$= \sqrt{(4 \times 1.3)/\pi}$$
$$= 1.3 \text{ m}$$

Diameter of the silo used = 1.30 m.

The circumference of the base = $\pi D = \pi \times 1.3$

$$= 4.08\text{m}$$

3.1.2 <u>Determination of Loads on the silo</u>

There are three main sources of loads in a grain silo. These are self-weight of the structure, wind load and grain load. Knowledge of the densities of the construction materials is necessary for the self-weight determination. Wind load is required because winds may cause silo failure by lifting and overturning. Its intensity depends on, among other factors, the height above ground level and wind speed.

Grain loads include lateral wall pressures, vertical wall load from friction between the grain and surface of silo material, vertical wall pressure and induced stress with the elements of the wall material.

3.1.2.1 Determination of lateral grain pressure on silo wall

The pressures to be determined are those induced by the grains on the walls and on the floor. The properties of maize required for these calculations include,

Specific weight, $W = 720 \times 9.81 \text{ N/ m}^3$

Angle of repose $\theta = 27^{o}$

Loadable height of silo, $h = 1.1$ m

Pressure ratio $k = (1 - \sin\theta)/(1 + \sin\theta)$

$$= (1 - \sin 27^{o})/(1 + \sin 27^{o})$$

$$= 0.38$$

In order to decide on the design equation, it is necessary that the silo dimensions be checked to determine whether the design should be for shallow or deep silo. Using the plane of rupture principle, a line is drawn from the intersection of wall and floor at an angle equal to the angle of repose of maize to the opposite wall.

For a shallow silo $H_p > H_s$

$$H_p = D\tan\theta$$
$$= 1.3 \times \tan(27°)$$
$$= 0.66m$$

Thus H_p is less than the design height of 1.1m. Therefore, the design will be Shallow for bins. As a result the Rankine equation will be used. Lateral pressure per unit area of wall is:

For a shallow bin Rankine equation (2.6) will be used. Thus lateral pressure induced by grains on wall:

$$L = W\,h\,(1 - \sin\theta)/(1 + \sin\theta)$$
$$= W\,h\,k$$

Where w = specific weight of the grain (N/m^3)

h = distance of the point at which the pressure is being considered from the grain surface (m)

θ = angle of internal friction of grain assumed to be = angle of repose

Substituting the appropriate values into the equation:

$$L = 720 \times 9.81 \times 1.1 \times (1 - \sin 27)/(1 + \sin(27)$$
$$= 720 \times 9.81 \times 1.1 \times 0.38$$
$$= 2952.42\ N/m^2$$

Allowing for dynamic pressures due to loading and unloading, the pressure must be multiplied by a factor of 2 to give,

$$L_{max} = 2952.42 \times 2$$

$$= 5904.84 \text{ N/m}^2$$

$$\mathbf{= 5.905 \times 10^{-3} \text{ N/mm}^2}$$

This is the maximum lateral stress developed by grain in the bin.

3.1.2.2 Grain pressures on silo floor

When the silo is filled to capacity, the grain will induce pressures on the floor. The magnitude of this pressure is determined from:

$$F_v = wh$$

$$= 720 \times 9.81 \times 1.1$$

$$= 7769.52 \text{ N/m}^2$$

$$= 7.77 \text{ kN/m}^2$$

The design floor load is obtained by multiplying this value by an over-pressure factor of 1.1 (Michael and Ojha, 1987). Thus maximum design load for the floor is:

$$F_d = 77.1 \times 1.1$$

$$= 8.55 \text{ kN/m}^2$$

Total grain load on floor $W = F_v$ x Area of floor cross section.

$$= 8.55 \times 1.3 = 11.12 \text{ kN.}$$

3.1.2.3 Wind Load

The steps for wind load design are described in Markus and Morris (1980). The first step is to determine the maximum wind speed appropriate to the structure. This is based on the maximum gust wind for the locality, which is then converted to design wind speed thus:

Wind speed, $V_s = V \times S_1 \times S_2 \times S_3$

Where , V = maximum wind speed for the locality (32.5 m/s: Source: International airport Minna).

S_1 = local topographic factor (= 1 for this location)

S_2 = surface roughness and height of structure factor = 0.47

S_3 = factor for the design life of the structure = 1.0

Thus for the test site, wind speed is,

$$V_s = 32.5 \times 1 \times 0.47 \times 1$$
$$= 15.275 m/s$$

According to the BRE Digest, when the wind rests against the windward face of the structure, all its kinetic energy is transformed to dynamic pressure. This pressure can be computed from,

$$q = k V_s^2$$

where $k = 0.613$

Therefore dynamic pressure due to wind effect on the silos is,

$$q = 0.613 \times (15.275)^2$$
$$= 143.03 N/m^2$$

3.1.3 Design of the Walls

The metal and clay silos will be treated as thin cylindrical shells because of their low thickness: diameter ratio (Singh, 1982). The wall design must be such that the maximum stress by grains would not exceed the allowable tensile strength of the wall material. Generally two major stresses are generated: circumferential and longitudinal stresses. According to Singh (1982), the circumferential hoop tension is the larger of the two and should therefore be used for the design. For a silo wall of thickness *t* and radius *r*, the hoop stress is:

$$P_h = \frac{P.r}{t}$$

Since P_h is not to exceed P_t,:

$$\frac{P.r}{t} \leq P_t$$

or

$$t \geq \frac{P.r}{P_t}$$

3.1.5 Determination of Floor thickness

Since the grains are to be spread over the entire floor it (floor) will be treated like a plate carrying a uniformly distributed load. The floor thickness can thus be obtained from (Singh, 1982):

$$t^2 = \frac{0.39.W}{p_a}$$

W = total grain load on floor (N); t = thickness and p_a= permissible stress for the floor material.

3.1.6 Design of the metal silo

It is envisaged that the thickness of the mud and steel bins shall be very small compared with the diameter. Consequently, the steel bin shall be treated as a thin cylindrical shell for the purpose of this design following the rules established in Singh (1982).

3.1.6.1 Determination of wall thickness

It is desired to determine the thickness of the sheet that is capable of withstanding the internal pressures due to the grain. The method is to ensure that the maximum stress developed in the silo does not exceed the allowable tensile stress (p_w) for the material of the silo. Two main stresses are developed in the bin; circumferential stress (or hoop stress) and longitudinal stress. However, according to Singh (1982), the hoop stress is the one that should be used in calculations since it is the greater of the two. In addition it is the one that resists the lateral pressure (L_{max}) that tends to burst the silo. Hoop stress is given as:

$$p_h = (L_{max} \times r)/ t$$

where,

t = thickness (m)

r = radius (m)

For failure not to occur, p_h must not exceed p_w.

Therefore,

$$(L_{max} \times r)/t \leq p_w$$

or

$$t \geq [(L_{max} \times r)/t] / p_w$$

Yield stress of MS = 210 N/mm^2

Diameter = 1.3m = 1300 mm

Radius, r = 650 mm

Since the sheet is to be welded longitudinally to make the bin, the hoop tension developed will be reduced by a factor equal to the efficiency of the weld. This should be taken as 70% (Singh, 1982).

Working or allowable tensile stress p_w = Yield stress / factor of safety. For steel design, a factor of safety of 3 is recommended (Michael and Ojha, 1987). Thus,

$$p_w = 210 / 3$$
$$= 70 \text{ N/ mm}^2$$

Maximum stress developed, L_{max} = 5904.84 N/m^2

Designing for hoop stress,

$$p_h = (p_w \times r)/(\eta \times t)$$

Therefore,

$$(p_w \times r)/(\eta \times t) \leq 70$$

or,

$$t \geq (p_w \times r)/(70 \times \eta)$$
$$\geq (5.905 \times 10^{-3} \times 650)/(70 \times 0.7)$$
$$\geq \mathbf{0.0783\ mm}$$

This is the minimum thickness required for the steel wall to withstand the grain pressure. For this work mild steel (MS) 20-gauge sheet has been chosen. The thickness of this sheet is 1.0mm. Since $1.0 \geq 0.0783$, the thickness chosen is adequate.

Design wind load

The total wind load on silo is given by (Reynolds, 1977):

$$F = A_e \times q \times C_f$$

Wall surface area = $2\ \pi \times 0.65 \times 1.1$

$$= 4.49 \text{ m}^2$$

For the purpose of the design the roof can be assumed to be a cone. Thus, the roof surface area will be approximately given by the area of a cone:

Area of a cone = $2\pi rl$

$= 2 \times \pi \times 0.65 \times 0.60$

$= 2.45\ m^2$

Total frontal area = frontal area of wall + frontal area of roof

$= 4.49 + 2.45$

$= 6.94\ m^2$

Effective frontal area $= 6.94/3 = 2.31 m^2$

Therefore, total wind load (from section 3.1.2.3) is:

$= 1.50 \times 143.03 \times 0.7$

$= 150.18$ N

Quantity of metal sheets required

The dimensions of a sheet are 2440mm x 1220mm. This is to be folded and welded longitudinally to form a cylinder of 1220m. Since the circumference of the silo is to be 4000mm, the number of sheets to be folded is determined from:

No. of sheets = 4000/2440

= 1.64 sheets

Since the cross-sectional area of base plate = 1.3 m^2 and that of the roof is 2.45 m^2 a sheet will be required for them. In order to provide for outlet and door fabrication, as well as for convenience of purchase, three (3) sheets will be required.

3.1.7 Clay mud silo

Determination of wall thickness

Tensile strength of the straw – impregnated mud = 1.25 N/mm^2 (determined in the laboratory)

Internal diameter, d = 1.3 m = 13900 mm

Radius, r = 1300/2 = 650mm

For clay structures, Mathur (1985) advised the use of a factor of safety of 4. Therefore, allowable tensile stress,

$$p_w = 1.25/4 = 0.3125 \text{ N/mm}^2$$

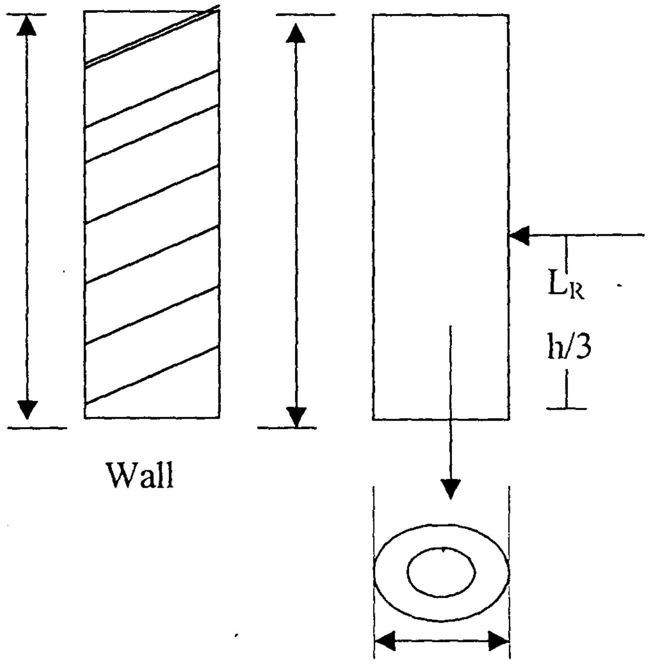
Designing for hoop stress,

$$T \geq (L_{max} \times r)/p_w$$

$$\geq (5.905 \times 10^{-3} \times 650)/0.3125$$

$$\geq \mathbf{12.28 \text{ mm}}$$

The wall thickness chosen for the mud wall is 50mm ≥ 12.28 mm.



3.1.4.2 Lateral Stability of the silo

Weight of the roof is approximately = 55 kg (FAO, 1987).

= 55 x 9.81 = 539.55 N

Self weight of wall = density of wall material x volume of wall

Volume of wall = area of cross section x height

Area $= [\pi (D^2 - d^2)]/4$

$= [\pi (1.35^2 - 1.3^2)/4$

$= \mathbf{0.1041 \text{ m}^2}$

Therefore, Volume $= 0.1041 \times 1.1$

$= \mathbf{0.115\ m^3}$

Density of the straw-impregnated mud = 2060 kg/m^3

Weight = $2060 \times 0.115 \times 9.81$

= 2313.89 N

Thus,

Total weight = self weight + weight of roof

= 2313.89 + 539.55

= 2853.44 N

Bending moment caused by grain thrust L_{max} about the base of the bin is,

$M = L_{max} \times h/3$ (Mohsenin, 1980)

$= 5904.84 \times 1.1/3$

= 2165.108 N.m

Section modulus for the bin cross - section is,

$Z = [\pi (D^4 - d^4)]/32D$

$= [\pi (1.35^2 - 1.3^2)]/(32 \times 1.35)$

= 0.0339 m^3

The direct stress at base of wall p_d = W/A = 2853.44/0.1041

= 27410.567 N/m^2

= 27.41 kN/m^2

Now, bending stress p_b = M/Z

= 2165.108/0.0339

= 63867.49 N/m^2

= 63.87 kN/m^2

Since the stress at internal end of the wall is permitted to be tensile (Singh, 1985), then

$$p_b > p_d$$

Therefore, tensile stress is given as

$$p_t = p_b - p_d = 63.87 - 27.41$$

$$= 36.46 \text{ kN/m}^2$$

It can be seen that the maximum stress developed by the grain in the bin is less than the allowable stress of the clay mud.

3.1.7 Design of the sandcrete silo

Wall thickness

According to Reynolds (1980), the minimum thickness for this type of structure is determined from:

$$t_{min} = \frac{Whd}{2\sigma_p}$$

Lateral grain pressure on wall = 5905 N; height of silo = 1.1m; diameter = 1.3m. The design strength (permissible stress) for sandcrete hollow blocks is obtained as:

$$= \frac{\text{characteristic strength}}{\text{partial safety factor}}$$

Reynolds (1980) also gives the design strength of the blocks as 4.8N/mm^2 and safety factor as 3.5. Putting these values in the equation yields

$$= \frac{5905 \times 1.1 \times 1.3}{2 \times 1.37 \times 10^6}$$

$$= 3.08 \text{ mm}$$

This is the minimum thickness required to withstand the lateral load imposed by the grains.

3.1.5 Lateral stability of the silo

The self weight of the silo is made up of the weight of the wall and that of the roof. Self weight of wall is:

= density of wall x volume

Volume = area x height

Area is calculated as for the others:

$$= \frac{\pi [(1.68)^2 - (0.65)^2]}{4}$$

$$= 1.89 m^2$$

Section modulus, Z $= \frac{\pi [(1.68)^4 - (0.65)^4]}{32 \times 1.68}$

$$= 0.46 m^3$$

Volume = $1.89 \times 1.1 = 2.08\ m^3$

Density of hollow block work in cement plastered inside and outside is given by Greer and Hancox (1977) as 1800 kg/m^3, and sò the weight of wall is:

$$= 2.08 \times 1800 \times 9.81$$

$$= 36728.64\ N$$

Weight of the roof is equal to weight of a 10 cm lightweight concrete (density = 2100kg/ m^3).

The volume of the roof slab is:

$$= (1.8 \times 1.2 \times 0.1) + (1.8 \times 0.5 \times 0.1)$$

$$= 0.216 + 0.09 = 0.306\ m^3$$

Weight of roof = $0.306 \times 2100 \times 9.81 = 6303.91 N$

Total weight of sandcrete silo = $36728.64 + 6303.91$

$$= 43062.55\ N$$

Direct stress $\sigma_d = W/A$

$$= \frac{43062.55}{1.89}$$

$$= 22784.42\ N/m^2$$

Moment due to grain pressure = 2165.17 Nm (from previous calculations) thus:

Bending stress = M/Z = 2165.17/0.46

$= 4.71 \times 10^3$ N/ m^2

Combined stress on the silo = 22784 + 4710

= 27494 N/ m^2

The strength of the wall material must be high enough to withstand this stress. Since combined stress = 27.494 k N/ m^2. This less than the strength of the wall it will be stable.

3.2 CONSTRUCTION DETAILS

3.2.1 The Steel Silo (Plate 1)

The main body (Wall and base): The main body was built with 20-gauge MS sheets. It was made by bending a sheet of 2440mm x 1220mm into a cylinder and welding the ends longitudinally. The bottom was welded onto one end circumferentially.

Roof: The roof consists of triangular panels of MS sheets welded together into a cone. It was later welded onto the main body to complete the bin. An opening, 400 mm long x 250 mm wide is provided on the roof for loading grains.

Openings: A lockable, hinged door is provided for inspection and monitoring. It is also made of flat 20 gauge steel sheet. It opens through nearly 180° giving an entrance of 400 x 400 mm. It is well fitted and there is a flange along the sides to ensure proper sealing when closed. When the door is closed the free space does not exceed 2mm.

Plate 1: Equipment for measuring temperature relative humidity and moisture content.

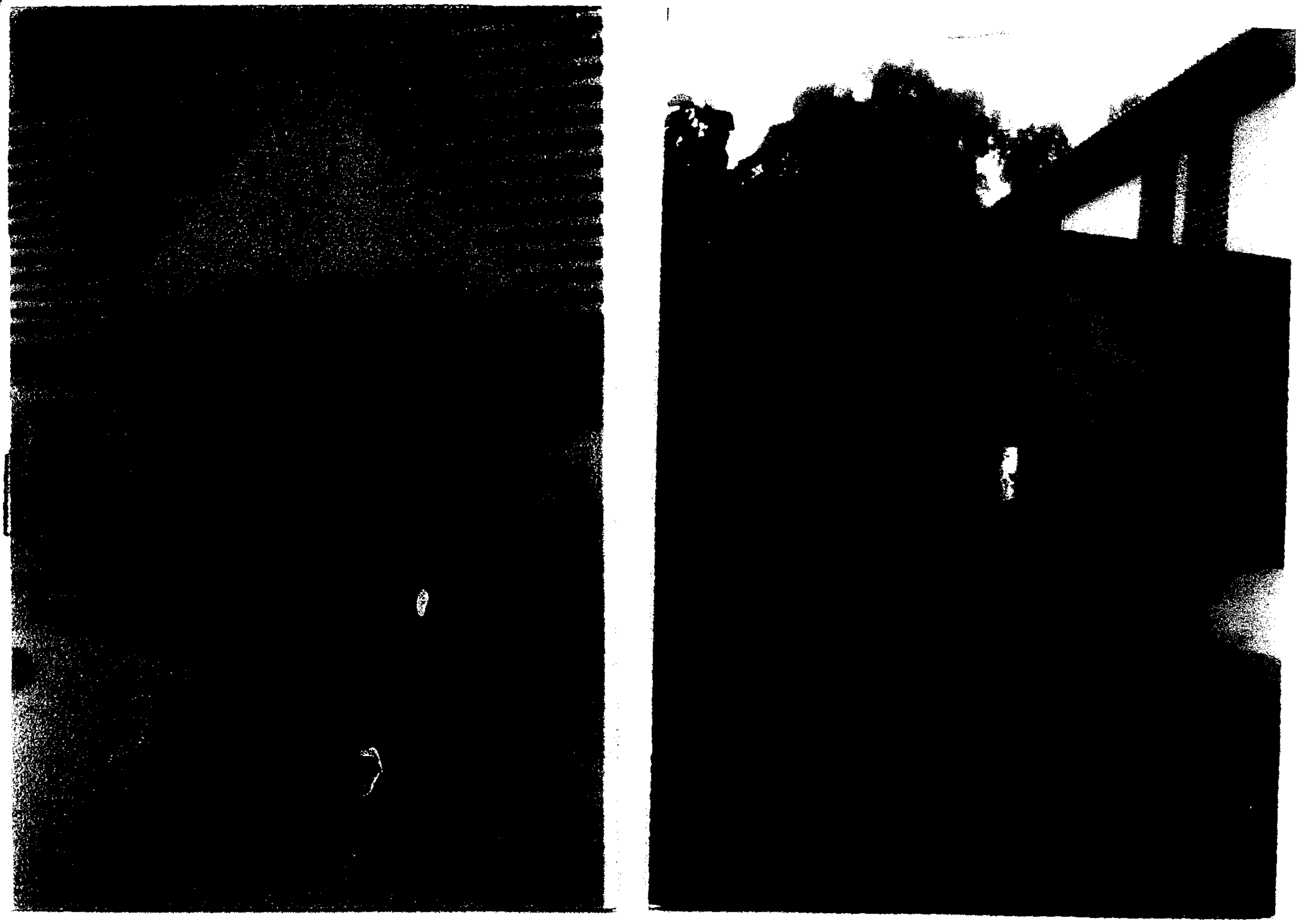


Plate 2: The steel silo showing the 3 openings.

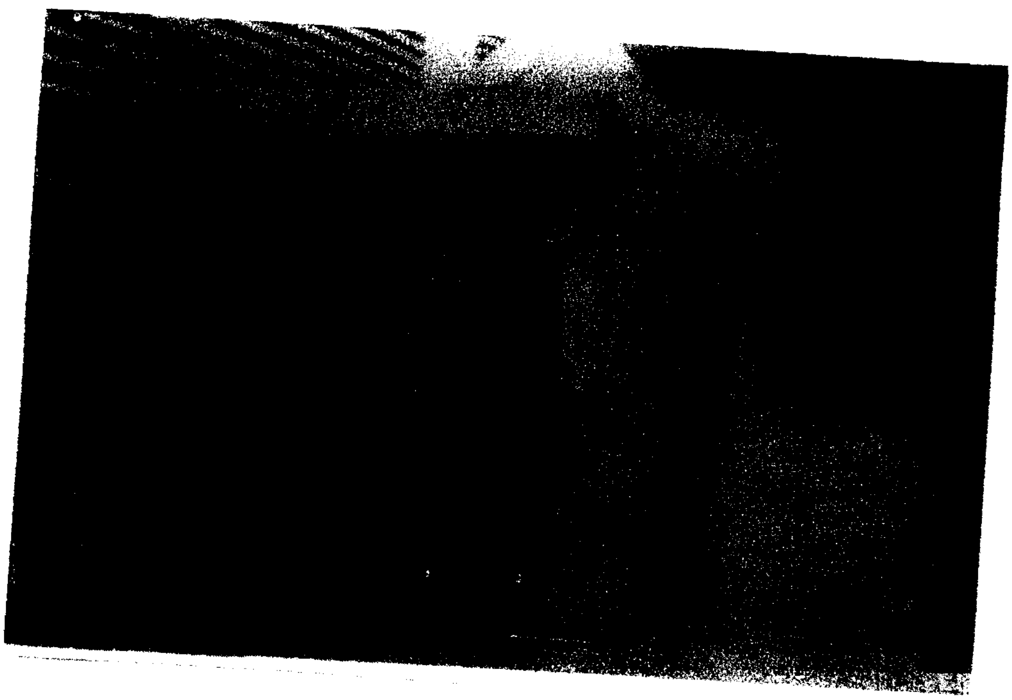


Plate 3: The sandcrete silo

Plate 4: The clay/straw silo.

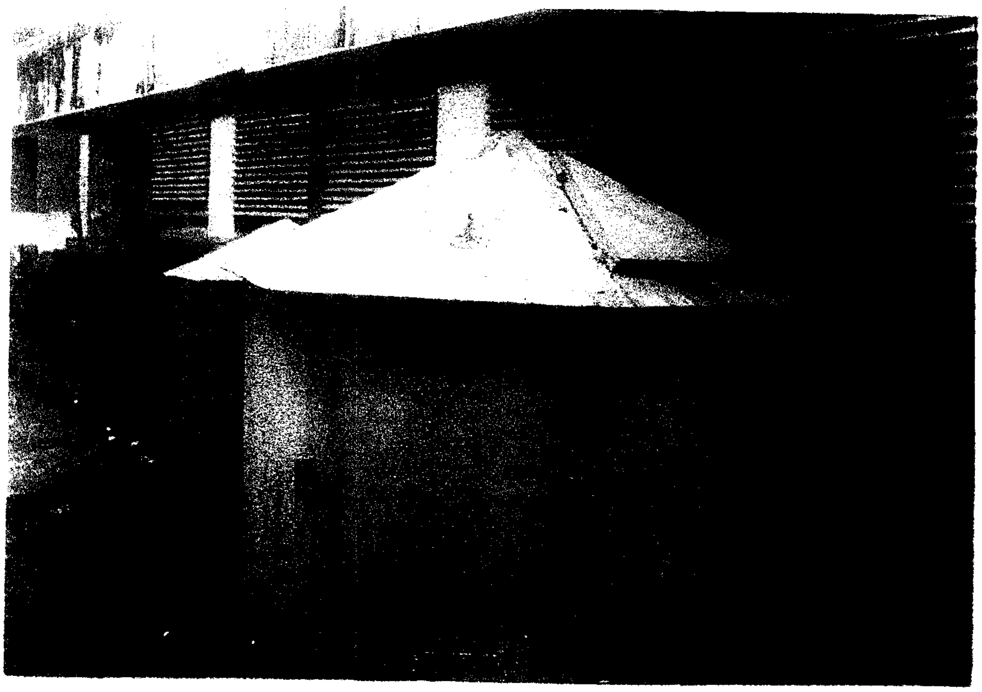


Plate 5: The wooden silo.

A cylindrical spout 150 mm diameter and 200mm long welded to an opening in the wall facilitates the discharge of grains. The spout has an angular inclination of more than 40 ^{o} to ease grain flow.

Support stand: The silo is placed on a 1250 x 1250 mm square steel frame support built with angle iron. The height of the stand above the ground is 0.6m. This gives enough clearance and prevents contact with ground moisture. It also facilitates emptying of the silo.

Ventilation: Two openings, each of 250 mm wide x 50 mm high, covered with perforated steel sheet provide natural ventilation. They are located just under the roof overhang. They can be closed with an adhesive tape when required.

Paint: The entire structure is painted in bright ash colour.

3.2.2 The Clay Silo (Plate 2)

Foundation: The foundation consists of a platform of sun-dried bricks upon which is spread a polythene sheet of about 0.7mm thickness. This is covered by another layer of bricks upon which the wall is raised. The floor is of slanted configuration to facilitate unloading of grain. It consists of well-packed soil covered with a 30mm cement-sand mortar. The entire base of the structure is covered with concrete to prevent erosion of the foundation.

Wall: The wall consists of well-compacted layers of clay mud mixed with rice straw.

Roof: The roof support consists of wooden braces fixed into the clay wall. In between these braces are other lighter woods for bracing the support. Two layers of woven reeds, interspersed with woven leaves complete the roof.

Openings: Two openings are available. One of these is a lockable door of 300mm x 300mm in a wooden frame. It is made of plywood sheet placed on a solid wood frame. It is located in the upper part of the wall and is meant for filling, inspection and monitoring. It opens through 180° and closes tightly. The other is a wooden grain discharge chute, 270mm x 15mm x 10mm high fixed into the wall. It slants at an angle of about 40° to facilitate grain discharge.

3.2.3 The Sandcrete silo (Plate 2)

The wall of this silo was built with cement hollow blocks of size 450mm x 225mm. The blocks were laid in cement: sand mortar. It is covered with a concrete slab at the top. Two openings, a discharge spout and an inspection door are provided.

3.3 COSTS OF CONSTRUCTION

The cost of building each silo consists of materials costs (including transportation for the procurement) and labour charges. All materials were procured from either Minna central market or within the town. Clay, grasses, and straw were obtained from Lukuchi village in Bosso Local Government area. The sand and rock chipping supplied by young men contractors selling in wheelbarrows. The total costs are: five thousand, three hundred and forty naira (N5,340.00) for the clay silo and eleven thousand, and thirty naira (N11,030.00) for the sandcrete silo. The costs are eight thousand and eighty five naira (N8,085.00) for the sheet metal silo and sixteen thousand, two hundred and thirty six naira (N16,236.00) for wood silo. A breakdown of costs for each silo now follows, except for the wooden silo, which can be found in Tolufase (1998).

Table 3.1. Total cost of the clay silo

Item	Specification	Quantity	Rate (N)	Amount (N)
Clay	Wheel barrow load	10 loads	100.00	1,000.00
Rice straw	Bundles	2	50.00	100.00
Grass/reeds	Bundles	10	50.00	500.00
Cement	50kg bags	½ bag	650.00	325.00
Rock chipping	Wheel barrow load	½	90.00	450.00
Bricks (sun-dried)	Single units	30	14.50	435.00
Polythene sheet	1.5m x 2.0m Sheet	1	150.00	150.00
Plywood/solid wood for window	-	-	-	100.00
Locking devices				80.00
Labour(carpentry) - construction	- -	-		200.00 2,000.00
		TOTAL	=	N 5,340.00

Table 3.2 Total cost of the sandcrete silo

Item	Spec.	Qty	Rate (N)	Amount (N)
Sandcrete hollow	450 x 225x 150mm	100	30.00	3,000.00
Cement	50kg bags	5	650	3,250.00
Sand	Barrow loads	20	30.00	600.00
Crushed rock	Loads	5	90.00	450.00
Door frame,	-	-	-	200.0
Paint	4-litre tin	1	450.00	450.00
Locking devices	-	-	-	80.00
Labour	-	-	-	3,000.00
		Total	=	N11,030.00

Table 3.3 Total cost of the metal silo

Item	Spec.	Qty	Rate (N)	Amount (N)
MS sheet	20 gauge 2.4 x1.2m	2½	1,300.00	3,250.00
Angle iron	4m length 40 x 40mm	1	500.00	500.00
Paint	5-litre tin	1½	650.00	975.00
Locking devices	-	2	80.00	160.00
Labour				3,200.00
			TOTAL =	**N 8,085.00**

3.3 EXPERIMENTATION

According to Arinze and Abdullahi (1989), the main aspects to consider when evaluating the performance of a grain storage structure are,

- Its capacity to resist the prevailing environmental hazards of heat, rain and moisture.
- Its limiting strength, hence its load-carrying capacity
- The extent of control it provides against external attacks by rodents and insects.

The characteristics of each silo required for these comparative performance studies are,

- Temperature gradients, heat absorptivity and conductivity
- Relative humidity gradients and occurrence of moisture migration
- Sprouting problem
- Insect penetration and infestation and development of "hot spot"
- Fungal attack on the structure

- Structural strength and durability
- Cost of materials and labour for construction

3.3.1 Rationale for Parameters Evaluated

Heat transfer characteristics of the silos can be assessed from the records of various temperatures. The air and wall surface temperatures are necessary data for determining the rate and pattern of heat flow and temperature gradients across the walls. These temperatures vary with time of day; hence the need to measure them at different times.

Grain temperatures are used to gauge the condition of the stored grain, and measuring these temperatures at different points would facilitate the drawing of a temperature distribution profile from which temperature gradients can be determined. Gauging the temperatures at different distances from the wall would also help establish the influence of external temperatures on the grain. This will at the same time reveal the occurrence of hot spots.

Moisture accumulation in the grain bulk will be evaluated by measuring grain moisture contents. Muir (1973) recommended that such measurements must be done at different zones in the bulk. This is based on evidence that the rate of deterioration is controlled mainly by the moisture contents of localised zones rather than the average moisture content of the whole bulk. Other indicators of moisture problem in a grain bulk are sprouting and caking. Therefore visual checks of the grains must be made.

3.3.2 Instrumentation

Atmospheric air and silo headspace temperatures were measured with a JENWAY 5105 Digital Psychrometer. Wall surface temperatures were gauged with TPG 122 mercury-in-glass thermometers. A PROTIMETER 3002 thermograph was placed permanently in the metal silo to monitor and automatically record hourly temperatures on charts. However during the tests on empty silos three Mason's minimum/maximum thermometers were used in the silos.

The temperatures of the stored grain were monitored with mercury-in-glass thermometer. Grain moisture contents were measured with Dickey John GAC 2000 moisture meter with a sensor at its end. However, laboratory measurements of moisture contents were done using the oven-drying method. The bulk densities of grain samples were determined with TR 400 AUTO equipment.

Daily minimum and maximum temperature and relative humidity data were obtained from the International Airport Maikunkele, Minna.

Infestation of grains by insects was regularly monitored. The presence of adult insects in the stored grain was visually monitored daily. Grain samples collected weekly were also checked for exit holes and other insect damages on the kernels. The presence of immature insects (larvae) was checked visually on the lit surface of the ***Illuminator rrb 5000***. The foreign matter contents of grain samples were also determined from results of visual examination on the illuminator.

3.3.3 Experimental Procedure

In order to evaluate the heat and moisture transfer characteristics of the silos, several variables and their effects (response factors) were identified as explained earlier. It is therefore very important to measure these parameters at various times of the day in order to get a picture of the pattern of their variations. It is known that most of these parameters interact with each other. For instance, the outer wall surface is expected to be considerably different from the ambient temperature because of the influence of solar radiation on it. The estimation of the influence of each variable and comparisons between the silos will be done. For each of the variables, 2 operating levels were mainly desired: the minimum and maximum values. This allowed for the maximal range between the levels. Temperatures and relative humidity are parameters that change with space and time and so they were measured three times daily. The corresponding effects of these variables were measured and treated as the response values.

Studies were initiated on March 3, 2000. The initial studies were aimed at monitoring temperatures in unloaded silos in order to determine the pattern of variation with ambient temperature and have base data for later comparisons with loaded conditions. Such studies have been done before and, as established in Bakshi and Bhatnagar (1972) are necessary for making comparative analysis of the performances of different silos. The months of March and April were chosen because they are the hottest in Minna (See Appendix I).

The studies consisted of measurements of air temperatures (outside and within the silo enclosure). Minimum and maximum temperatures were gauged daily. In addition, spot readings were taken three times daily in line with established procedures as in Lucas and Mijinyawa (1996). These measurements were taken at 09.00hrs, 14.00hrs and 18.00hrs. The periods of measurements were selected on the basis that ambient temperature in Minna generally peaks between 14.00hrs and 18.00hrs and drops to a minimum between 05.00 and 06.00 hrs. Added to this is the assumption that the internal conditions would reach their extremes after certain time lag (IHVE Guide, 1970).

Precautions were taken while taking measurements in the silos to minimise heat exchanges that would naturally occur as a result of opening the doors.

The extent of airtightness of each silo was gauged by fumigating the interiors of the silos. Knowing the exposure time and other specifications of the fumigant (phostoxin) one was able to make comparisons among the silos.

The second phase of the studies, involving loaded silos, commenced in October 2000. Maize grain for the experiments was purchased from Minna central market. Three silos (clay, steel and sandcrete) were filled with maize with a constant capacity of 400 kg at an initial moisture content of 13.8%, w.b. Other parameters of the maize were: bulk density- 75.5 kg/hl (755 kg/m^3)

Air and grain temperatures, as well as relative humidity of external and internal air were gauged three times daily.

3.3.3.1 Measurement of temperature and relative humidity

Grain temperatures were measured at two positions in each silo in the centre of the bulk: near the surface (grain surface temperature) and at 20-30cm depth (core temperature). The temperatures of the air above the grain surface (headspace temperature) were also measured. The procedures consist of first measuring the outside conditions: temperatures of the air and wall surface as well as air the relative humidity. After these the silo was opened and the temperature of the headspace air was gauged. Next, the internal wall surface temperature was measured. The temperature of grains just beneath the surface of the bulk was then measured. Finally, the thermometer stuck in the middle of the grain bulk was then removed and read for the temperature of the centre of grain bulk.

3.3.3.2 Measurement of moisture content

Moisture contents of the stored maize were gauged weekly at the periphery and at two depths in the centre of the grain bulk: just at the surface and at 30cm depth in each silo. Samples were collected from three locations in a silo using a grain-sampling spear.

3.3.3.3 Monitoring of activities of fungi, insects and rodents

Deep probe samples were taken at the central portion of the bottom of the bulk. All together every week (precisely on Sunday's) three maize samples were drawn from each silo for inspection. As stated earlier, the temperatures of the grains at the points of probing were gauged before drawing the samples. The samples were smelled to see if they had any unnatural odour. All the probe samples were later taken to the laboratory of the NSGR, Silo Complex, Minna. There, each sample was subjected to visual checks for moisture and mould damage such as caked or lumpy grain mass, sprouting, decayed and/or discoloured grains. The presence of rodent droppings was also checked in order to ascertain possible entry of rodents into the silos. However visual checks for sprouting of grains and rodent droppings were carried out on a daily basis and not restricted to weekly checks only.

In addition to internal checks, certain external ones were made regularly in order to monitor insect and rodent penetration from outside. All cracks and fissures in the silo walls (excluding metal silo) were checked for insect presence. Checks were made for signs of gnawing and burrowing especially in the wooden and clay silos. Other checks included signs of mould growth on the walls and in the case of the wooden silo and the roof of the clay silo, signs of decay and rot.

Further checks were carried out to ascertain the behaviour of the structures under loads. These comprised visual checks for sinking and consolidation of foundation during the loading and unloading process (for the wooden and metal silos), deflection, buckling, lateral and vertical stability, and rigidity of the structure through out the duration of the studies. Simple durability checks such as corrosion on metal surfaces, wear in walls due to weathering (clay silo), splits and cracks in walls and peeling of paint were also made.

CHAPTER FOUR
RESULTS AND DISCUSSION

4.1 RESULTS

Data from the two measurement periods are presented in Appendix B. The first period consist of measurements of temperatures of ambient conditions outside and within unloaded silos. Data from the second period represent measurements of temperature and relative humidity of ambient conditions wall surfaces and grains as well as the moisture content of the grains.

4.1.1 Ambient Conditions

The ambient conditions considered were those within the silo and the external condition. In the silos the temperature of the air in the headspace was measured and outside it was of the atmosphere.

4.1.1.1 Temperature variations

The minimum and maximum temperatures recorded in unloaded clay, sandcrete and wooden silos for the period March 25, 2000 to April 23, 2000 are presented in Table B1 in Appendix B. The maximum daily outside temperature ranged between 32 °C and 40 °C .On the other hand, the minimum outside temperatures varied between 22 °C and 28 °C. The minimum temperature observed in the wooden silo was 23.5 °C (on April 11, 2000) while the maximum was 37.5 °C recorded on several days. The corresponding figures were 26.5 °C and 37.5 °C for the clay silo and 24.5 °C and 41.5 for the sandcrete silo. The daily variations i.e. difference between the maximum and minimum readings for a day, are shown in Fig. 4.1. The curves represent the variations for the 30 days duration. A study of the curves shows that similarities exist in the patterns of temperature variations within the silos. However, the magnitude of the variations differs between them since the curves are distinct from one another except for the few days when they

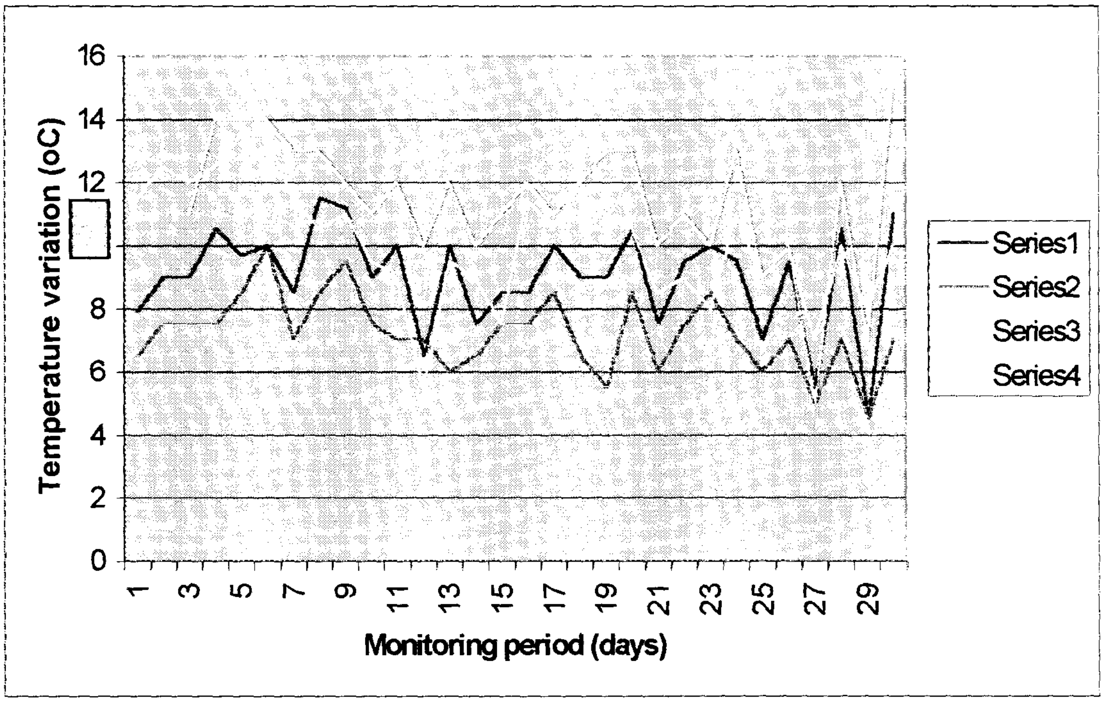


Fig. 4.1 Variations of external and internal temperatures with time for unloaded conditions

Sandcrete silo — Wooden silo

Atmospheric air — Clay silo

overlap. The average temperature gradient recorded in the sandcrete silo was 10.2 °C; it was 9.0 °C and 7.2 °C in the wooden and clay silos respectively. At the same time, the mean diurnal temperature gradient of atmospheric air was 11.4 °C. On the average lower temperatures were recorded in the clay silo than in the others.

Temperature data for the internal conditions of the silos when loaded with maize grains are presented in Tables B2 - B4. Diurnal changes in the headspace temperatures were relatively slow and so the data obtained were averaged on a weekly time interval. These weekly averages of daily measurements are given in Tables 4.1- 4.3. They are grouped into morning, afternoon and evening measurements. Expectedly, maximum values of the temperature of the atmospheric air were attained in the afternoons while minimum measurements were observed in the mornings. This was also the general trend within the silo enclosures. Temperatures in the steel silo were highest attaining an average of 43.7 °C in the 7th week of storage. Average afternoon temperatures over the period were 40.8 °C in the steel silo, 37.7 °C in the sandcrete bin and 35.6 °C in the clay bin. Fig. 4.2 shows the variations of the weekly averages of daily temperature gradients in the silos over the storage period. A comparison of Fig. 4.1 with Fig. 4.2 shows that the patterns of variation of external and internal air temperatures with time was fairly stable in silos loaded with grains than in empty ones. Almost all through the period of initial tests on empty silos, the curve of the fluctuations of atmospheric air temperatures was above those of the silo enclosures. In contrast, the curve remained below the curves of temperature gradients in loaded silos.

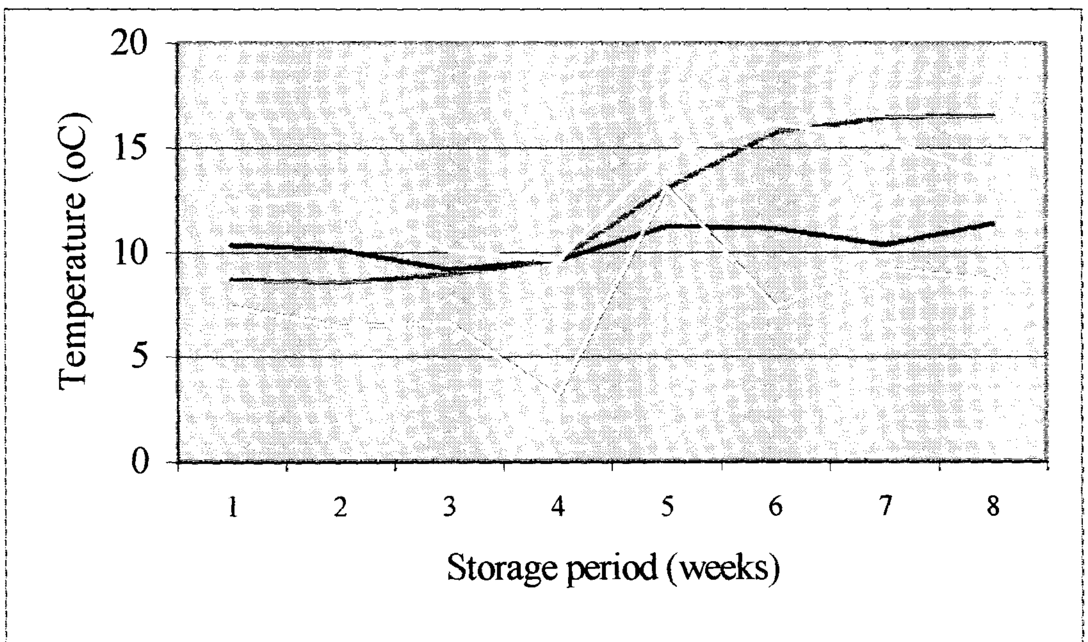


Fig. 4.2 Weekly averages of daily variations of external and internal temperatures over the storage period (loaded condition)

External air Sandcrete silo Clay silo Steel silo

A comparison of the periodic variations in temperatures in the silos reveals that the temperature of the air in the steel silo reached its maximum much earlier than in the other silos. In the others there were delays of various duration in the attainment of maximum temperatures. The longest delay (i.e. time lag between when the atmospheric air reaches its maximum and when maximum is attained in the silo air) occurred in the sandcrete silo.

Hourly temperatures of the steel silo headspace recorded for the entire duration of the study are presented in Appendix C. Fig. 4.3 shows the measurements for some selected days. A notable feature is the similarity between the curves and that of the atmospheric air. The temperature usually rises uniformly from the lowest values attained between 05.00hrs and 07.00hrs until it reaches a maximum around 13.00hrs – 15.00hrs. Thereafter, the temperature begins to fall, not uniformly though but rapidly sometimes, through the evening and night until it reaches a minimum in the early hours of the following day when the cycle is repeated. The peaking of the temperature in the steel silo occurred within the same time frame that it occurs in the atmospheric air.

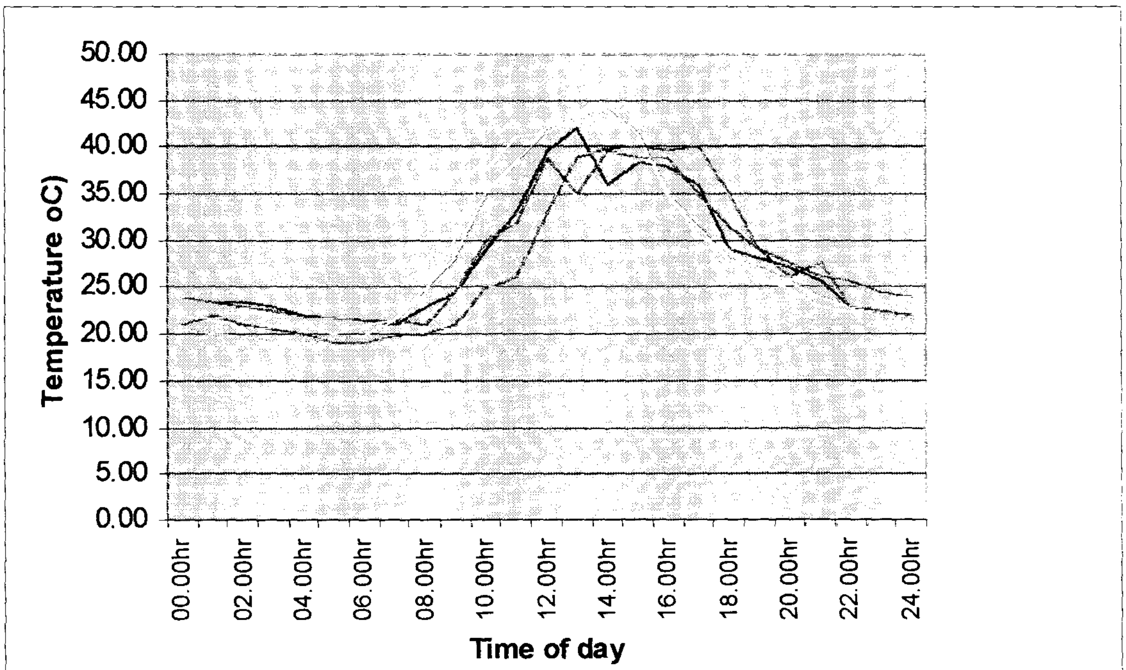


Fig. 4.3 Temperature fluctuation in the steel silo –for selected days

4.1.1.2 Relative Humidity variations

Fig. 4.4 shows the variation of the relative humidity of atmospheric air silo internal air over the storage period. The relative humidity of the atmospheric air fell steadily from a high of 69.1% in the first week to 50.7% in the last week. The highest relative humidity value 98% was measured in the sandcrete silo in the

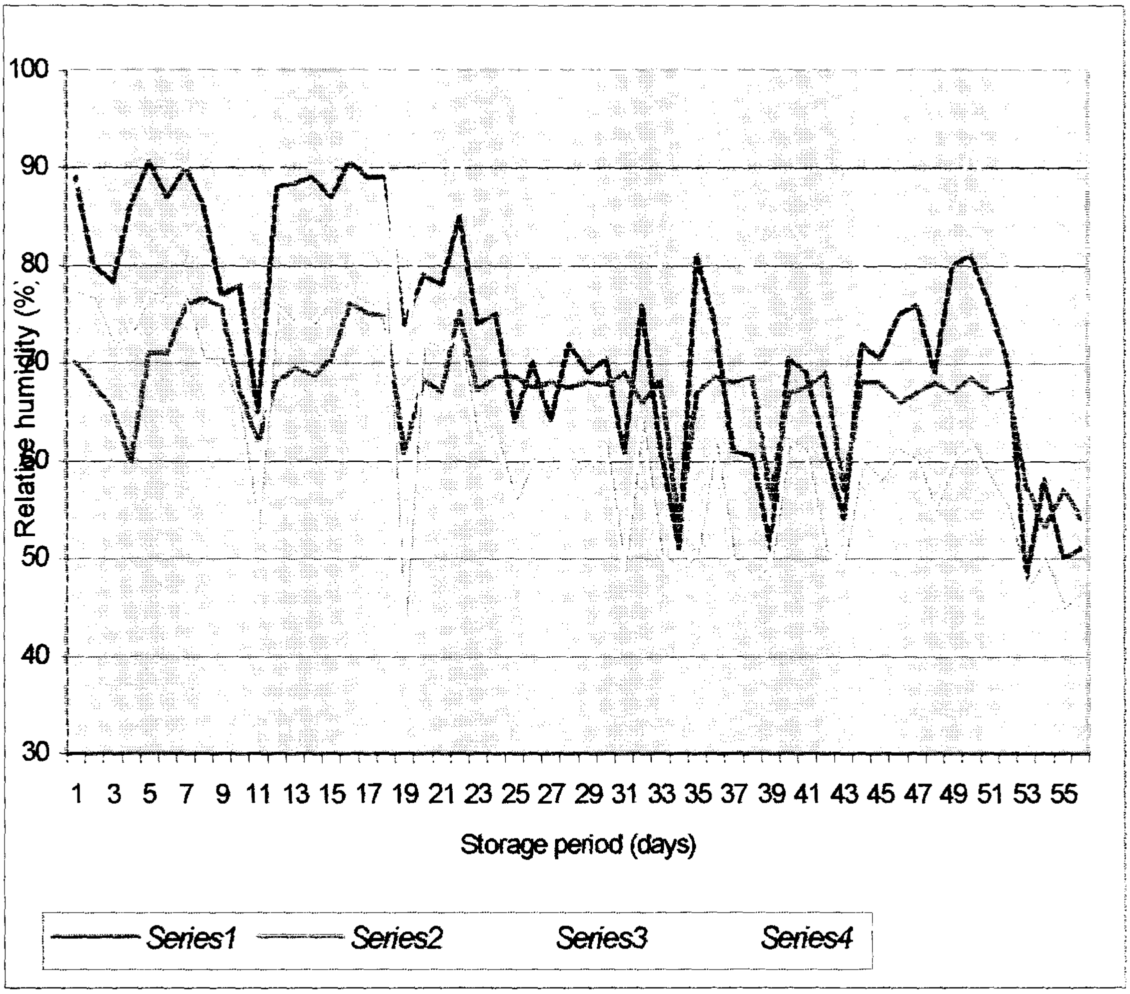


Fig. 4.4 Variation of relative humidity outside and inside the silos

Legend

Series 1 – Atmosphere Series 2 – Clay silo

Series 3 – Sandcrete silo Series 4 – Steel silo

evening of October 18, 2000, while the lowest measurement (28.7%) was recorded in the steel silo in the afternoon of November 8, 2000. Generally, the lowest relative humidity values were recorded in the afternoons when the sun normally exerts a drying effect on the ambient air. Relative humidity gradients between atmospheric air and internal air were lowest in the clay silo while the highest gradients (up to 30.8%) were attained in the sandcrete bin.

4.1.2 Grain Conditions

The data for the conditions of the grain in storage are given in Appendix B. Temperatures observed at the top surface of the grain bulk are indicated by T_{gs} while those for the centre of the bulk are marked as T_{gm}. Variations of grain temperatures in individual silo with period of storage are shown in Figs. 4.5 – 4.7. It can be observed from Fig. 4.5 that a clear similarity exists between the curves of temperature at the grain surface and internal air temperatures in the steel silo. This is an indication that temperature changes at the top surface are closely related to ambient temperatures. The result confirms the assumption by White (White, 1988) that a close relationship exists between the two conditions and so could be used in modeling seasonal changes in grain stores.

The temperature at the centre of the grain bulk in the steel silo rapidly reached a level, which remained constant throughout the period of study. This is demonstrated by the nearly straight horizontal nature of the curve. The average daily surface temperature of the grain bulk varied between a low of 33 °C and a high of 38°C. Surface temperature in the steel silo fell during the first 3 weeks of storage, thereafter it began to rise until it peaked at 38 °C after 6 weeks. From then onwards it began a uniform downward slide. In the clay and sandcrete silos temperatures changed more often at both depths of measurement. In the case of the clay silo (Fig. 4.6) the two curves are similar in pattern of fluctuation except for the initial period. At the initial stage, temperature at the centre of the grain bulk rose by just 0.2 °C to coincide with the surface temperature which fell from 32 °C to 31.8 °C in just under 2 weeks. However the temperatures at both depths reached maximum at the same period i.e. in the 4th week. In the sandcrete bin, grain temperatures changed rapidly

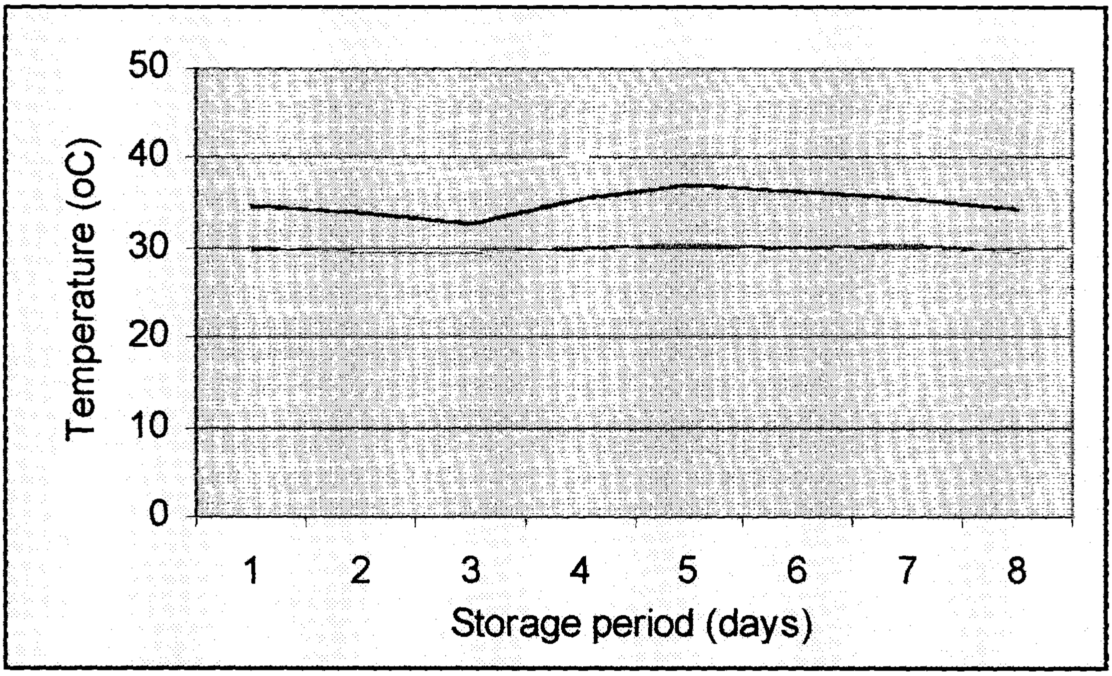


Fig.4.5 Variation of grain surface and centre temperatures with storage period in steel silo

Centre of grain bulk   Grain surface   Headspace

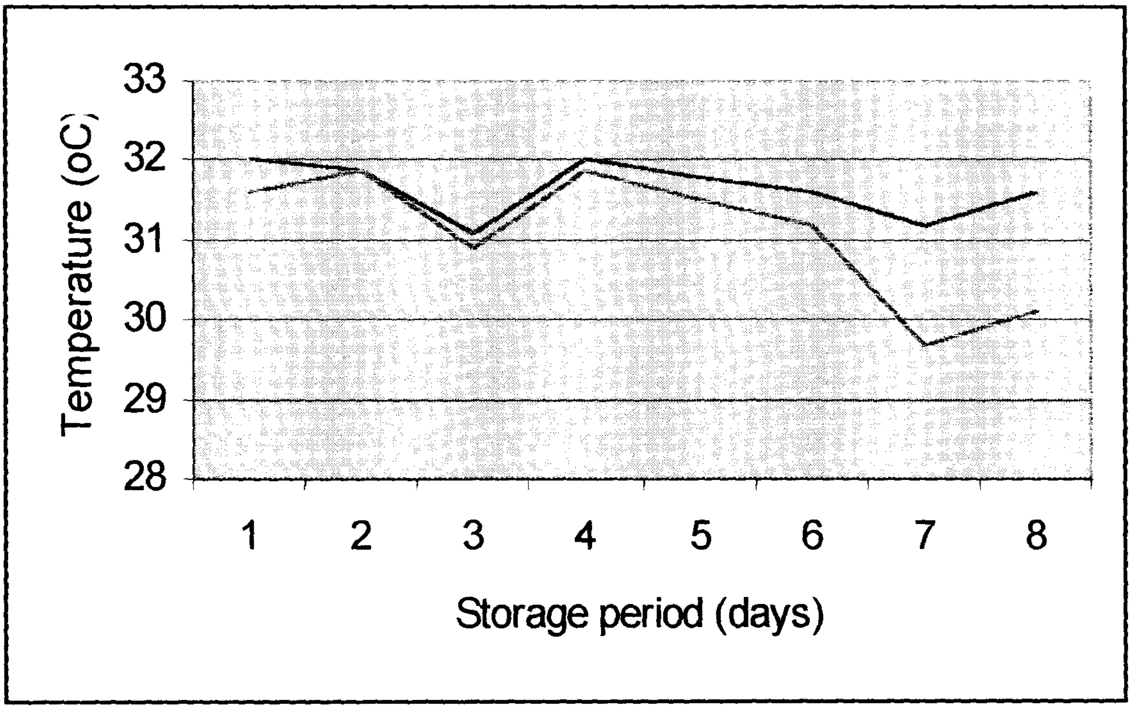


Fig.4.6 Variation of grain surface and centre temperatures with storage period in clay silo

Centre of grain bulk   Grain surface

with time, attaining an increase of 4 °C in one week. (Fig. 4.7)

In general, fairly low temperature gradients were observed in all silos. These temperature gradients, between the centre of the grain bulk and the top surface, can be deduced from Figs.4.5 to 4.7. It would be seen that the highest temperature gradient of 7.5 °C was recorded in the steel silo, while the lowest was measured in the clay silo.

4.1.3 Wall surface temperatures

The temperatures of the wall surfaces are given in appendix B. In the measurements T_{wo} (T_{so}) represent the temperature of the external or outside surface while T_{wi} (T_{si}) stands for the internal surface of the silo wall. Variations in external surface temperatures were closely related to changes in temperature of the atmosphere; as maximum air temperature of air occurred in the afternoons, so did it occur on the external surface. The highest wall temperatures were recorded in the steel silo which had a maximum of 51.0 °C in the afternoon of October 16, 2000 when atmospheric temperature was 32.3 °C and relative humidity was 56%. The maximum temperature of the sandcrete wall surface was 48 °C (recorded on October 23, 2000). In contrast the lowest wall temperature was recorded in the clay silo in which temperatures did not exceed 38 °C (October 10, 2000). A study of the pattern of daily fluctuations shows that wall temperatures dropped more rapidly in the steel silo (up to 20 °C in 4 hours) as opposed to 14 °C in the sandcrete silo and 10 °C in the clay silo.

In all afternoon measurements, external wall temperatures exceeded atmospheric temperature. A comparison of these afternoon temperatures averaged on a weekly interval is shown in Fig. 4.8. Records of the internal surface temperatures show a clear distinction between the silos. Whereas

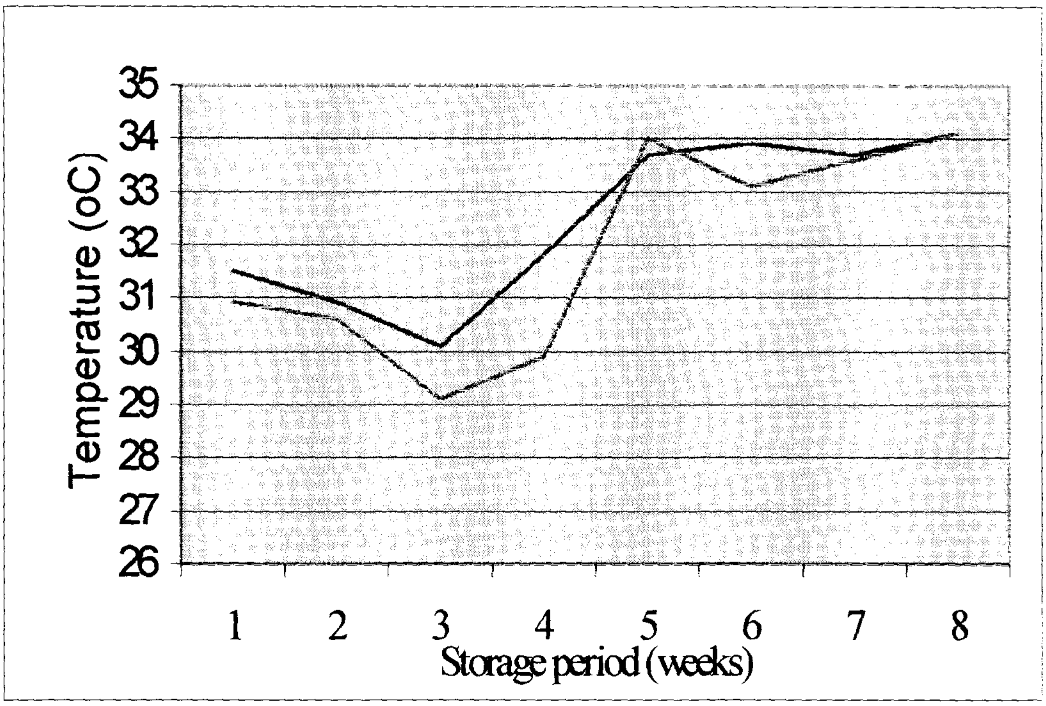


Fig.4.7 Variation of grain surface and centre temperatures with storage period in sandcrete silo

Grain surface   Centre of grain bulk

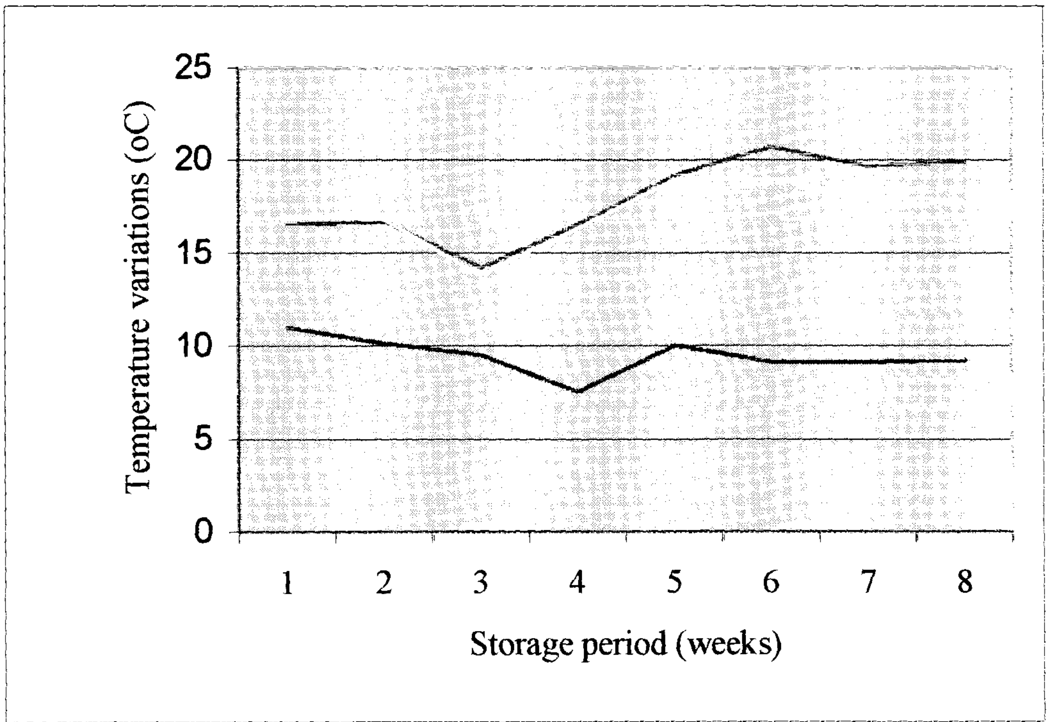


Fig 4.8 Average weekly variations of wall external surface temperatures

Clay silo   Sandcrete silo   Steel silo external surfaces were generally hotter than internal surfaces in the steel and sandcrete silos in the afternoons, the reverse was the case in the clay silo. The measurements shown in Tables 4.1 to 4.3 clearly support this observation. The highest temperature gradients at any period of the day occurred across the sandcrete wall (up to 11.2 °C). On the other hand, the lowest gradient (0.5 °C) was registered in the clay silo. The maximum temperature gradient across the wall of the clay silo was 2.0 °C. Moderate gradients were recorded in the steel silo (average of 7.0 °C).

4.1.4 Moisture variations

Moisture contents measured at the 3 gauging positions are presented in Tables B5 in the appendix. Moisture contents in all gauging locations in the steel and clay silos varied only slightly from the original condition; the values never exceeded 14.5%. In contrast, moisture contents in the sandcrete silo varied widely over the storage period reaching 35.5% at the end of the third week. Figs. 4.9 to 4.11 show the pattern of variations of moisture content at the 3 gauging locations in the silos. In Fig. 4.9 it would be seen that there were no significant differences in the moisture content at the various points throughout the duration of the study. Variation of moisture content in the steel silo was similar to that within the clay silo. In the sandcrete silo distinct fluctuations occurred between the locations. The highest values were obtained at the location near the wall by the inspection door. As for location beneath the top surface of the grain bulk the moisture contents were lowest. Moisture accumulation in the sandcrete silo may be due to the occurrence of condensation resulting from high temperatures as well as high relative humidity. It may probably be the result of slight leakage through the doorframe. A third possibility is that the increase in moisture content was caused by floor seepage considering that grains at the top surface of the bulk were not seriously affected.

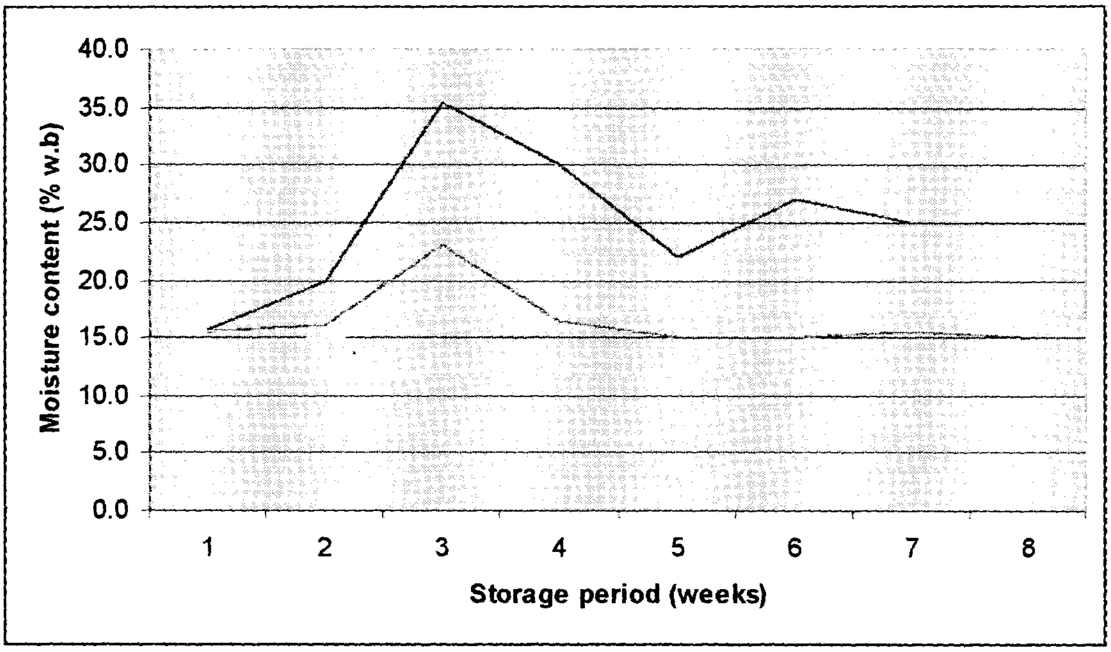


Fig 4.9 Moisture content at different points in the sandcrete silo

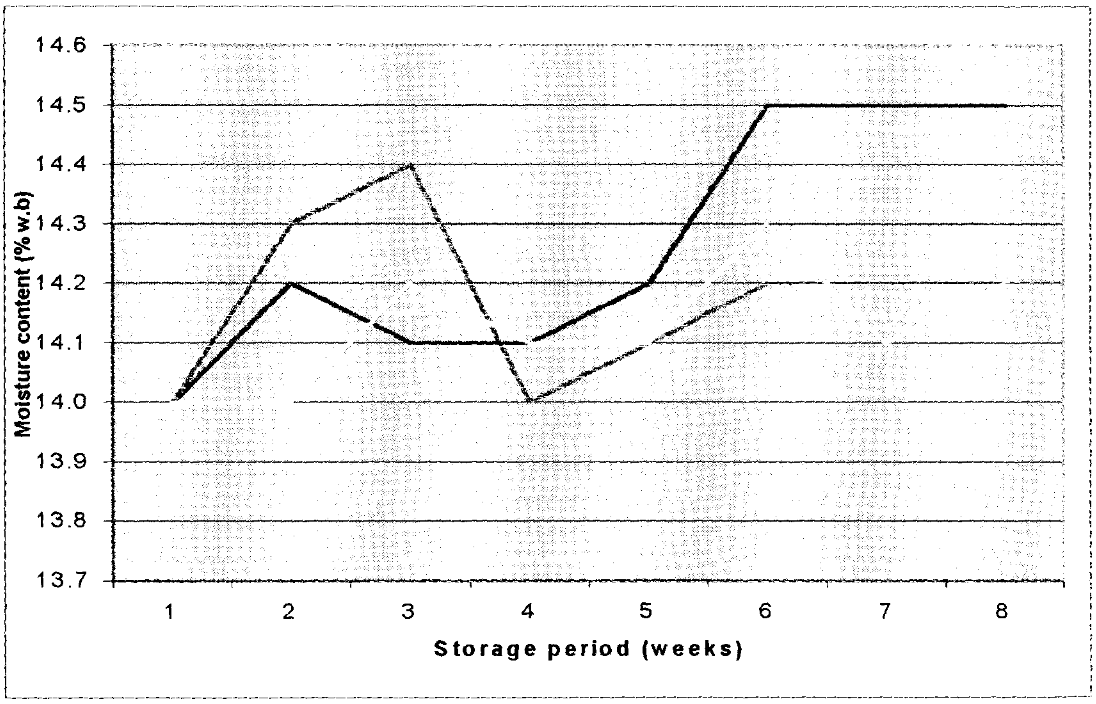


Fig. 4.10 Moisture contents at different points in the steel silo

Near the wall (door) Centre near surface

Centre near bottom

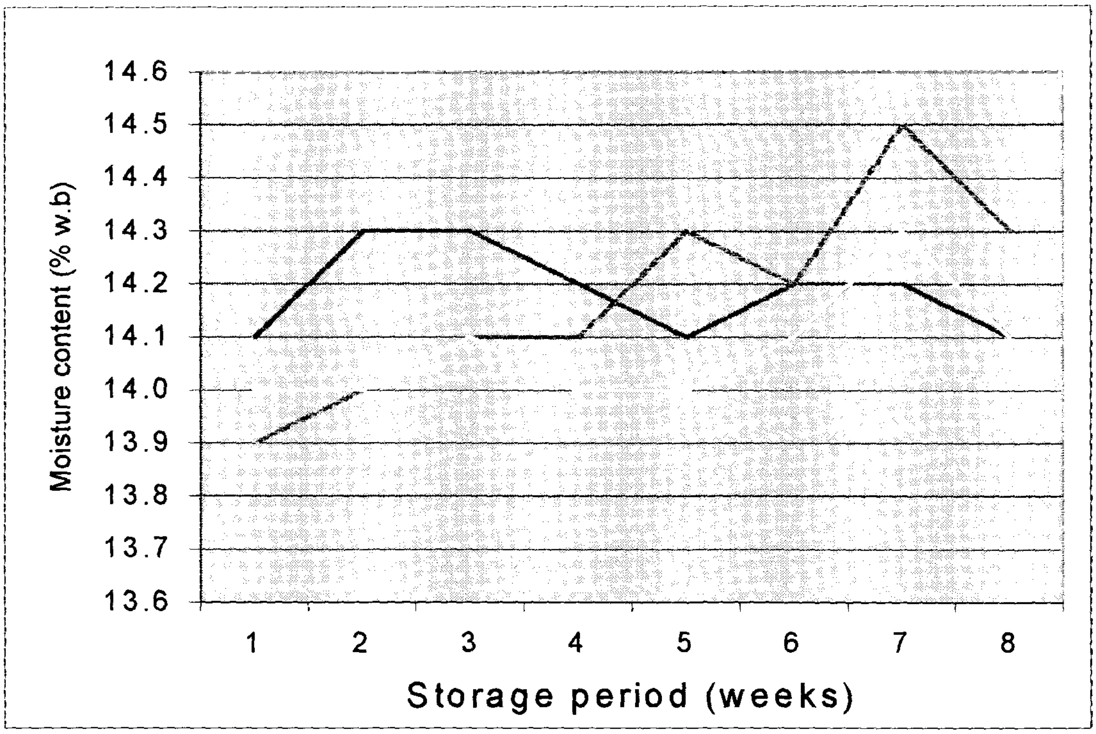


Fig. 4.11 Moisture contents at different points in the clay silo

Near the wall   Centre near the bottom   Centre near surface

Table 4.1 Weekly means of data from steel silo

Morning	Week 1	Week 3	Week 5	Week 7
Rho(%)	85.8	83.8	67.1	73.8
Rhi(%)	75.5	70.5	54.8	59.0
Tao(°C)	25.0	25.6	26.6	26.9
Tai(°C)	26.3	27.9	28.1	28.3
Tso(°C)	26.1	27.8	28.1	29.7
Tsi(°C)	26.8	28.2	28.4	29.1
Tgs(°C)	27.2	27.5	28.0	28.6
Tgm(°C)	28.9	28.8	29.3	29.9
		Afternoon		
Rho(%)	55.7	56.5	39.7	42.4
Rhi(%)	46.2	47.4	33.0	36.2
Tao(°C)	32.4	32.3	39.7	34.7
Tai(°C)	38.6	38.0	42.8	43.7
Tso(°C)	43.1	41.6	47.0	47.0
Tsi(°C)	38.3	37.0	42.3	41.2
Tgs(°C)	34.8	32.5	36.9	35.4
Tgm(°C)	30.0	29.7	30.3	30.2
		Evening		
Rho(%)	65.7	67.5	52.7	54.0
Rhi(%)	69.5	70.0	56.4	57.1
Tao(°C)	29.8	29.3	30.6	29.0
Tai(°C)	30.7	29.6	30.9	29.2
Tso(°C)	30.3	29.2	30.4	28.9
Tsi(°C)	30.3	30.0	31.3	30.4
Tgs(°C)	31.5	31.4	32.8	31.1
Tgm(°C)	27.6	28.4	29.9	29.4

Morning	Week 2	Week 4	Week 6	Week 8
Rho(%)	81.6	72.0	63.9	58.8
Rhi(%)	68.9	61.8	54.7	50.3
Tao(°C)	25.8	28.0	27.0	25.5
Tai(°C)	27.4	30.6	26.4	27.4
Tso(°C)	26.9	30.3	27.0	28.4
Tsi(°C)	27.9	29.9	28.1	29.0
Tgs(°C)	27.0	28.3	28.2	28.8
Tgm(°C)	59.0	29.8	29.4	29.7
		Afternoon		
Rho(%)	50.5	51.0	39.7	39.0
Rhi(%)	44.0	39.5	32.4	32.0
Tao(°C)	32.2	31.1	34.4	34.3
Tai(°C)	39.2	40.2	42.5	41.0
Tso(°C)	43.7	46.5	45.8	45.4
Tsi(°C)	38.2	39.7	41.8	39.8
Tgs(°C)	33.4	35.4	36.1	34.3
Tgm(°C)	29.6	29.8	29.9	29.6
		Evening		
Rho(%)	65.0	63.3	53.4	52.5
Rhi(%)	68.2	62.8	50.8	53.3
Tao(°C)	26.5	29.4	30.2	30.6
Tai(°C)	30.8	31.3	30.0	27.9
Tso(°C)	30.0	30.2	29.2	27.6
Tsi(°C)	30.6	31.3	29.8	30.2
Tgs(°C)	32.4	32.8	31.8	33.0
Tgm(°C)	29.1	29.3	29.3	29.8

Rho(%) = relative humidity of atmospheric air	Tao(°C) = atmospheric air temperature
Tso(°C) = external wall surface temperature	Tgs(°C) = temperature of grain near the surface
Rhi(%) = rel humidity silo headspace air	Tai(°C) = internal air temperature
Tsi(°C) = internal wall surface temperature	Tgm(°C) = grain temperature at the central portion

Table 4.2 Weekly means of data from clay silo

Morning	Week1	Week3	Week5	Week7
Rho(%)	85.8	83.8	67.1	70.9
Rhi(%)	68.7	70.3	65.6	65.9
Tao(°C)	25.0	25.7	26.6	29.9
Tai(oC)	24.7	24.8	25.5	25.6
Tso(oC)	24.9	26.1	26.4	26.2
Tsi(oC)	25.4	25.8	26.3	26.5
Tgs(oC)	26.6	26.4	26.9	26.8
Tgc(°C)	28.7	28.4	29.1	28.8
Afternoon				
Rho(%)	56.7	56.5	39.7	41.4
Rhi(%)	45.3	45.6	41.4	37.8
Tao(°C)	32.4	32.3	34.2	34.9
Tai(oC)	35.0	33.9	36.7	35.9
Tso(oC)	35.9	35.6	36.4	35.3
Tsi(oC)	35.9	35.4	35.1	34.1
Tgs(oC)	32.0	31.1	31.8	31.2
Tgc(°C)	31.6	30.9	31.5	29.7
Evening				
Rho(%)	81.6	72.0	63.9	62.0
Rhi(%)	52.1	58.8	56.5	57.8
Tao(°C)	29.8	29.3	31.1	29.1
Tai(oC)	31.8	31.4	33.0	32.0
Tso(oC)	29.4	29.2	31.0	29.2
Tsi(oC)	31.2	30.6	32.0	30.9
Tgs(oC)	31.5	29.2	32.3	31.0
Tgc(°C)	30.6	29.4	30.4	28.7

Morning	Week2	Week4	Week6	Week8
Rho(%)	81.6	72.0	63.9	62.0
Rhi(%)	69.7	69.0	66.3	60.7
Tao(°C)	25.8	28.0	26.6	25.5
Tai(oC)	25.2	25.9	25.7	24.7
Tso(oC)	25.8	27.1	27.1	26.0
Tsi(oC)	25.5	27.0	27.2	25.7
Tgs(oC)	27.0	27.9	27.5	26.1
Tgc(°C)	28.6	29.3	29.3	28.7
Afternoon				
Rho(%)	50.5	51.0	39.7	38.4
Rhi(%)	42.5	43.8	37.5	37.7
Tao(°C)	32.2	31.1	34.4	34.1
Tai(oC)	35.3	35.5	36.8	36.0
Tso(oC)	35.9	34.6	36.2	35.2
Tsi(oC)	35.7	35.1	35.3	33.6
Tgs(oC)	31.9	32.0	31.6	31.6
Tgc(°C)	31.9	31.9	31.2	30.1
Evening				
Rho(%)	65.0	63.3	53.4	51.8
Rhi(%)	58.8	56.3	56.9	56.5
Tao(°C)	26.5	29.4	30.2	30.7
Tai(oC)	32.7	31.8	32.2	32.7
Tso(oC)	30.7	29.3	30.6	30.6
Tsi(oC)	32.1	31.0	31.7	31.8
Tgs(oC)	31.9	30.9	31.8	32.0
Tgc(°C)	30.1	29.5	30.2	30.3

Rho(%) = relative humidity of atmospheric air	Tao(°C) = atmospheric air temperature
Tso(°C) = external wall surface temperature	Tgs(°C) = temperature of grain near the surface
Rhi(%) = rel humidity silo headspace air	Tai(°C) = internal air temperature
Tsi(°C) = internal wall surface temperature	Tgm(°C) = grain temperature at the central portion

Table 4.3. Weekly means of data from sandcrete silo

Morning	Week 1	Week 3	Week 5	Week 7
Rho(%)	85.8	83.8	67.1	70.9
Rhi(%)	90.6	86.3	73.2	84.2
Tao(°C)	25.0	25.7	26.6	26.9
Tai(oC)	26.3	26.0	25.3	24.4
Tso(oC)	27.5	26.8	26.7	26.7
Tsi(oC)	27.0	26.2	28.0	28.7
Tgs(oC)	27.6	27.3	28.6	29.1
Tgc(°C)	28.7	28.6	31.9	32.2
Afternoon				
Rho(%)	55.7	56.5	39.7	41.4
Rhi(%)	79.9	77.0	76.8	74.6
Tao(°C)	32.4	32.3	34.2	34.9
Tai(oC)	35.0	34.9	38.3	40.8
Tso(oC)	44.0	41.0	46.2	46.4
Tsi(oC)	34.3	33.0	35.0	35.4
Tgs(oC)	31.5	30.1	33.7	33.7
Tgc(°C)	30.9	29.1	34.0	33.6
Evening				
Rho(%)	65.7	67.5	52.7	53.4
Rhi(%)	88.6	94.1	94.8	88.3
Tao(°C)	29.8	29.3	30.6	29.1
Tai(oC)	32.9	33.9	36.4	34.1
Tso(oC)	31.6	31.1	32.8	31.8
Tsi(oC)	32.9	32.4	34.3	33.1
Tgs(oC)	31.9	32.1	35.4	34.3
Tgc(°C)	29.7	29.0	32.1	31.6
Morning	Week 2	Week 4	Week 6	Week 8
Rho(%)	81.6	72.0	63.9	62.0
Rhi(%)	91.9	82.9	83.5	78.7
Tao(°C)	25.8	28.0	27.0	25.5
Tai(oC)	26.3	27.3	24.4	24.2
Tso(oC)	26.4	28.7	25.6	26.3
Tsi(oC)	26.2	27.5	28.3	27.9
Tgs(oC)	27.1	28.5	29.3	28.3
Tgc(°C)	28.3	30.5	31.5	31.6
Afternoon				
Rho(%)	50.5	51.0	39.7	38.4
Rhi(%)	81.9	81.3	74.3	72.6
Tao(°C)	32.2	31.1	34.4	34.1
Tai(oC)	34.8	36.9	40.1	40.7
Tso(oC)	43.1	45.2	46.3	46.2
Tsi(oC)	35.0	35.5	35.7	35.5
Tgs(oC)	30.9	31.8	33.9	34.1
Tgc(°C)	30.6	29.9	33.1	34.1
Evening				
Rho(%)	65.0	63.3	53.4	51.8
Rhi(%)	94.8	94.1	91.6	85.4
Tao(°C)	30.1	29.0	30.2	30.7
Tai(oC)	32.1	37.0	34.6	34.0
Tso(oC)	31.5	33.0	32.4	32.8
Tsi(oC)	32.1	34.3	34.1	34.2
Tgs(oC)	31.3	34.0	34.7	34.6
Tgc(°C)	29.0	31.1	31.8	32.2

Rho(%) = relative humidity of atmospheric air	Tao(°C) = atmospheric air temperature
Tso(°C) = external wall surface temperature	Tgs(°C) = temperature of grain near the surface
Rhi(%) = rel humidity silo headspace air	Tai(°C) = internal air temperature
Tsi(°C) = internal wall surface temperature	Tgm(°C) = grain temperature at the central portion

Table 4.4 Maximum and minimum of temperatures of external and silo air (°C)

	Wooden silo			Clay silo			Sandcrete silo			Atmosphere		
Day	Min	Max	Diff	Min	Max	Diff	Min	Max	Diff	Min	Max	Diff
1	28.6	36.5	7.9	28.0	34.5	6.5	29.5	41.0	11.5	28.0	39.0	11.0
2	28.5	37.5	9.0	28.5	36.0	7.5	28.0	40.5	12.5	27.0	38.0	11.0
3	28.0	37.0	9.0	29.0	36.5	7.5	28.5	40.5	12.0	28.0	39.0	11.0
4	26.5	37.0	10.5	30.0	37.5	7.5	27.5	40.0	12.5	26.0	40.0	14.0
5	26.8	36.5	9.7	28.0	36.5	8.5	28.0	41.5	13.5	26.0	40.0	14.0
6	26.5	36.5	10.0	27.0	37.0	10.0	28.5	42.0	13.5	26.0	40.0	14.0
7	28.5	37.0	8.5	28.5	35.5	7.0	29.0	40.5	11.5	27.0	40.0	13.0
8	27.5	39.0	11.5	28.5	37.0	8.5	29.0	39.5	10.5	26.0	39.0	13.0
9	26.8	38.0	11.2	28.0	37.5	9.5	28.5	39.5	11.0	26.0	38.0	12.0
10	28.5	37.5	9.0	29.0	36.5	7.5	29.5	39.0	9.5	27.0	38.0	11.0
11	26.5	36.5	10.0	28.5	35.5	7.0	29.0	38.0	9.0	26.0	38.0	12.0
12	27.5	34.0	6.5	27.5	34.5	7.0	30.0	35.5	5.5	26.0	36.0	10.0
13	26.5	36.5	10.0	28.0	34.0	6.0	28.5	38.0	9.5	26.0	38.0	12.0
14	28.5	36.0	7.5	29.0	35.5	6.5	28.5	37.5	9.0	27.0	37.0	10.0
15	28.0	36.5	8.5	29.0	36.5	7.5	29.0	36.5	7.5	27.0	38.0	11.0
16	28.0	36.5	8.5	28.5	36.0	7.5	27.0	38.5	11.5	27.0	39.0	12.0
17	27.5	37.5	10.0	28.0	36.5	8.5	29.0	39.5	10.5	28.0	39.0	11.0
18	23.5	32.5	9.0	26.5	33.0	6.5	24.5	36.5	12.0	22.0	34.0	12.0
19	24.0	33.0	9.0	27.0	32.5	5.5	26.5	37.5	11.0	24.0	37.0	13.0
20	25.5	36.0	10.5	27.5	36.0	8.5	27.0	37.5	10.5	25.0	38.0	13.0
21	28.5	36.0	7.5	29.0	35.0	6.0	30.0	38.5	8.5	28.0	38.0	10.0
22	27.0	36.5	9.5	28.5	36.0	7.5	29.0	38.0	9.0	26.0	37.0	11.0
23	26.5	36.5	10.0	27.0	35.5	8.5	30.5	38.5	8.0	28.0	38.0	10.0
24	26.0	35.5	9.5	28.0	35.0	7.0	28.5	39.5	11.0	25.0	38.0	13.0
25	29.0	36.0	7.0	30.0	36.0	6.0	28.5	37.5	9.0	27.0	36.0	9.0
26	28.0	37.5	9.5	28.5	35.5	7.0	29.0	39.0	10.0	28.0	38.0	10.0
27	29.0	34.5	5.5	30.5	35.5	5.0	27.5	34.5	7.0	27.0	32.0	5.0
28	25.5	36.0	10.5	28.0	35.0	7.0	27.0	37.0	10.0	24.0	36.0	12.0
29	27.0	31.5	4.5	26.5	31.0	4.5	26.5	34.5	8.0	25.0	32.0	7.0
30	26.5	37.5	11.0	30.0	37.0	7.0	30.5	40.5	10.0	25.0	40.0	15.0

Table 4.5 Moisture content of stored maize (% wb) at 3 gauging positions in silos

Week	Gauging positions								
	Steel silo			Clay silo			Sandcrete silo		
	1	2	3	1	2	3	1	2	3
1	14.0	14.0	14.0	14.1	13.9	14.0	15.8	15.5	14.5
2	14.2	14.3	14.0	14.3	14.0	14.0	20.0	16.0	15.0
3	14.1	14.4	14.2	14.3	14.1	14.1	35.5	23.0	15.5
4	14.1	14.0	14.1	14.2	14.1	14.0	30.0	16.5	17.0
5	14.2	14.1	14.1	14.1	14.3	14.0	22.0	15.0	18.0
6	14.5	14.2	14.3	14.2	14.2	14.1	27.0	15.0	18.0
7	14.5	14.2	14.1	14.2	14.5	14.3	25.0	15.56	17.5
8	14.5	14.2	14.2	14.1	14.3	14.1	25.0	15.0	16.5

Gauging positions: 1 – Near the wall by the inspection door

2 – Beneath the surface of the maize bulk

3 – Depth near the bottom surface

4.1.5 Other observations

In all the silos evidence of occurrence of moisture condensation was found only in the sandcrete silo. Within two weeks of storage, caking of grains was evident in certain portions. By the end of the third week grains near the wall by the opening were already sprouting. Deep probe samples from the bottom revealed some live insect.

The internal surfaces of the clay and steel silos remained dry throughout the period of tests.

A comparison of the influence of external air and wall surface temperatures on grain temperatures in the silo is necessary. This can be done by determining the coefficient of correlation between the variables and the grain temperatures.

Considering the weekly means of external air fluctuations and the variations in wall surface temperatures, a correlation for the silos will yield the following results for clay silo.

Corrected sum of squares = $\Sigma x^2 = 7.25$

$\Sigma y^2 = 56.65$

Corrected sum of cross products $\Sigma xy = 9.92$

Coefficient of correlation $r = (\Sigma xy)/\sqrt{[(\Sigma x^2)(\Sigma y^2)]}$

$= 9.92/\sqrt{[(7.25)(56.65)]}$

$= 0.49$

Similar calculations for the steel and sandcrete silos yield r = 0.56 and 0.52 respectively. The coefficient of correlation calculated for the external air temperature with internal air temperatures are r = 0.66 for clay silo; r = 0.49 for sandcrete and r = 0.68 for steel.

STORAGE ASSESSMENT LOG

1. Silo type: Steel
2. Date filled: 2/10/2000
3. Initial conditions of maize:
   (i). Bulk density (kg/hl): 75.5
   (ii). Moisture (% w.b): 13.8
   (iii). Insect - damaged kernels (%): 1.2
   (iv). Foreign material (%): 0.1
   (v). Mould – damaged kernels (%): 1.6
4. Weekly averages of data:

Week No. ending date	Silo air Temp (°C)		Relative humidity (%)		Moisture content (%)
	Minimum	Maximum	Minimum	Maximum	
1. 9/10	26.3	38.6	46.2	75.5	14.0
2. 16/10	26.5	39.2	44.0	68.9	14.2
3. 23/10	27.9	38.0	47.4	70.5	14.2
4. 30/12	30.6	40.2	39.5	62.8	14.1
5. 6/11	28.1	42.8	33.0	56.4	14.1
6. 13/11	26.4	42.5	32.4	54.7	14.3
7. 20/11	28.3	43.7	36.2	59.0	14.3
8. 27/11	27.4	41.0	32.0	53.3	14.3

5.Date experiment halted: 28/11/2000

6.Final conditions of grain:

(i). Bulk density (kg/hl): 75.4
(ii). Moisture (% w.b): 14.3
(iii). Insect - damaged kernels (%): 1.2
(iv). Foreign material (%): 0.15
(v). Mould – damaged kernels (%): 1.6

7. Remarks: No sprouts; condensation on walls not experienced; fumigation adequate.

STORAGE ASSESSMENT LOG

5. Silo type: Clay
6. Date filled: 2/10/2000
7. Initial conditions of maize:
   (i). Bulk density (kg/hl): 75.5
   (ii). Moisture (% w.b): 13.8
   (iii). Insect - damaged kernels (%): 1.2
   (iv). Foreign material (%): 0.1
   (v). Mould – damaged kernels (%): 1.6
8. Weekly averages of data:

Week No. ending date	Silo air Temp (°C)		Relative humidity (%)		Moisture content (%)
	Minimum	Maximum	Minimum	Maximum	
1. 09/10	24.7	35.0	45.2	68.7	14.0
2. 16/10	25.2	35.3	42.5	69.7	14.1
3. 23/10	24.8	33.9	45.6	70.3	14.2
4. 30/12	25.9	35.5	43.8	69.0	14.1
5. 06/11	25.5	36.7	41.4	65.6	14.1
6. 13/11	25.7	36.8	37.5	66.3	14.2
7. 20/11	25.6	35.9	37.8	65.9	14.3
8. 27/11	24.7	36.0	32.7	60.7	14.2

5.Date experiment halted: 28/11/2000

6.Final conditions of grain:

(i). Bulk density (kg/hl): 74.8

(ii). Moisture (% w.b): 14.2

(iii). Insect - damaged kernels (%): 0.2

(iv). Foreign material (%): 0.25

(v). Mould – damaged kernels (%): 1.6

7.Remarks: No sprouts; fumigation fairly adequate. Moisture condensation not experienced.

STORAGE ASSESSMENT LOG

1. Silo type: Sandcrete
2. Date filled: 2/10/2000
3. Initial conditions of maize:
   (i). Bulk density (kg/hl): 75.5
   (ii). Moisture (% w.b): 13.8
   (iii). Insect - damaged kernels (%): 1.2
   (iv). Foreign material (%): 0.1
   (v). Mould – damaged kernels (%): 1.6
4. Weekly averages of data:

Week No. ending date	Silo air Temp (°C)		Relative humidity (%)		Moisture content (%)
	Minimum	Maximum	Minimum	Maximum	
1. 09/10	26.3	35	79.9	90.6	15.3
2. 16/10	26.3	34.8	81.9	94.8	17
3. 23/10	26	34.9	77	94.1	24.7
4. 30/12	27.3	36.9	82.9	94.1	21.2
5. 06/11	25.3	38.3	73.2	94.8	18.3
6. 13/11	24.4	40.1	74.3	91.6	20
7. 20/11	24.4	40.8	74.6	88.3	19.3
8. 27/11	24.2	40.7	72.6	85.4	18.8

5.Date experiment halted: 28/11/2000

6.Final conditions of grain:
   (i). Bulk density (kg/hl): 75.4
   (ii). Moisture (% w.b): 19.0
   (iii). Insect - damaged kernels (%): 1.35
   (iv). Foreign material (%): 0.5
   (v). Mould – damaged kernels (%): 2.1

7.Remarks: No sprouts; fumigation fairly adequate. Moisture condensation not experienced.

4.1.6 Costs of construction and maintenance

The clay silo was built in September 1999 at an estimated cost of five thousand, three hundred and forty (N5,340.00) naira. After about a year, the thatched roof had rotted and was replaced. The entire roof covering was rebuilt and placed at a cost of seven hundred and twenty naira (N720.00).

Apart from the roof, certain portions of the wall were already showing signs of wear caused by the impact of rains.

The steel bin, which cost eight thousand and eighty five naira (N8,085.00) to build has retained its physical stability and so far the only form of maintenance done on it was cleaning. It is envisaged that the steel silo would require a new coat of paint after some years.

The sandcrete silo cost eleven thousand, and thirty naira (N11,030.00) to build. It is very sturdy and should last long. However, one and a half-year after construction a few cracks have developed. These cracks were patched easily with cement/sand mortar.

The wooden silo was constructed at a cost sixteen thousand, two hundred and thirty six naira (N16,236.00). After about a year in service it required many repairs to put in good condition again. Some of the repairs carried done on it included- mending of the joints, replacement of the window latch and repainting of the structure. All the faults were caused by prolonged exposure to rain and heat of the sun. The estimated cost of the repair and maintenance carried out was one thousand four hundred and fifteen naira (N1,415.00).

4.2 DISCUSSION

This study provided data on temperature and moisture variations in small grain silos built with different materials. Temperature changes within the grain bulk were primarily due to daily fluctuations in atmospheric temperature, which were transferred through the walls by conduction. However, it is clear from the results that the diurnal changes in temperature are only very slowly transmitted to the centre of the grain bulk. This is evident from Fig. 4.5 where the curve indicates a fairly uniform centre temperature despite the daily variations. This validates the claim (Muir, 1973) that changes in diurnal temperature affect grain temperatures in bins only up to 15cm from the bin wall. It was also observed that temperatures of wall surfaces rose considerably above that of the atmospheric air. This clearly shows the effect of radiant heat on the walls; and confirms the need to apply the concept of sol-air temperature rather than only the effect of atmospheric temperature in computing heat flow into a building. However, the differences exhibited varied among the silos depending upon the wall material's heat absorptivity and solar reflectance.

Temperatures in the steel silo dropped most rapidly. This can be attributed to steel's high thermal and solar reflectance, as well as high thermal conductivity. The sandcrete silo remained warm longer than others possibly because its wall is denser than the others. This makes its heat storage capacity higher (thermal capacity is a product of volume of wall, density of the wall and the specific heat capacity of the wall material). Thus, not only is it denser than the other structures, it has the highest specific heat capacity among them.

Grain temperature data demonstrate that grain, normally harvested at 28 °C to 45 °C, when stored under the conditions that prevailed during this study, would remain at optimal temperatures for development of the maize weevil and beetle throughout the period. These insects are the major insect pests of stored maize in Nigeria. The absence of insects in the stored maize (except for the sandcrete silo) was probably due to the initial fumigation of the grain. This shows that effective fumigation can be achieved in the steel, wooden and clay silos. The emergence of insects in the sandcrete silo was possibly due to the availability of increased moisture, which could have softened the grain for increased insect feeding.

Caking and mouldiness of grain in the sandcrete silo was due mainly to condensation occurring in the silo. Fungi activity was also apparent in the portion of maize that was discoloured. The low temperature gradients observed in the clay, steel and wooden silos could account for the lack of visible evidence of condensation or moisture movement and accumulation within the bulk maize. This possibly explains why moisture contents of maize stored in the clay silo were stable.

The difference in the timing of maximum temperatures among the silos can be explained by the difference in the wall materials' thermal conductivity and transmittance. Thermal conductivity of MS sheet is put between 15 – 64W/m°K/ for plywood it is about 0.094 – 0.42W/m°K and for clay mixed with straw around 0.2 – 0.65W/m°K. The thermal transmittance of a cement-sand hollow block covered on both sides with cement plaster is 1.28W/m°K. From these it can be inferred that a steel wall with the highest conductivity would more readily conduct heat from outside to the interior so that temperature variation pattern would closely follow that of the atmosphere.

A comparison of the costs of construction shows that the wooden silo cost the most. With a storage capacity of 1.0 metric tonne, the fixed costs per unit capacity are N16.24/kg, N8.09/kg; N11.03/kg and N5.34/kg for the wooden, steel, sandcrete and clay silos in that order. In terms of durability, the life expectancy of the wooden bin is short unless it can be put under some form of shade to prevent exposure to direct impact of rain and heat from the sun. The cost of the sandcrete silo may be reduced by as much as 20% if the blocks are moulded on site.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

The results of the parameters measured in the silos are presented in summary in order to draw out adequate conclusions.

Steel silo

Air temperatures within the steel silo ranged between 18 °C and 44 °C following the pattern of fluctuation of the atmospheric temperatures. Grain surface temperatures varied as the headspace temperatures. On the other hand, temperatures at the center of the grain bulk remained uniform at about 30 °C during the tests. The difference between the temperatures of the surface and center of the grain bulk ranged between 4 °C and 6.5 °C. Relative humidity measured in the silo varied from 42% to 78% while grain moisture content was between 14% and 14.5% (wb).

Sandcrete silo

The temperatures of maize stored in this silo fluctuated between 29 °C and 35 °C during the period of the test. Maximum temperature gradient between surface and center of the grain bulk was 2 °C. Silo headspace temperatures varied from 26 °C to 41 °C. Relative humidity measurements ranged from 72% to 95% while the moisture contents of the stored maize varied from 15% to 35%.

Clay silo

Temperatures in the headspace varied from 26 °C to 36 °C on a daily basis. The temperatures of stored grains fluctuated between 30 °C and 32 °C during the test period. Maximum temperature gradient between surface and center of grain bulk was 1.4 °C. Relative humidity varied from 52% to 77% while grain moisture content ranged between 13.9% and 14.5%.

Wooden silo

Maximum temperature recorded in the wooden silo was 39 °C while the lowest was 25.5 °C. Temperature gradients between the external and internal conditions ranged between 4.5 °C and 11 °C.

From the pattern of temperature variations in the silos it is clear that the influence of external heat was most felt in the steel silo. Generally, the difference between temperatures beneath grain surface and centre of the bulk were low. This would eliminate occurrence of convective air currents and prevent moisture migration in the grain bulk. Temperatures of external surfaces of silo walls were significantly higher than atmospheric air temperatures. This shows that the walls are subjected to radiative heat of the sun. From the correlation coefficients obtained, the external air has greater influence on the steel silo than on the others.

In terms of durability and cost of maintenance, the steel silo has the edge over the rest. Apart from maintaining the coat of paint to prevent corrosion, there is not much else to be done maintenance wise. The roof of the clay silo will require replacement after about every two years. This however, would cost the farmer almost nothing (unless he employs someone to weave the grasses) as he can readily obtain the grasses required.

5.2 RECOMMENDATIONS

Temperatures in the sandcrete silo were very high. The relative humidity was high too. Thus sandcrete structures should not be used for farmer level grain storage. It can only be effectively used where there are facilities for aeration and regular grain movement.

The steel silo may be used at farmer level. Its fabrication is not beyond a village artisan's skill. Considering its durability and the fact that it can be used indoors, the initial cost should not discourage a farmer from owning and using one. The wooden and sandcrete silos are relatively very expensive.

Although the wooden silo would maintain safe storage conditions the cost is clearly beyond a small-scale farmer' capability.

The cost of the clay silo in reality would be much less than was obtained in this work. This is because the most of the materials would not cost the farmer much capital to procure. The labour for the construction could be supplied by the farmer and his family and thus eliminate labour costs which in the case here was the highest.

REFERENCES

Aboaba, F.O. (1989) Post harvest technology in storage: recent advances. In Proc. Seminar on Crop Storage in Nigeria, Dec 11-13 1989, Abuja, 87-92.

Agboola, S.D. (1987) Preserving the harvest: a crucial factor in Nigeria's self-sufficiency in food availability. A keynote address at the AERLS/NSPRI Joint National Crop Production Workshop, AERLS, Zaria, Dec. 1-3, 1987.

Agricultural compendium for rural development in the tropics and subtropics (1989) Ed. EUROCONSULT, Elsevier Publishers, 557—571.

Airapetov, D. (1985) Architectural materials science. Mir Publishers, Moscow, 45-60

Ajakaiye. M.B (1989) Investment opportunities and problems in Grain Storage. In proceeding of a seminar on Crop Storage in Nigeria. FMARD. Abuja Dec. 11-13 1989, 33-40.

Anderson, J. A. (1973) Problems of controlling quality in grain. In Grain storage: part of a system. R.N. Sinha and Muir, W.E. (ed.). AVI Publishing Co. Westport Conn., 1-15.

Anon.(1988a) Field study of existing storage structures in Nigeria. Crop Storage Unit Pamphlet No.1, CSU, FMARD, Ibadan.

Anon. (1988b) Suggested improvements of existing storage structures in Nigeria. CSU Pamphlet No.2, CSU, FMARD, Ibadan.

Arinze. E.A and Abdullahi, O. (1989) Traditional Grain Storage Structures in Nigeria: Past/Present and Future Possibilities. In Proc. Seminar on Crop Storage in Nigeria. FMARD, Abuja Dec, 11-13, 1989, 87-92.

Bakshi, A.S. and Bhatnagar, A.P. (1973) Temperature studies in grain storage bins. Indian Journal of Agr. Eng. 9(2) 20-43.

Barre, H. J. and Sammet, L. L. (1966) Farm structures. John Wiley and Sons, New York, 57-90.

Bengston, P. and Whitaker, H. (1986) Farm structures in tropical climates. FAO, Rome.

Caswell, G.H. (1968) Storage of Cowpea in the Northern States of Nigeria Proc. Agric Sc. 5:4

Chirife, J. and Iglesias H. A. (1978) Equations for fitting water sorption isotherms of foods: Part 1 – review. J. Food Tech., 13,159-174.

Cruz, J. F and Diop, A (1989) Agricultural Engineering in Development: Warehouse Techniques FAO. Agricultural Services Bulletin 74, 115pp FAO Rome, 1989

de Lucia. M and Assennato, D. (1994) Agricultural Engineering in Development: Post-harvest Operation and Management of Food Grain FAO Agric Bulletin 93, v+157 FAO Rome, 1994.

Donahaye, E. (1990) Laboratory selection of the resistance of the red flour beetle *Tribolium casteneum* to an atmosphere of low oxygen concentration. Phytoparasitica, 18(2): 189-202.

El-Okene, A.M.I., Sulaiman, M.L., Dauda, D.Y. and Ali, M.A. (1996) Suitability of existing mud storage bins "Rumbu" for storage of threshed grains. In Proc. Ann.Conf. NSAE Vol. 18, NSAE, 1996.

Evans, D.E. (1987) The influence of rate of heating on the mortality of *rhyzopertha dominica* (F) (*Coleoptera Bostrichidae*). Journal. Stored Product Res., 23, 73-77.

Ezedinma, D. A. (1993) Economics of grain storage. Unpublished paper presented at an In-house Training Workshop for Engineers, CSU, FMARD, Ibadan, Dec. 6-10, 1993.

FAO (1985) Standardised design for grain stores in hot dry climates. FAO Agric. Services Bulletin 62, FAO, Rome, 1985.

FAO (1994)Grain Storage Techniques: Evolution and Trends in Developing Countries. D. L. Proctor (ed.) FAO Agricultural Services Bulletin 109, vi +277pp, FAO Rome.

Fetuga, B.L.A (1987) Research Strength in Storage and Marketing of Agricultural Products in Nigeria Paper presented at a seminar on Storage and Marketing of Agricultural Produce, IMB, Lagos Sept. 19-30, 1987.

Geiger, R. (1965) The climate near the ground. Harvard Univ. Press, Cambridge, Mass., 13-14.

Giles, P. H. (1965) Control of insects infesting stored sorghum in Northern Nigeria. Journal of Stored Product Research (1) 145-158.

Gratz, N. G. (1988) Rodents and human disease: a global appreciation. In Rodent Pest Management. I. Prakash (ed.) CRC Press Boca Raton, Florida, 101-169.

Hall, D.W. (1970) Handling and storage of food grains in tropical and sub— tropical areas. Oxford/IBH Pvt Ltd., New Delhi, India.

Hartman, H.T., Flocker, W.J. and Kofranek, .A.M. (1984) Plant science: growth, development and utilization of cultivated plants. Prentice-Hall Inc. New Jersey.

Hayes, J. (1966) Protecting our food. Yearbook of Agriculture. Washinton D.C, U.S.A Government printing press.

Hindmarsh, P and Trotter, B. (1989) Developments in Grain Storage for Food Security. In Developing World Agriculture. Grosvenor Press International 126-132.

Hyde M.B. Baker, A.A. Ross, A. C. and Lopez-Cesar, O. (1973) Airtight Grain Storage. FAO Agric. Services Bulletin 17, FAO Rome v+71pp

Idachaba, F.S (1987) Organisation of Agricultural Produce Storage System: The Roles of Public and Private Sector. Paper Presented at a seminar on Storage and Marketing of Agricultural Produce, IMB, Lagos. Sept 19-30, 1987.

Igbeka, J. G. (1983) Evaluation of grain storage techniques in Nigeria. African Journal of Sc. And Tech. 2(2): 23-31.

Igbeka, J. G. and Ajisegiri, E.S.A. (1986) Appropriate grains storage structures in the humid tropics. Paper presented at 10th Ann. Conf. NSAE, Univ. of Ife, Ile-Ife. Sept. 1-5, 1986.

Igbeka J. C. and Olumeko, D.O (1993) An Appraisal of the Village-Level Grain Storage Practices in Nigeria. Paper Presented at an In-service Training Workshop for staff of Crop Storage Unit of FMARD, Ibadan. Dec. 6-10, 1993.

IHVE Guide (1970) Heat flow in Buildings. IHVE Current Paper No. 32.

Institute of Heating and Ventilation Engineers, London.

IITA (1982) Maize production manual. Manual series No 8 Vol. 1, IITA, Ibadan

IITA (1994) 1994 Annual Report, International Institute for Tropical Agriculture IITA, Ibadan.

Ivbijaro, M.F. (1989) Evaluation of Existing System for Grain and Tubers, and Loss Estimates at Different Points in the Distribution and Marketing Chain. Report of a study on private sector participation in National Food Storage Programme. Peat Marwick & Co. Lagos 1989

Janick, J., Delaney, R. P. and Kumar, A (1974) Effect of grain quality on storability of grains. Bulletin of Grain Technology, 16(2) 130-138.

Labuza, T. P. (1968) Sorption properties of foods. Food Technology, 2(2) 263.

Linbald,C. and Druben, L. (1977) Small Farm Grain Storage: Enemies of Stored Grain Vol. II. Appropriate Technologies for Development Manual Series 35, VITA, Washington, DC, 103 – 169.

Lucas, E.B. and Mijinyawa, Y. (1996) Comparative studies of temperature fluctuations within wooden and steel silos erected in Ibadan. In: Proc. Ann.Conf. NSAE Vol. 18, NSAE, 1996.

Maier, D.E., Rulon, R.A. and Mason, L.J. (1996) Chilled aeration of stored popcorn-part 1: temperature management. Purdue Agric. Research

Program Manuscript No. 14934, Purdue Univ., West Lafayette, IN., USA.

Markus E. P. and Morris A. (1980) Buildings, climate and energy. John Wileys, London, 46-76.

Mason, L.J., Rulon, R.A. and Maier, D.E. (1996) Chilled aeration of stored popcorn- Part 2: pest management. Purdue AR Prog. Manuscript No. 14940, Purdue Univ., West Lafayette, IN., USA.

Mathur, G.C. (1983) Development and promotion of appropriate technology in the field of construction and building materials industry in India. UNIDO, Vienna.

McFarlane, J.A. (1970) Insects control by airtight storage in small containers. Tropical Stored Produce (19) 10-14

Mian, Y., Ahmed, S. and Brooks, J. E. (1984) Post-harvest stored food losses at farm and viullage level; small mammal. composition and population estimates. Bangladesh Agricultural Research Institute, Joydebpur, Bangladesh, Technical Report No. 25

Michael, A. M. and Ojha, H. (1987) Principles of Agricultural Engineering. McGraw-Hill New York, 45-89.

Mijinyawa, Y. (1989) The use of wood products in the design and construction of a grain silo for the humid tropics. Being a Ph.D. thesis in the Department of Agric. Eng., Univ. of Ibadan, 1989.

Mohsenin, N.N. (1978) Physical properties of plant and animal materials. Vol. I: Structure, physical characteristics and mechanical properties. Gordon and Breach Science Publishers, New York.

Muir, W.E. (1973) Temperature and moisture in grain storage. In: R.N. Sinha and Muir, W.E. (ed.) "Grain storage: part of a system", AVI Publishing Co. Westport Conn., USA.

Muir, W.E. and Wallace, H.A.H. (1983) Storage of high moisture grain in an airtight butyl rubber bin. Can. Agr. Eng. 13: 31-42.

O'Dowd. E.T. (1971) Hermetic Storage of cowpea (*Vigna unguicula* Walp.) in small Granaries, Silos and Pits in Northern Nigeria. Samaru Misc Paper No. 31, 1-38.

Ogunfowora, B. (1989) Role of Private Sector in Farm Produce Storage. In proc. Seminar FMARD, Abuja, Dec, 11-13, 1989, 11-22

Ojo, J.B. (1977) Climate of West Africa. Longmans, Nigeria.

Olumeko, D.O (1989) Importance of traditional storage structures in Nigeria. In Proc. Seminar on Crop Storage in Nigeria, FMARD, Abuja, Dec. 11-13, 1989, FMARD, Abuja, 35-50

Olumeko, D.O. (1993) Design of 1.0 metric tonne bin. Paper presented at the in-service training Workshop for Project NRI/92/014, NCRI Ibadan Dec. 6-10, 1993.

Onayemi, O., Osibogun, O.A. and Obembe, O. (1986) Effects of different storage and cooling methods on some biochemical, nutritional and sensory characteristics of cowpea. J. of Food Sc. 51(1): 151-156.

Onwuzulu, O.C. (1986) Bulk storage of grains in silos. Paper presented at a Seminar on "Grain storage in the humid tropics, IITA, Ibadan, 1986.

Osikanlu, Y.O.K. (1993) Microbial infestation of stored produce and its control. Paper presented at an In-service training workshop, NCRI, Ibadan, Dec. 6-10, 1993)

Osunde, Z.D., Okusanya, S.O. and Ajisegiri, E.S.A. (1996) Grain storage methods and structures in Niger State. In Proc. 18th Ann. Conf. of NSAE, Obafemi Awolowo Univ., Ile Ife, Vol. 18, 1996.

Oxford Advance Learners Dictionary (1989) (4th ed.) Oxford, England.

Oxley, T.A. and Wickenden, G. (1963) The effect of restricted air supply on some insects which infest grain. Ann. Appl. Biol., 51(2): 313-324.

Oyeniran, J.O. (1990) Microbiological deterioration of stored products: its causes, effects, and control Paper presented at a training workshop on

"Presidential Project on on-farm storage of produce in Nigeria", NSPRI, Ilorin, May 14-18, 1990.

Phillips O. A. (1989) Food Security for the Nation: Strategic Grain Reserve Scheme: In Proc. Seminar on Crop Storage in Nigeria FMARD, Abuja. Dec. 11-13, 1989, 50-53

Pingale, S.V. (1976) Handling and storage of food grains. Indian Council of Agric. Res., New Delhi.

Potter, N.N. (1987) Food Science. CBS Publishers, India.

Reynolds, R. (1980) Reinforced Concrete Design. McGraw-Hill Publishers Toronto.67- 120.

Rulon, R.A. (1996) In-bin conditioning and pest management of popcorn using chilled aeration. Being a MSc. Thesis in the Faculty of Purdue University, Purdue, West Lafayette, IN., USA. May 1996.

Salunkhe, D.K., Kadan, S.S. and Chavan, J.K. (1985) Post-harvest biotechnology of cereals. CRC Press, Boca Raton, Fla. USA.

Sinha, R.N. (1973) Interrelations of physical, chemical, and biological variables in the deterioration of stored grains. In: R.N. Sinha and Muir, W.E. (ed.) "Grain storage: part of a system", AVI Publishing Co. Westport Conn., USA.

Smith, J. E. (1947) The sorption of water vapour by high polymers. J. of Am. Chem. Soc (69(, 646-651.

Steele, J.L., and Saul, R.A. (1962) Laboratory measurements of the rate of deterioration of grain during drying. ASAE Mid-central Paper, Lincoln, Neb. Mar. 30-31, 1962.

Stewart, B. R. and Britton, M.G. (1973) Design of farm grains storage. In: R.N. Sinha and Muir, W.E. (ed.) "Grain storage: part of a system", AVI Publishing Co. Westport Conn., USA, 274-288.

Tolufase, J.S. (1998) Design and construction of wooden grain silo. B. ENG. Thesis in the Department of Agricultural Eng. Federal Univ. of Tech. Minna, March, 1998.

Welty, J.R., Wicks, C.E., and Wilson, R.E. (1983) Fundamentals of momentum heat, and mass transfer. John Wiley's and Son. New York.

Young, J.H., and Nelson, G.L. (1967) Research of hysterisis between sorption and desorption isotherms of wheat. Trans. ASAE 10, 756-761.

APPENDIX A

WEATHER RECORDS FOR MINNA, NIGER STATE

Table A1. Mean monthly daily max temp. (°C) for Minna: 1991-1994

Year	Months											
	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
1991	36.0	34.4	38.5	36.6	33.1	33.0	31.0	30.7	32.5	33.6	36.5	35.2
1992	34.0	37.3	38.2	36.5	34.1	32.1	30.8	29.9	30.9	33.6	35.3	35.8
1993	33.8	32.9	37.3	38.1	36.0	31.3	24.7	27.4	28.8	31.1	33.1	32.4
1994	31.6	32.9	36.8	33.9	32.9	31.8	30.9	30.3	31.1	15.8	27.5	29.8

Table A2.Mean monthly minimum daily temperature (°C) for Minna: 1991- 1994

Year	Months											
	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
1991	21.6	25.1	26.1	25.2	23.5	23.0	22.3	22.6	21.7	22.0	20.7	20.4
1992	19.7	22.2	25.9	25.3	24.3	23.3	22.7	22.2	21.6	22.5	20.6	19.5
1993	19.9	21.2	23.9	25.0	23.9	22.7	21.7	22.6	20.5	22.7	21.3	20.7
1994	21.7	22.9	26.8	25.9	25.1	25.2	24.4	23.9	24.5	13.7	21.6	21.7

Table A3. Mean daily relative humidity (%) for Minna: 1991-1994

Year	Months											
	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
1991	29.0	47.8	50.0	63.8	75.8	77.8	83.8	85.0	86.0	71.8	51.8	48.1
1992	29.0	25.5	49.8	63.8	70.3	77.5	81.3	82.0	80.0	71.8	45.0	36.2
1993	30.0	37.3	49.3	57.5	68.0	77.8	82.0	81.0	78.0	70.3	57.0	39.0
1994	39.0	26.5	49.0	56.9	68.6	75.2	80.0	83.7	81.0	76.1	45.4	33.0
Mean	31.8	34.3	49.5	60.5	70.7	77.1	81.8	82.9	81.3	72.5	49.8	39.1

Source: Niger State Agricultural Development Project (NSADP)

Table A4. Average solar radiation received at different hours of the day

Time	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
6.00h	3.0	3.0	3.5	3.5	3.2	3.5	3	2	2	3	2	2
7.00	4.0	4.0	4.0	6.0	6	7	4.5	4	2	2	3	3
8.00	12	12	15	17	16	17	15	12	13	15	15	16
9.00	27	28	36	35	35	30	27	25	28	27.5	32	35
10.00	32.5	40	48	46	45	40	35	33.5	34	37.5	40	42
11.00	43	45	57.5	62	55	45	42.5	42	45	48	50	47
12.00	52.5	59	67	64	62.5	50	48	50	50	50	62	60
13.00	58	60	70	67	62.5	50	50	55	58	62	65	60
14.00	52	56	63	63	57.5	48	50	55	58	57	65	62
15.00	39	45	52.5	58	48	47.5	46.5	46	48	50	50	47
16.00	27	30.5	38	35	34	33	32.5	35	34	30	31	27
17.00	14	15	17	17.5	16	17	16.5	19	18	16	17	15
18.00	3.5	4.5	5	6	6.5	6.5	8	8	7	4.5	4	4

Source: International Airport, Minna.

Table A5. Ambient temperatures (°C) during the test period								
	March		*April*		*October*		*November*	
Day	*max*	*min*	*max*	*min*	*max*	*min*	*max*	*min*
1	35	23	39	26	30	21	34	21
2	37	25	38	26	29	20	34	21
3	38	21	38	27	31	22	35	20
4	39	24	38	26	31	23	36	19
5	38	26	36	26	31	22	35	17
6	38	25	38	26	30	22	34	21
7	38	26	37	27	27	23	35	20
8	37	25	38	27	30	20	35	18
9	37	25	39	27	30	21	36	19
10	37	24	39	28	30	22	37	18
11	37	23	34	22	31	21	35	19
12	38	24	37	24	31	22	35	21
13	38	25	38	25	31	21	36	20
14	39	25	38	28	31	21	36	18
15	38	26	37	26	32	22	33	19
16	38	25	38	28	32	22	35	20
17	37	26	38	25	32	22	36	17
18	37	27	36	27	32	23	35	18
19	37	27	38	28	27	23	34	19
20	37	26	32	27	31	21	37	19
21	39	26	36	24	33	22	36	18
22	40	21	32	25	32	23	36	21
23	37	24	40	25	33	21	36	16
24	38	26	39	27	33	21	37	15
25	39	28	37	27	31	21	34	17
26	38	27	39	27	34	21	36	18
27	39	28	37	27	35	21	37	18
28	40	26	37	25	35	21	36	18
29	40	26	37	27	33	22	36	20
30	40	26	38	27	34	22	36	19
31	40	27			34	21		
Mean	38.1	25.3	37.3	26.2	31.5	21.6	35.4	18.8

Source: Minna International Airport, Minna.

Table A6. Mean values of some data at specific periods of the day

Hour	March, 2000 Relative Hum.(%)	March, 2000 Vapour press(mb)	March, 2000 Dew pt (°C)	April, 2000 Relative Hum.(%)	April, 2000 Vapour press(mb)	April, 2000 Dew pt (°C)
00.00hr	38.00	15.10	12.40	63.00	25.90	21.30
03.00hr	42.00	14.90	12.00	71.00	26.30	21.90
06.00hr	44.00	14.80	11.50	75.00	26.60	22.00
09.00hr	34.00	15.20	11.70	63.00	27.70	22.80
12.00hr	28.00	16.00	12.70	50.00	27.30	22.50
15.00hr	23.00	15.00	12.30	42.00	25.80	21.50
18.00hr	27.00	15.00	12.50	46.00	24.70	20.80
21.00hr	32.00	15.30	12.80	55.00	25.30	21.20
Wind speed (km/h)	144.30			120.30		

Hour	October, 2000 Relative Hum.(%)	October, 2000 Vapour press(mb)	October, 2000 Dew pt (°C)	November, 2000 Relative Hum.(%)	November, 2000 Vapour press(mb)	November, 2000 Dew pt (°C)
00.00hr	90.00	26.40	21.90	63.00	18.60	16.10
03.00hr	92.00	25.40	21.30	70.00	17.70	15.30
06.00hr	92.00	25.50	21.30	75.00	17.30	14.90
09.00hr	74.00	26.90	22.20	45.00	18.10	15.30
12.00hr	65.00	27.10	22.30	33.00	17.60	15.00
15.00hr	60.00	26.80	22.60	30.00	16.70	14.30
18.00hr	72.00	27.60	22.60	45.00	19.90	17.20
21.00hr	83.00	27.10	22.30	55.00	19.30	16.60
Wind speed (km/h)	44.10			46.30		

Source: Minna International Airport, Minna.

APPENDIX B

Table B4.1 Temperature and relative humidity data for steel silo

Table B4.2 Temperature and relative humidity data for clay silo

Table B4.3 Temperature and relative humidity data for sandcrete silo

Table B1. Temperature and relative humidity data for Metal silo

Date / Parameter	3-Oct	4-Oct	5-Oct	6-Oct	7-Oct	8-Oct	9-Oct
	Morning						
Rho(%)	89.00	80.00	78.30	86.00	90.50	87.00	90.00
Rhi(%)	77.00	76.50	72.00	73.00	77.00	76.50	76.50
Tao(°C)	24.50	24.80	24.50	24.70	26.80	24.80	25.10
Tai(°C)	26.20	25.70	25.40	27.00	27.50	26.50	26.00
Two(°C)	26.00	25.20	25.00	27.80	27.20	25.90	25.80
Twi(°C)	26.80	26.10	26.20	28.20	28.10	26.10	26.20
Tgs(°C)	27.00	27.20	27.50	27.80	27.70	27.20	26.00
Tgm(°C)	29.00	29.30	28.50	29.20	29.30	28.80	28.50
	Afternoon						
Rho(%)	60.00	59.30	50.00	54.30	49.00	60.00	57.00
Rhi(%)	50.00	52.00	40.20	42.00	44.10	52.50	42.80
Tao(°C)	31.70	33.20	32.60	31.80	33.80	31.50	32.00
Tai(°C)	36.80	37.30	41.50	40.00	37.20	37.00	40.10
Two(°C)	38.20	39.80	47.70	47.50	42.50	39.20	46.80
Twi(°C)	37.30	37.00	38.20	38.60	39.20	38.50	39.20
Tgs(°C)	34.80	32.80	35.10	33.70	38.50	34.50	34.00
Tgm(°C)	30.00	29.20	29.50	29.20	33.00	29.80	29.60
	Evening						
Rho(%)	65.00	64.80	66.70	65.00	68.50	65.00	65.10
Rhi(%)	70.80	71.00	71.00	68.00	70.00	66.00	70.00
Tao(°C)	30.10	30.80	29.80	27.90	29.60	30.00	30.20
Tai(°C)	31.20	31.30	30.80	30.00	30.30	30.50	30.60
Two(°C)	29.40	30.20	31.20	30.60	30.80	30.10	29.80
Twi(°C)	30.00	30.80	30.30	29.80	29.80	30.60	30.80
Tgs(°C)	32.00	32.00	31.80	30.80	31.50	31.20	31.50
Tgm(°C)	28.50	29.00	28.70	28.20	28.50	28.80	28.80
	10-Oct	11-Oct	12-Oct	13-Oct	14-Oct	15-Oct	16-Oct
	Morning						
Rho(%)	86.00	77.00	78.00	65.00	88.00	88.30	89.00
Rhi(%)	70.20	70.20	65.00	53.20	76.00	74.00	74.00
Tao(°C)	26.90	28.50	24.50	24.50	28.70	23.70	23.90
Tai(°C)	28.00	29.80	26.10	25.60	31.40	25.40	25.40
Two(°C)	27.40	28.60	25.80	25.10	30.40	25.50	25.50
Twi(°C)	28.10	29.80	26.20	26.50	30.00	27.20	27.20
Tgs(°C)	28.00	28.70	26.40	28.00	28.00	27.00	27.00
Tgm(°C)	29.50	29.50	28.80	29.20	29.40	28.50	28.50
	Afternoon						
Rho(%)	50.00	50.00	48.70	40.80	45.30	62.60	56.00
Rhi(%)	42.80	37.20	50.00	39.20	36.70	55.20	47.00
Tao(°C)	35.50	29.20	34.00	32.00	31.50	31.10	32.30
Tai(°C)	41.60	40.50	38.50	41.00	40.60	31.40	40.90
Two(°C)	40.10	46.80	42.00	45.00	46.20	35.00	51.00
Twi(°C)	35.80	38.50	37.20	39.70	38.30	33.50	44.30
Tgs(°C)	29.40	33.50	30.50	32.60	34.00	36.00	37.50
Tgm(°C)		29.80	28.70	29.80	30.10	29.50	29.50
	Evening						
Rho(%)	68.80	64.70	60.20	58.00	65.40	72.00	66.00
Rhi(%)	72.00	67.00	65.00	62.00	70.70	75.00	66.00
Tao(°C)	2.80	29.70	30.70	31.00	30.60	30.00	31.00
Tai(°C)	27.20	31.00	32.00	32.50	31.00	29.80	31.90
Two(°C)	28.00	30.00	30.20	31.20	29.80	29.20	31.30
Twi(°C)	29.50	30.00	31.10	32.20	30.20	29.00	32.00
Tgs(°C)	31.50	30.50	33.20	33.50	31.50	31.50	35.00
Tgm(°C)	29.00	29.10	29.80	29.50	28.00	29.00	29.00

Rho(%) = relative humidity of atmospheric air
Rhi(%) = rel humidity silo headspace air
Tao(°C) = atmospheric air temperature
Tai(°C) = internal air temperature
Two(°C) = external wallsurface temperature
Twi(°C) = internal wall surface temperature
Tgs(°C) = temperature of grain near the surface
Tgm(°C) = grain temperature at the central portion

Table B1.cont'd

Date / Parameter	17/10	18/10	19/10	20/10	21/10	22/10	23/10
	Morning						
Rho(%)	87.00	90.60	89.00	89.00	73.80	79.00	78.00
Rhi(%)	77.00	77.00	76.00	77.00	42.80	72.00	71.50
Tao(°C)	24.80	24.80	24.50	23.70	28.50	26.90	26.20
Tai(°C)	26.20	26.20	25.40	24.10	38.30	27.80	27.40
Two(°C)	26.00	27.00	25.00	24.80	38.00	27.50	26.50
Twi(°C)	26.00	27.20	26.00	25.20	37.00	28.00	27.80
Tas(°C)	27.00	27.60	27.30	25.00	31.00	27.50	27.00
Tam(°C)	29.00	29.00	29.20	28.50	28.50	29.00	28.50
	Afternoon						
Rho(%)	59.00	50.00	81.00	55.00	56.00	48.20	46.20
Rhi(%)	52.10	43.10	72.00	39.30	40.50	49.00	36.00
Tao(°C)	31.20	35.50	26.80	32.90	31.70	33.80	34.00
Tai(°C)	36.50	38.70	29.00	40.30	41.50	37.80	42.20
Two(°C)	38.00	41.00	29.50	47.00	46.50	40.00	49.50
Twi(°C)	37.00	39.50	29.00	39.00	40.00	37.00	37.50
Tas(°C)	34.50	37.00	29.00	33.50	32.80	26.50	34.00
Tam(°C)	29.50	32.00	29.50	29.00	29.50	29.20	29.50
	Evening						
Rho(%)	66.90	68.00	79.10	65.00	64.40	69.00	60.00
Rhi(%)	66.60	70.00	75.40	71.00	70.00	73.00	64.00
Tao(°C)	29.90	31.40	26.70	30.00	29.70	26.90	30.50
Tai(°C)	30.30	30.80	26.60	30.40	30.30	27.50	31.20
Two(°C)	30.00	29.60	26.50	29.60	30.60	27.80	30.50
Twi(°C)	30.50	31.00	27.50	30.00	29.50	30.00	31.60
Tas(°C)	31.00	32.00	29.00	31.50	30.80	32.00	33.50
Tam(°C)	29.00	28.00	28.00	28.20	28.10	28.00	29.20
	24/10	25/10	26/10	27/10	28/10	29/10	30/10
	Morning						
Rho(%)	85.00	74.00	75.00	64.00	70.00	64.20	72.00
Rhi(%)	72.70	62.00	63.00	55.80	60.00	59.00	60.20
Tao(°C)	25.10	28.50	29.80	27.00	29.30	28.80	27.50
Tai(°C)	26.90	31.00	32.00	29.10	32.40	30.90	31.80
Two(°C)	27.50	30.20	30.20	30.00	33.00	31.20	30.00
Twi(°C)	27.00	30.00	29.80	29.50	32.00	31.00	30.20
Tas(°C)	26.70	28.00	28.30	28.20	29.20	28.80	29.20
Tam(°C)	29.50	29.50	29.10	30.00	30.00	30.00	30.60
	Afternoon						
Rho(%)	41.00	58.00	50.00	56.50	54.30	55.20	42.30
Rhi(%)	44.50	38.50	37.20	43.40	37.60	36.90	38.10
Tao(°C)	33.20	30.00	29.30	32.20	29.20	30.10	33.50
Tai(°C)	40.20	40.00	41.50	40.80	39.10	39.50	40.50
Two(°C)	44.00	47.00	48.00	45.60	48.00	47.50	45.50
Twi(°C)	40.00	40.90	36.80	39.00	41.20	40.50	39.60
Tas(°C)	38.50	33.80	34.00	35.00	34.50	34.10	38.00
Tam(°C)	33.00	29.20	28.60	28.20	30.10	29.50	29.80
	Evening						
Rho(%)	60.50	61.30	65.40	87.80	66.00	57.00	45.00
Rhi(%)	64.50	64.50	66.60	74.70	62.00	53.00	54.50
Tao(°C)	28.70	29.50	29.80	29.70	29.30	26.60	32.00
Tai(°C)	31.70	30.80	31.90	30.80	30.10	30.30	33.80
Two(°C)	30.80	30.20	29.50	30.00	30.00	30.00	31.00
Twi(°C)	32.00	31.50	30.00	31.20	31.00	31.00	32.30
Tas(°C)	32.20	33.40	30.70	33.50	32.00	33.00	35.00
Tam(°C)	28.00	29.50	28.80	29.50	29.80	29.80	30.00

Rho(%) = relative humidity of atmospheric air
Rhi(%) = rel humidity silo headspace air
Tao(°C) = atmospheric air temperature
Tai(°C) = internal air temperature
Two(°C) = external wallsurface temperature
Twi(°C) = internal wall surface temperature
Tgs(°C) = temperature of grain near the surface
Tgm(°C) = grain temperature at the central portion

Table B1.cont'd

Date / Parameter	31/10	1-Nov	2-Nov	3-Nov	4-Nov	5-Nov	6-Nov
	Morning						
Rho(%)	69.00	70.50	60.90	76.00	61.00	51.00	81.00
Rhi(%)	59.00	61.50	49.00	64.00	50.30	49.00	50.50
Tao(°C)	26.30	28.20	28.70	25.80	26.60	23.40	27.30
Tai(°C)	27.90	29.10	32.30	27.30	31.00	24.30	25.10
Two(°C)	28.30	28.90	32.00	27.50	29.60	25.50	25.00
Twi(°C)	28.30	29.20	31.20	28.70	30.30	25.50	25.60
Tgs(°C)	27.20	29.80	29.40	27.00	30.30	26.00	26.20
Tgm(°C)	29.20	30.30	30.50	30.10	27.40	29.00	28.80
	Afternoon						
Rho(%)	41.00	44.00	35.00	34.10	45.00	34.10	45.00
Rhi(%)	40.50	36.50	34.00	33.20	27.40	29.00	30.20
Tao(°C)	41.00	44.00	35.00	34.10	45.00	34.10	45.00
Tai(°C)	38.20	40.30	44.40	43.50	45.20	44.30	43.50
Two(°C)	46.80	46.50	49.00	47.80	45.10	47.10	46.70
Twi(°C)	40.00	40.50	44.00	42.90	43.50	43.20	42.20
Tgs(°C)	31.50	37.10	38.00	37.00	38.40	39.00	37.50
Tgm(°C)	30.00	30.50	31.00	29.70	30.10	31.00	29.80
	Evening						
Rho(%)	45.00	50.00	58.00	46.20	60.00	58.50	51.00
Rhi(%)	54.00	56.00	63.00	54.30	56.00	55.60	55.70
Tao(°C)	32.60	32.50	32.00	30.30	29.50	28.10	29.20
Tai(°C)	32.80	31.60	33.00	30.10	30.70	29.70	28.10
Two(°C)	32.50	31.50	31.50	30.60	30.00	29.40	27.50
Twi(°C)	33.60	32.00	32.70	31.00	31.50	30.30	28.00
Tgs(°C)	36.20	31.80	34.50	30.50	34.00	33.30	29.50
Tgm(°C)	30.00	30.00	30.50	29.20	30.00	29.80	29.80

	7-Nov	8-Nov	9-Nov	10-Nov	11-Nov	12-Nov	13/11
	Morning						
Rho(%)	74.00	61.00	60.50	51.00	70.50	69.00	61.00
Rhi(%)	62.00	50.00	48.00	49.50	62.00	61.00	50.50
Tao(°C)	26.50	27.80	28.30	26.50	26.60	27.00	26.50
Tai(°C)	26.20	24.80	28.00	27.60	26.20	26.10	26.20
Two(°C)	26.00	25.20	28.60	27.10	27.50	26.80	27.50
Twi(°C)	26.50	28.00	29.00	29.00	28.00	28.80	27.20
Tgs(°C)	27.00	27.70	30.00	29.20	27.80	28.50	27.10
Tgm(°C)	29.00	28.70	30.20	30.10	29.10	30.00	29.00
	Afternoon						
Rho(%)	43.00	35.00	45.00	34.70	42.50	41.00	37.00
Rhi(%)	36.00	28.70	29.00	30.20	31.00	28.70	43.00
Tao(°C)	33.50	33.00	34.00	35.00	37.20	33.20	34.80
Tai(°C)	41.50	44.50	43.60	44.00	43.20	40.50	40.20
Two(°C)	45.20	47.50	46.10	48.00	45.20	43.90	44.50
Twi(°C)	40.30	42.60	42.40	44.50	43.20	39.20	40.10
Tgs(°C)	35.20	38.40	35.50	37.00	38.00	33.20	35.60
Tgm(°C)	30.00	30.10	30.50	30.00	29.10	29.50	30.20
	Evening						
Rho(%)	50.00	55.00	49.00	57.80	58.00	46.00	58.00
Rhi(%)	54.20	57.00	52.00	27.00	53.40	56.00	56.00
Tao(°C)	32.00	29.50	30.20	29.00	30.50	30.50	29.50
Tai(°C)	29.50	31.20	31.30	28.40	29.80	30.10	30.00
Two(°C)	29.00	29.80	30.00	27.80	29.50	29.20	29.20
Twi(°C)	29.50	30.20	30.10	29.00	29.80	30.00	29.70
Tgs(°C)	30.10	32.00	33.20	34.00	32.20	30.70	30.50
Tgm(°C)	29.60	30.00	29.50	28.80	29.80	28.50	28.60

Rho(%) = relative humidity of atmospheric air
Rhi(%) = rel humidity silo headspace air
Tao(°C) = atmospheric air temperature
Tai(°C) = internal air temperature
Two(°C) = external wallsurface temperature
Twi(°C) = internal wall surface temperature
Tgs(°C) = temperature of grain near the surface
Tgm(°C) = grain temperature at the central portion

Table B1.cont'd

Date / Parameter	14/11	15/11	16/11	17/11	18/11	19/11	20/11
Morning							
Rho(%)	54.00	72.00	70.50	75.00	76.00	69.00	80.00
Rhi(%)	49.80	60.00	58.00	61.00	60.00	55.00	60.00
Tao(°C)	27.00	26.80	27.50	26.00	27.00	26.50	27.50
Tai(°C)	27.10	28.50	27.00	29.00	31.20	26.50	27.60
Two(°C)	28.20	30.00	30.10	31.20	32.00	27.00	28.00
Twi(°C)	27.80	28.80	28.50	30.50	31.70	27.00	28.20
Tas(°C)	28.00	28.50	27.80	29.20	29.80	28.00	28.00
Tam(°C)	29.50	29.20	29.70	30.00	30.50	30.00	30.20
Afternoon							
Rho(%)	35.00	44.00	45.00	41.00	35.50	42.00	47.00
Rhi(%)	38.80	39.70	36.00	46.00	35.50	30.20	29.90
Tao(°C)	36.20	37.10	37.00	34.50	34.00	33.00	32.50
Tai(°C)	43.00	44.00	44.30	43.70	42.80	44.30	43.20
Two(°C)	46.80	47.80	47.50	46.50	46.50	47.60	45.80
Twi(°C)	42.70	42.80	40.00	40.10	42.70	40.80	40.50
Tas(°C)	37.20	37.50	34.80	33.60	36.40	35.70	34.60
Tam(°C)	30.00	32.00	31.00	30.00	29.80	28.90	29.50
Evening							
Rho(%)	50.00	60.00	58.00	50.00	46.80	51.00	58.00
Rhi(%)	54.00	60.00	61.00	56.00	56.20	55.20	54.10
Tao(°C)	29.80	28.50	29.00	30.50	30.00	28.10	28.10
Tai(°C)	27.80	30.00	31.20	25.60	29.80	30.20	28.10
Two(°C)	28.20	29.50	30.80	26.00	29.40	29.80	27.60
Twi(°C)	29.40	30.20	31.50	29.80	30.50	30.60	29.50
Tas(°C)	30.00	30.50	33.20	30.60	31.20	30.80	30.00
Tam(°C)	28.80	29.50	30.00	28.60	29.80	29.20	29.10
	21/11	**22/11**	**23/11**	**24/11**	**25/11**	**26/11**	**27/11**
Morning							
Rho(%)	81.00	76.00	70.00	48.00	58.00	50.00	51.00
Rhi(%)	62.00	58.00	55.00	47.00	50.00	45.00	47.00
Tao(°C)	25.50	26.10	23.80	26.00	25.80	26.00	25.50
Tai(°C)	28.80	30.50	28.80	29.00	24.60	25.20	26.50
Two(°C)	29.00	30.00	29.50	31.50	25.50	25.50	28.50
Twi(°C)	29.10	30.20	29.20	30.00	27.20	28.00	29.20
Tas(°C)	28.70	29.50	29.00	29.00	27.10	28.60	29.80
Tam(°C)	29.80	29.50	29.80	29.80	29.50	29.80	30.00
Afternoon							
Rho(%)	35.00	44.00	44.00	34.30	35.00	36.80	40.00
Rhi(%)	30.50	33.00	29.50	31.20	35.20	34.30	28.50
Tao(°C)	33.50	34.20	33.20	32.80	35.50	34.00	35.80
Tai(°C)	43.90	43.00	40.70	42.30	41.50	39.50	38.80
Two(°C)	45.80	46.00	43.80	45.80	46.20	45.40	45.00
Twi(°C)	40.20	39.50	38.80	39.60	40.80	40.00	39.80
Tas(°C)	34.20	33.20	35.30	34.20	36.50	34.10	32.50
Tam(°C)	30.00	29.00	29.50	29.50	30.00	29.80	29.80
Evening							
Rho(%)	47.40	55.00	45.20	50.00	57.00	58.00	50.00
Rhi(%)	60.50	53.00	64.00	54.00	54.00	50.00	45.00
Tao(°C)	31.00	32.00	32.20	32.50	29.40	28.50	29.20
Tai(°C)	28.30	28.80	27.70	28.00	28.80	26.80	27.00
Two(°C)	29.00	28.60	27.20	27.80	28.50	26.50	27.10
Twi(°C)	31.60	30.00	31.20	29.70	30.00	29.80	30.50
Tas(°C)	32.00	34.00	33.50	32.00	31.60	32.50	34.20
Tam(°C)	30.00	29.80	29.20	29.00	30.00	31.00	29.50

Rho(%) = relative humidity of atmospheric air
Rhi(%) = rel humidity silo headspace air
Tao(°C) = atmospheric air temperature
Tai(°C) = internal air temperature
Two(°C) = external wallsurface temperature
Twi(°C) = internal wall surface temperature
Tgs(°C) = temperature of grain near the surface
Tgm(°C) = grain temperature at the central portion

Table B2 Temperatures and relative humidity measured in clay silo

Date	Oct. 3	Oct.4	Oct. 5	Oct. 6	Oct.7	Oct. 8	Oct. 9
	Morning						
Rho(%)	89.0	80.0	78.3	86.0	90.5	87.0	90.0
Rhi(%)	70.0	67.8	65.2	59.8	71.0	71.0	76.0
Tao(°C)	24.5	24.8	24.5	24.7	26.8	24.8	25.1
Tai(oC)	23.1	24.1	24.4	25.2	24.2	24.3	27.5
Tso(oC)	24.3	23.8	24.6	24.3	25.4	26.0	25.6
Tsi(oC)	24.6	24.7	25.0	26.2	27.0	25.8	24.3
Tgs(oC)	27.1	26.2	26.0	27.0	27.3	26.8	25.7
Tgc(°C)	29.3	28.6	29.7	28.8	29.4	28.0	26.8
	Afternoon						
Rho(%)	60.0	59.3	50.0	54.3	49.0	60.0	57.0
Rhi(%)	54.2	48.5	38.4	39.7	36.2	52.0	48.1
Tao(°C)	31.7	33.2	32.6	31.8	33.8	31.5	32.0
Tai(oC)	32.8	36.7	37.1	35.3	34.6	35.2	33.5
Tso(oC)	34.1	36.1	36.8	36.2	35.8	36.8	35.6
Tsi(oC)	34.6	35.3	37.2	37.5	36.3	35.3	35.2
Tgs(oC)	33.2	32.5	31.5	32.0	33.0	30.0	31.5
Tgc(°C)	31.8	32.0	31.5	31.5	32.5	30.2	32.0
	Evening						
Rho(%)	86.0	77.0	78.0	65.0	88.0	88.3	89.0
Rhi(%)	52.0	53.5	51.0	49.8	50.6	53.0	55.0
Tao(°C)	30.1	30.8	29.8	27.9	29.6	30.0	30.2
Tai(°C)	32.5	34.6	32.3	29.3	30.4	31.8	31.5
Tso(oC)	29.8	30.1	29.2	27.3	29.8	29.5	30.2
Tsi(oC)	31.2	31.5	30.5	29.8	32.0	31.8	31.5
Tgs(oC)	31.5	32.0	30.6	31.0	32.0	31.8	31.6
Tgc(°C)	30.4	31.0	30.1	31.1	30.8	29.7	30.8
	Oct. 10	Oct. 11	Oct. 12	Oct. 13	Oct. 14	Oct. 15	Oct. 16
	Morning						
Rho(%)	86.0	77.0	78.0	65.0	88.0	88.3	89.0
Rhi(%)	76.6	75.7	67.2	62.0	68.1	69.5	68.7
Tao(°C)	26.9	28.5	24.5	24.5	28.7	23.7	23.9
Tai(°C)	26.2	27.3	27.1	23.2	25.3	23.5	24.1
Tso(°C)	27.5	29.2	25.2	24.3	26.5	23.4	24.2
Tsi(°C)	26.4	29.0	24.8	24.0	26.3	24.1	23.8
Tgs(°C)	27.2	29.0	26.8	27.0	26.4	26.4	26.2
Tgc(°C)	28.4	30.2	28.6	29.0	27.6	27.8	28.5
	Afternoon						
Rho(%)	50.0	50.0	48.7	40.8	45.3	62.6	56.0
Rhi(%)	35.8	41.2	49.4	37.5	38.1	52.8	42.7
Tao(°C)	35.5	29.2	34.0	32.0	31.5	31.1	32.3
Tai(°C)	36.8	32.5	36.2	35.1	35.8	35.6	35.2
Tso(°C)	38.0	34.6	34.5	36.2	34.1	37.0	37.1
Tsi(°C)	36.8	34.0	35.8	36.5	34.3	35.2	37.3
Tgs(oC)	32.0	33.0	33.2	32.1	30.9	30.0	32.4
Tgc(°C)	31.8	32.2	32.8	32.0	30.8	31.7	32.0
	Evening						
Rho(%)	68.8	64.7	60.2	58.0	65.4	72.0	66.0
Rhi(%)	57.0	48.0	52.4	61.0	64.0	67.5	61.8
Tao(°C)	2.8	29.7	30.7	31.0	30.6	30.0	31.0
Tai(°C)	28.2	31.4	34.5	33.8	34.1	32.5	34.2
Tso(°C)	27.1	29.2	32.5	31.6	31.7	30.6	32.2
Tsi(°C)	29.2	31.6	33.6	32.4	33.0	31.8	33.1
Tgs(oC)	29.8	31.5	33.8	32.5	33.2	32.0	30.5
Tgc(°C)	28.2	28.8	31.5	30.8	30.9	31.0	29.8

Rho(%) = relative humidity of atmospheric air
Rhi(%) = rel humidity silo headspace air
Tao(°C) = atmospheric air temperature
Tai(°C) = internal air temperature
Two(°C) = external wallsurface temperature
Twi(°C) = internal wall surface temperature
Tgs(°C) = temperature of grain near the surface
Tgm(°C) = grain temperature at the central portion

Table B2 cont'd

	Oct. 17	Oct. 18	Oct. 19	Oct. 20	Oc. 21	Oct. 22	Oct. 23
	Morning						
Rho(%)	87.0	90.6	89.0	89.0	73.8	79.0	78.0
Rhi(%)	70.3	76.1	75.0	74.7	60.7	68.3	67.0
Tao(°C)	24.8	24.8	24.5	24.5	28.5	26.9	26.2
Tai(oC)	24.5	27.1	21.2	21.2	27.8	26.1	25.7
Tso(oC)	26.1	24.9	24.2	24.2	29.0	27.1	27.2
Tsi(oC)	25.7	22.2	26.1	26.1	27.3	26.6	26.8
Tgs(oC)	24.5	24.7	26.8	26.8	27.1	27.2	27.4
Tgc(°C)	26.2	28.5	29.1	29.1	28.5	28.6	28.8
	Afternoon						
Rho(%)	59.0	50.0	81.0	55.0	56.0	48.2	46.2
Rhi(%)	47.2	40.0	73.0	43.0	42.4	36.5	37.2
Tao(°C)	31.2	35.5	26.8	32.9	31.7	33.8	34.0
Tai(oC)	33.2	37.7	24.2	35.1	33.5	36.6	37.0
Tso(oC)	35.5	36.5	28.7	37.2	37.0	36.9	37.3
Tsi(oC)	35.3	34.3	28.9	37.5	37.2	37.3	37.6
Tgs(oC)	30.5	32.5	26.7	33.0	32.5	31.4	30.9
Tgc(°C)	30.7	30.8	29.5	30.0	32.4	31.8	31.1
	Evening						
Rho(%)	85.0	74.0	75.0	64.0	70.0	64.2	72.0
Rhi(%)	58.0	52.0	72.7	61.1	55.0	60.7	52.0
Tao(°C)	29.9	31.4	26.7	30.0	29.7	26.9	30.5
Tai(oC)	31.4	30.7	30.1	34.1	31.2	30.2	32.4
Tso(oC)	29.2	29.8	26.2	32.3	29.0	27.8	30.0
Tsi(oC)	31.3	30.3	26.8	33.1	31.0	29.3	32.2
Tgs(oC)	31.2	26.1	26.0	33.5	31.1	29.6	31.9
Tgc(°C)	29.7	28.0	27.7	31.8	29.8	28.0	30.5
	Oct. 24	**Oct. 25**	**Oct. 26**	**Oct. 27**	**Oct. 28**	**Oct. 29**	**Oct. 30**
	Morning						
Rhi(%)	85.0	74.0	75.0	64.0	70.0	64.2	72.0
Tao(°C)	75.3	67.3	68.5	68.6	67.5	68.0	67.5
Tai(oC)	25.1	28.5	29.8	27.0	29.3	28.8	27.5
Tso(oC)	22.5	27.0	24.6	26.3	27.1	27.6	26.1
Tsi(oC)	22.6	27.4	28.4	27.1	28.5	29.2	26.5
Tgs(oC)	23.7	27.8	28.0	26.6	28.0	28.3	26.8
Tgc(°C)	26.5	28.1	29.1	26.8	29.1	28.5	27.0
	28.1	29.6	30.6	27.1	30.2	31.0	28.8
	Afternoon						
Rho(%)	41.0	58.0	50.0	56.5	54.3	55.2	42.3
Rhi(%)	38.0	46.3	42.5	49.4	46.0	47.2	37.5
Tao(°C)	33.2	30.0	29.3	32.2	29.2	30.1	33.5
Tai(oC)	37.1	35.6	33.5	36.7	33.3	35.3	36.8
Tso(oC)	36.7	34.2	32.3	35.1	32.4	34.3	37.0
Tsi(oC)	36.9	34.6	34.1	34.8	34.0	33.5	37.5
Tgs(oC)	32.4	30.6	32.3	32.4	31.9	32.7	31.8
Tgc(°C)	32.6	32.1	31.7	32.6	30.9	31.9	31.8
	Evening						
Rho(%)	60.5	61.3	65.4	87.8	66.0	57.0	45.0
Rhi(%)	52.5	52.0	57.0	73.6	56.1	52.5	50.1
Tao(°C)	28.7	29.5	29.8	29.7	29.3	26.6	32.0
Tai(oC)	32.0	31.6	31.6	31.8	31.2	30.9	33.8
Tso(oC)	29.0	29.2	30.3	30.0	29.3	26.8	30.5
Tsi(oC)	30.9	31.4	32.0	31.1	31.5	28.2	32.0
Tgs(oC)	31.1	31.3	31.8	31.0	31.0	29.9	30.5
Tgc(°C)	29.2	29.9	30.5	28.9	29.6	28.1	30.4

Rho(%) = relative humidity of atmospheric air
Rhi(%) = rel humidity silo headspace air
Tao(°C) = atmospheric air temperature
Tai(°C) = internal air temperature
Two(°C) = external wallsurface temperature
Twi(°C) = internal wall surface temperature
Tgs(°C) = temperature of grain near the surface
Tgm(°C) = grain temperature at the central portion

Table B2 cont'd

	Oct. 31	Nov. 1	Nov. 2	Nov. 3	Nov. 4	Nov. 5	Nov. 6
	Morning						
Rho(%)	69.0	70.5	60.9	76.0	61.0	51.0	81.0
Rhi(%)	68.0	67.8	69.0	66.0	68.2	53.0	67.0
Tao(°C)	26.3	28.2	28.7	25.8	26.6	23.4	27.3
Tai(oC)	25.6	25.9	27.5	25.4	25.8	23.2	24.8
Tso(oC)	27.0	26.8	29.1	27.0	26.8	23.5	24.8
Tsi(oC)	27.0	26.5	28.0	26.5	26.4	24.0	25.6
Tgs(oC)	27.2	27.8	28.0	27.4	26.5	25.0	26.1
Tac(°C)	29.2	29.6	30.0	28.6	27.8	29.8	28.7
	Afternoon						
Rho(%)	41.0	44.0	35.0	34.1	45.0	34.1	45.0
Rhi(%)	38.1	36.5	37.0	37.1	33.4	71.0	36.5
Tao(°C)	32.3	32.8	34.3	33.6	38.2	36.1	32.3
Tai(oC)	37.2	35.8	37.3	36.7	36.8	37.6	35.4
Tso(oC)	36.5	37.0	36.0	35.7	37.0	36.2	36.5
Tsi(oC)	36.8	37.1	34.0	33.8	35.7	33.5	34.8
Tgs(oC)	32.6	32.4	32.0	33.1	31.4	30.0	31.4
Tac(°C)	32.5	32.0	31.5	32.2	31.5	30.2	30.6
	Evening						
Rho(%)	74.0	61.0	60.5	51.0	70.5	69.0	61.0
Rhi(%)	48.0	60.0	59.0	61.2	52.0	53.5	62.0
Tao(°C)	32.6	32.5	32.0	30.3	29.5	28.1	32.5
Tai(oC)	34.2	33.0	33.4	34.2	31.6	31.8	33.0
Tso(oC)	31.5	31.6	31.3	32.5	29.0	28.8	32.0
Tsi(oC)	32.1	32.0	31.5	33.2	31.5	30.4	33.5
Tgs(oC)	32.0	32.6	30.2	33.4	35.0	30.8	32.4
Tac(°C)	30.5	30.0	30.0	31.3	31.2	28.6	31.1

	Nov. 7	Nov. 8	Nov. 9	Nov. 10	Nov. 11	Nov. 12	Nov. 13
	Morning						
Rho(%)	74.0	61.0	60.5	51.0	70.5	69.0	61.0
Rhi(%)	68.5	68.0	68.5	56.0	66.8	67.5	69.0
Tao(°C)	26.5	27.8	28.3	23.5	26.6	27.0	26.5
Tai(oC)	25.2	27.2	27.2	23.0	25.7	25.8	25.6
Tso(oC)	27.1	29.3	28.7	23.7	28.0	26.3	26.6
Tsi(oC)	27.4	29.1	28.2	24.8	28.2	26.6	26.2
Tgs(oC)	28.0	29.4	28.0	25.6	28.3	27.0	26.4
Tac(°C)	28.9	31.2	30.0	27.8	29.8	29.1	28.5
	Afternoon						
Rho(%)	43.0	35.0	45.0	34.7	42.5	41.0	37.0
Rhi(%)	39.8	37.2	37.5	37.0	33.8	38.0	39.0
Tao(°C)	33.5	33.0	34.0	35.0	37.2	33.2	34.8
Tai(oC)	36.5	37.0	37.2	36.2	37.0	37.5	36.5
Tso(oC)	37.0	35.8	35.7	35.2	37.3	36.6	36.0
Tsi(oC)	35.3	34.1	34.6	34.3	36.5	36.8	35.5
Tgs(oC)	32.0	32.6	33.0	31.0	30.5	31.2	31.0
Tac(°C)	31.6	32.0	32.5	31.2	30.9	31.0	29.0
	Evening						
Rho(%)	50.0	55.0	49.0	57.8	58.0	46.0	58.0
Rhi(%)	59.2	52.6	60.0	52.6	60.5	61.0	52.5
Tao(°C)	32.0	29.5	30.2	29.0	30.5	30.5	29.5
Tai(oC)	33.2	31.2	33.1	31.0	32.0	33.4	31.6
Tso(oC)	31.5	29.0	32.3	28.4	31.2	31.6	30.2
Tsi(oC)	31.9	31.2	32.8	31.0	31.9	31.8	31.6
Tgs(oC)	31.7	31.6	32.5	31.5	32.0	31.5	31.8
Tac(°C)	30.8	29.5	30.7	29.8	30.5	30.2	29.8

Rho(%) = relative humidity of atmospheric air	Two(°C) = external wallsurface temperature
Rhi(%) = rel humidity silo headspace air	Twi(°C) = internal wall surface temperature
Tao(°C) = atmospheric air temperature	Tgs(°C) = temperature of grain near the surface
Tai(°C) = internal air temperature	Tgm(°C) = grain temperature at the central portion

Table B2 cont'd

	Nov. 14	Nov. 15	Nov. 16	Nov. 17	Nov. 18	Nov. 19	Nov. 20
	Morning						
Rho(%)	54.0	72.0	70.5	75.0	76.0	69.0	80.0
Rhi(%)	57.0	68.0	68.0	66.0	67.0	68.0	67.0
Tao(°C)	27.0	26.8	27.5	26.0	27.0	26.5	27.5
Tai(oC)	25.5	26.4	26.8	25.6	24.5	25.6	24.9
Tso(oC)	25.6	26.9	27.1	27.2	24.8	27.0	25.0
Tsi(oC)	26.2	27.5	27.0	26.5	25.5	27.2	25.6
Tgs(oC)	26.5	27.8	27.5	27.5	26.0	27.5	25.1
Tgc(°C)	29.2	28.8	29.2	28.8	28.0	29.0	28.3
	Afternoon						
Rho(%)	35.0	44.0	45.0	41.0	35.5	42.0	47.0
Rhi(%)	39.5	37.5	38.5	38.0	37.8	38.5	35.1
Tao(°C)	36.2	37.1	37.0	34.5	34.0	33.0	32.5
Tai(oC)	36.0	36.5	36.8	35.8	36.0	35.2	35.2
Tso(oC)	36.6	37.0	37.0	36.0	35.2	32.8	32.4
Tsi(oC)	35.4	35.8	34.8	35.5	33.5	32.0	31.6
Tgs(oC)	30.5	30.5	31.0	32.5	32.5	30.7	30.5
Tgc(°C)	28.9	29.4	30.0	30.3	30.6	29.4	29.2
	Evening						
Rho(%)	81.0	76.0	70.0	48.0	58.0	50.0	51.0
Rhi(%)	61.0	54.0	53.5	61.5	60.7	61.0	53.0
Tao(°C)	29.8	28.5	29.0	30.5	30.0	28.1	28.1
Tai(oC)	31.8	31.5	31.8	32.5	32.8	32.0	31.5
Tso(oC)	29.6	28.8	29.4	30.0	29.7	28.0	29.0
Tsi(oC)	31.2	30.7	31.5	31.5	30.5	30.2	30.8
Tgs(oC)	31.6	30.8	31.6	31.8	30.8	30.5	30.2
Tgc(°C)	29.8	29.7	28.8	28.0	27.1	28.0	29.2

	Nov. 21	Nov. 22	Nov. 23	Nov. 24	Nov. 25	Nov. 26	Nov. 27
	Morning						
Rho(%)	81.0	76.0	70.0	48.0	58.0	50.0	51.0
Rhi(%)	68.5	67.0	67.5	57.5	53.1	57.0	54.0
Tao(°C)	25.5	26.1	23.8	26.0	25.8	26.0	25.5
Tai(oC)	23.8	25.6	23.5	25.1	24.8	25.1	25.0
Tso(oC)	24.3	28.0	24.1	26.5	26.7	26.5	25.6
Tsi(oC)	24.8	26.7	23.8	26.2	26.2	26.3	26.2
Tgs(oC)	25.0	27.0	24.8	26.4	26.8	26.5	26.5
Tgc(°C)	29.2	29.0	28.7	28.8	29.7	28.1	27.3
	Afternoon						
Rho(%)	35.0	44.0	44.0	34.3	35.0	36.8	40.0
Rhi(%)	38.2	37.5	38.1	37.2	37.5	38.1	37.6
Tao(°C)	33.5	34.2	33.2	32.8	35.5	34.0	35.8
Tai(oC)	36.4	36.8	36.1	36.0	36.2	35.0	35.6
Tso(oC)	35.6	35.8	34.5	33.2	37.2	34.5	35.4
Tsi(oC)	34.5	34.2	34.2	32.5	35.0	32.3	32.4
Tgs(oC)	31.6	32.0	31.6	31.0	32.7	31.2	30.8
Tgc(°C)	31.0	30.0	29.6	30.0	31.5	29.0	29.7
	Evening						
Rho(%)	47.4	55.0	45.2	50.0	57.0	58.0	50.0
Rhi(%)	61.0	63.0	52.1	59.0	51.0	53.0	56.7
Tao(°C)	31.0	32.0	32.2	32.5	29.4	28.5	29.2
Tai(oC)	34.5	33.1	33.7	33.4	31.8	31.0	31.6
Tso(oC)	32.6	30.8	31.2	31.2	29.5	29.3	29.8
Tsi(oC)	33.4	31.5	32.5	31.5	31.3	30.6	31.6
Tgs(oC)	33.0	32.5	33.4	30.4	31.8	31.0	31.7
Tgc(°C)	30.8	32.7	31.5	30.1	28.7	29.4	28.8

Rho(%) = relative humidity of atmospheric air
Rhi(%) = rel humidity silo headspace air
Tao(°C) = atmospheric air temperature
Tai(°C) = internal air temperature
Two(°C) = external wallsurface temperature
Twi(°C) = internal wall surface temperature
Tgs(°C) = temperature of grain near the surface
Tgm(°C) = grain temperature at the central portion

Table B3. Temperature and relative humidity measured in the Sandcrete silo

Date / Parameter	Oct. 3	Oct.4	Oct. 5	Oct. 6	Oct.7	Oct. 8	Oct. 9
	Morning						
Rho(%)	89.00	80.00	78.30	86.00	90.50	87.00	90.00
Rhi(%)	88.00	90 40	91.00	90.80	92.50	91.20	90.00
Tao(°C)	24.50	24.80	24.50	24.70	26.80	24.80	25.10
Tai(oC)	26.50	27.10	26.40	26.20	26.90	25.10	26.00
Tso(oC)	28.00	27.30	26.80	28.00	27.40	26.80	28.40
Tsi(oC)	27.40	27.40	27.00	26.50	27.40	25.70	27.90
Tgs(oC)	26.80	27.50	27.10	27.40	28.10	27.50	28.50
Tgc(°C)	28.70	29.00	28.70	29.00	28.60	28.40	28.80
	Afternoon						
Rho(%)	60.00	59.30	50.00	54.30	49.00	60.00	57.00
Rhi(%)	88.00	76.40	78.00	84.60	82.00	75.50	74.50
Tao(°C)	31.70	33.20	32.60	31.80	33.80	31.50	32.00
Tai(oC)	34.10	36.40	36.00	34.20	35.40	33.80	35.10
Tso(oC)	42.80	46.30	45.00	44.10	44.60	43.40	41.60
Tsi(oC)	34.00	35.80	35.40	32.40	33.80	35.00	33.60
Tgs(oC)	30.10	33.80	33.50	33.50	30.00	29.70	30.00
Tgc(°C)	29.80	33.70	30.80	30.50	29.70	30.50	31.10
	Evening						
Rho(%)	65.00	64.80	66.70	65.00	68.50	65.00	65.10
Rhi(%)	91.00	87.00	90.00	85.40	88.90	87.80	90.00
Tao(°C)	30.10	30.80	29.80	27.90	29.60	30.00	30.20
Tai(oC)	33.40	35.00	33.40	30.40	32.60	33.50	32.10
Tso(oC)	31.50	33.50	31.60	29.60	32.00	31.80	31.40
Tsi(oC)	32.00	34.60	35.60	32.40	33.00	32.10	30.60
Tgs(oC)	31.40	32.60	34.20	30.90	31.20	33.00	30.10
Tgc(°C)	29.80	29.60	30.10	30.00	30.00	29.80	28.90

	Oct. 10	Oct. 11	Oct. 12	Oct. 13	Oct. 14	Oct. 15	Oct. 16
	Morning						
Rho(%)	86.00	77.00	78.00	65.00	88.00	88.30	89.00
Rhi(%)	92.00	94.00	92.50	94.10	90.00	91.00	90.00
Tao(°C)	26.90	28.50	24.50	24.50	28.70	23.70	23.90
Tai(oC)	27.00	28.90	25.40	25.30	29.00	24.60	24.00
Tso(oC)	27.40	28.90	26.00	25.60	29.20	24.00	24.00
Tsi(oC)	27.80	28.50	24.70	25.30	28.10	24.50	24.20
Tgs(oC)	29.00	26.50	26.80	25.70	28.60	26.00	27.00
Tgc(°C)	29.40	28.00	28.40	27.80	28.70	28.00	28.00
	Afternoon						
Rho(%)	50.00	50.00	48.70	40.80	45.30	62.60	56.00
Rhi(%)	76.00	74.60	74.00	88.00	84.00	82.00	95.00
Tao(°C)	35.50	29.20	34.00	32.00	31.50	31.10	32.30
Tai(oC)	36.40	33.80	35.10	35.60	34.20	33.20	35.30
Tso(oC)	44.50	40.70	43.50	41.20	44.50	39.50	48.00
Tsi(oC)	36.50	33.80	36.10	34.80	34.20	34.50	35.00
Tgs(oC)	31.20	29.80	31.80	30.40	30.40	31.00	32.00
Tgc(°C)	29.80	34.00	30.00	30.60	29.80	30.00	30.00
	Evening						
Rho(%)	68.80	64.70	60.20	58.00	65.40	72.00	66.00
Rhi(%)	94.50	95.00	94.30	89.00	96.00	97.00	98.00
Tao(°C)	28.00	29.70	30.70	31.00	30.60	30.00	31.00
Tai(oC)	30.00	29.40	33.40	32.80	33.20	32.20	33.90
Tso(oC)	29.50	29.20	32.70	32.00	32.50	32.00	32.30
Tsi(oC)	30.20	30.50	33.00	32.50	33.20	31.00	34.00
Tgs(oC)	29.80	30.20	32.00	31.80	32.40	31.00	32.10
Tgc(°C)	29.20	29.40	29.80	29.40	29.00	27.50	29.00

Rho(%) = relative humidity of atmospheric air
Rhi(%) = rel humidity silo headspace air
Tao(°C) = atmospheric air temperature
Tai(°C) = internal air temperature
Two(°C) = external wallsurface temperature
Twi(°C) = internal wall surface temperature
Tgs(°C) = temperature of grain near the surface
Tgm(°C) = grain temperature at the central portion

Table B3 cont'd

	Oct. 17	Oct. 18	Oct. 19	Oct. 20	Oc. 21	Oct. 22	Oct. 23
	Morning						
Rho(%)	87.00	90.60	89.00	89.00	73.80	79.00	78.00
Rhi(%)	90.00	91.00	90.00	93.00	69.00	86.00	85.00
Tao(°C)	24.80	24.80	24.50	24.50	28.50	26.90	26.20
Tai(oC)	24.60	25.30	25.60	23.30	30.10	26.80	26.50
Tso(oC)	24.70	26.00	25.00	24.00	34.00	27.70	26.00
Tsi(oC)	26.00	25.00	26.00	24.50	28.50	27.00	26.30
Tgs(oC)	26.50	27.50	27.50	25.50	28.00	28.00	28.20
Tgc(°C)	28.00	29.00	28.50	27.00	29.20	29.10	29.10
	Afternoon						
Rho(%)	59.00	50.00	81.00	55.00	56.00	48.20	46.20
Rhi(%)	75.00	76.00	83.00	68.70	69.50	85.00	82.00
Tao(°C)	31.20	35.50	26.80	32.90	31.70	33.80	34.00
Tai(oC)	34.00	35.90	28.00	35.00	35.50	38.90	37.30
Tso(oC)	38.50	40.50	27.40	45.00	45.20	42.70	48.00
Tsi(oC)	35.00	35.00	29.00	30.00	33.00	34.00	35.00
Tgs(oC)	29.50	31.00	28.20	28.60	28.50	32.00	33.00
Tgc(°C)	29.00	29.50	28.60	29.00	27.20	30.00	30.50
	Evening						
Rho(%)	66.90	68.00	79.10	65.00	64.40	69.00	60.00
Rhi(%)	94.50	98.00	91.00	90.00	96.00	95.20	94.00
Tao(°C)	29.90	31.40	26.70	30.00	29.70	26.90	30.50
Tai(oC)	33.00	34.40	28.00	34.70	35.70	34.00	37.30
Tso(oC)	31.60	31.50	27.50	31.80	31.20	30.00	34.00
Tsi(oC)	32.00	32.00	27.80	33.30	33.50	33.00	35.50
Tgs(oC)	32.00	31.00	28.50	31.20	33.20	34.00	35.00
Tgc(°C)	28.80	29.00	28.00	28.00	29.00	29.50	30.80

	Oct. 24	Oct. 25	Oct. 26	Oct. 27	Oct. 28	Oct. 29	Oct. 30
	Morning						
Rho(%)	85.00	74.00	75.00	64.00	70.00	64.20	72.00
Rhi(%)	93.00	81.00	86.00	83.00	79.00	78.00	80.40
Tao(°C)	25.10	28.50	29.80	27.00	29.30	28.80	27.50
Tai(oC)	25.50	27.70	26.40	26.90	28.30	28.00	28.30
Tso(oC)	25.80	29.00	27.80	28.50	30.80	29.00	29.80
Tsi(oC)	26.00	27.00	28.20	27.50	28.00	27.50	28.50
Tgs(oC)	27.70	28.00	28.50	29.10	29.00	28.20	28.80
Tgc(°C)	29.20	30.60	29.30	31.20	31.50	31.50	30.10
	Afternoon						
Rho(%)	41.00	58.00	50.00	56.50	54.30	55.20	42.30
Rhi(%)	85.00	69.00	83.00	82.50	83.50	82.90	83.40
Tao(°C)	33.20	30.00	29.30	32.20	29.20	30.10	33.50
Tai(oC)	38.20	36.50	36.70	37.00	37.50	36.10	36.20
Tso(oC)	40.00	46.00	47.00	45.80	46.00	46.20	45.30
Tsi(oC)	36.50	35.00	36.50	34.80	35.10	34.90	35.80
Tgs(oC)	34.00	28.60	33.80	29.00	32.50	30.20	34.60
Tgc(°C)	31.50	27.20	31.10	27.80	29.80	28.50	33.50
	Evening						
Rho(%)	60.50	61.30	65.40	87.80	66.00	57.00	45.00
Rhi(%)	95.30	94.50	94.40	95.50	92.30	95.00	92.00
Tao(°C)	28.70	29.50	29.80	29.70	29.30	26.60	32.00
Tai(oC)	38.00	38.20	36.20	37.40	34.00	36.00	40.40
Tso(oC)	33.80	33.70	33.50	32.60	31.50	32.00	34.00
Tsi(oC)	34.50	35.20	34.80	35.00	33.00	32.70	35.20
Tgs(oC)	35.00	35.00	33.50	34.50	33.00	32.50	34.30
Tgc(°C)	31.50	31.00	29.60	31.00	32.00	31.00	31.70

Rho(%) = relative humidity of atmospheric air
Rhi(%) = rel humidity silo headspace air
Tao(°C) = atmospheric air temperature
Tai(°C) = internal air temperature
Two(°C) = external wallsurface temperature
Twi(°C) = internal wall surface temperature
Tgs(°C) = temperature of grain near the surface
Tgm(°C) = grain temperature at the central portion

Table B3 cont'd

	Oct. 31	Nov. 1	Nov. 2	Nov. 3	Nov. 4	Nov. 5	Nov. 6
	Morning						
Rho(%)	69.00	70.50	60.90	76.00	61.00	51.00	81.00
Rhi(%)	90.00	85.00	81.00	83.00	80.10	88.00	85.10
Tao(°C)	26.30	28.20	28.70	25.80	26.60	23.40	27.30
Tai(oC)	25.60	26.80	27.30	25.40	26.50	23.40	22.20
Tso(oC)	26.50	27.10	29.30	26.60	27.20	25.50	24.60
Tsi(oC)	27.00	28.50	28.50	26.50	28.40	29.00	28.00
Tgs(oC)	28.80	27.90	28.50	28.00	26.90	30.00	29.90
Tgc(oC)	31.50	30.80	32.50	32.00	30.20	33.00	33.50
	Afternoon						
Rho(%)	41.00	44.00	35.00	34.10	45.00	34.10	45.00
Rhi(%)	80.40	81.30	76.00	78.00	74.00	72.00	76.00
Tao(°C)	32.30	32.80	34.30	33.60	38.20	36.10	32.30
Tai(oC)	36.20	38.20	41.40	40.20	38.40	37.40	36.10
Tso(oC)	45.00	46.20	48.00	47.30	47.70	44.50	45.00
Tsi(oC)	36.00	36.50	35.50	34.20	35.00	33.50	34.00
Tgs(oC)	35.50	35.10	34.00	33.00	33.30	32.10	33.20
Tgc(oC)	34.60	34.00	34.80	34.50	33.50	33.00	33.60
	Evening						
Rho(%)	45.00	50.00	58.00	46.20	60.00	58.50	51.00
Rhi(%)	93.00	94.00	96.00	95.00	96.00	95.50	94.20
Tao(°C)	32.60	32.50	32.00	30.30	29.50	28.10	29.20
Tai(oC)	39.70	38.00	36.30	39.20	34.40	33.40	33.80
Tso(oC)	34.70	34.00	34.20	33.30	31.50	30.40	31.20
Tsi(oC)	36.50	36.00	35.00	37.10	32.10	31.10	32.50
Tgs(oC)	35.30	36.00	35.40	36.50	35.00	34.40	35.00
Tgc(oC)	32.50	32.50	32.40	33.40	31.20	30.50	32.00

	Nov. 7	Nov. 8	Nov. 9	Nov. 10	Nov. 11	Nov. 12	Nov. 13
	Morning						
Rho(%)	74.00	61.00	60.50	51.00	70.50	69.00	61.00
Rhi(%)	84.00	80.50	80.00	87.00	85.00	82.00	86.20
Tao(°C)	26.50	27.80	28.30	26.50	26.60	27.00	26.50
Tai(oC)	23.50	22.50	25.00	26.70	23.60	25.60	24.20
Tso(oC)	25.00	24.30	26.30	27.80	25.20	26.10	24.80
Tsi(oC)	29.00	28.80	27.20	28.10	28.10	29.00	27.80
Tgs(oC)	29.50	29.20	29.10	29.00	29.70	29.50	29.40
Tgc(°C)	33.20	31.00	30.80	30.00	31.40	32.70	31.70
	Afternoon						
Rho(%)	43.00	35.00	45.00	34.70	42.50	41.00	37.00
Rhi(%)	75.00	72.50	75.00	73.00	76.50	72.10	75.80
Tao(°C)	33.50	33.00	34.00	35.00	37.20	33.20	34.80
Tai(oC)	38.40	40.20	41.50	40.10	42.00	38.50	39.80
Tso(oC)	45.70	47.80	46.50	47.40	45.60	44.50	46.30
Tsi(oC)	36.20	36.40	35.20	37.20	35.40	35.00	34.80
Tgs(oC)	33.60	34.20	34.10	35.80	33.20	33.40	33.00
Tgc(°C)	33.80	34.50	34.60	33.40	30.50	32.10	32.60
	Evening						
Rho(%)	50.00	55.00	49.00	57.80	58.00	46.00	58.00
Rhi(%)	94.00	92.00	94.50	93.10	90.50	89.00	88.00
Tao(°C)	32.00	29.50	30.20	29.00	30.50	30.50	29.50
Tai(oC)	36.40	33.60	34.00	34.20	35.00	34.10	35.10
Tso(oC)	34.10	31.30	32.00	32.50	32.40	32.50	31.80
Tsi(oC)	34.80	34.20	33.70	34.10	34.60	35.20	32.20
Tgs(oC)	35.00	34.80	34.10	34.20	34.00	36.60	34.00
Tgc(°C)	32.40	32.00	31.50	31.50	30.50	33.00	32.00

Rho(%) = relative humidity of atmospheric air
Rhi(%) = rel humidity silo headspace air
Tao(°C) = atmospheric air temperature
Tai(°C) = internal air temperature
Two(°C) = external wallsurface temperature
Twi(°C) = internal wall surface temperature
Tgs(°C) = temperature of grain near the surface
Tgm(°C) = grain temperature at the central portion

Table B3 cont'd

	Nov. 14	Nov. 15	Nov. 16	Nov. 17	Nov. 18	Nov. 19	Nov. 20
	Morning						
Rho(%)	54.00	72.00	70.50	75.00	76.00	69.00	80.00
Rhi(%)	84.00	80.20	82.00	87.00	85.00	87.00	84.00
Tao(°C)	27.00	26.80	27.50	26.00	27.00	26.50	27.50
Tai(oC)	22.80	24.00	25.00	23.70	25.10	24.60	25.30
Tso(oC)	25.00	25.10	27.80	26.50	27.20	27.10	28.20
Tsi(oC)	28.10	29.00	29.20	28.80	28.10	28.10	29.40
Tgs(oC)	29.50	28.40	30.00	29.40	28.50	28.70	29.00
Tgc(oC)	33.00	32.50	33.10	32.60	30.00	31.20	32.80
	Afternoon						
Rho(%)	35.00	44.00	45.00	41.00	35.50	42.00	47.00
Rhi(%)	71.60	75.00	76.00	75.40	74.50	76.00	74.00
Tao(°C)	36.20	37.10	37.00	34.50	34.00	33.00	32.50
Tai(oC)	40.50	39.80	42.00	40.30	40.20	41.00	41.50
Tso(oC)	47.00	46.50	47.00	47.00	46.50	45.30	45.60
Tsi(oC)	36.10	35.10	35.40	36.10	34.50	35.70	34.80
Tgs(oC)	33.70	34.00	34.20	34.50	33.10	33.60	32.80
Tgc(oC)	33.90	34.20	34.60	33.40	33.10	32.80	33.50
	Evening						
Rho(%)	50.00	60.00	58.00	50.00	46.80	51.00	58.00
Rhi(%)	85.00	90.00	91.50	90.40	87.00	86.00	88.00
Tao(°C)	29.80	28.50	29.00	30.50	30.00	28.10	28.10
Tai(oC)	34.10	33.40	33.80	35.60	34.20	33.80	33.70
Tso(oC)	32.60	31.80	31.60	32.50	32.40	30.50	31.00
Tsi(oC)	33.60	32.70	32.40	33.10	33.00	32.50	34.20
Tgs(oC)	35.00	33.80	34.00	34.50	34.20	33.80	34.60
Tgc(oC)	30.80	31.10	31.70	32.00	31.40	31.40	33.00

	Nov. 21	Nov. 22	Nov. 23	Nov. 24	Nov. 25	Nov. 26	Nov. 27
	Morning						
Rho(%)	81.00	76.00	70.00	48.00	58.00	50.00	51.00
Rhi(%)	92.00	88.00	83.00	70.20	74.00	71.00	72.60
Tao(°C)	25.50	26.10	23.80	26.00	25.80	26.00	25.50
Tai(oC)	24.00	24.80	23.50	25.10	24.30	24.10	23.80
Tso(oC)	26.70	25.50	25.40	27.20	26.40	26.60	26.40
Tsi(oC)	27.80	27.00	28.40	27.80	27.40	28.80	28.20
Tgs(oC)	27.40	27.60	29.00	28.00	28.40	29.10	28.40
Tgc(oC)	31.50	32.40	31.60	31.00	32.00	31.50	31.20
	Afternoon						
Rho(%)	35.00	44.00	44.00	34.30	35.00	36.80	40.00
Rhi(%)	70.40	72.40	74.50	71.50	70.60	76.10	72.50
Tao(°C)	33.50	34.20	33.20	32.80	35.50	34.00	35.80
Tai(oC)	40.70	41.20	39.70	39.80	41.70	40.00	41.70
Tso(oC)	46.80	43.70	45.80	46.70	46.50	46.80	47.20
Tsi(oC)	35.20	36.10	34.90	34.60	37.00	35.60	34.80
Tgs(oC)	33.40	35.50	34.00	33.10	34.70	34.10	33.70
Tgc(oC)	33.50	33.60	34.10	33.50	35.10	34.20	34.50
	Evening						
Rho(%)	47.40	55.00	45.20	50.00	57.00	58.00	50.00
Rhi(%)	85.60	85.80	84.00	78.00	86.70	88.00	89.50
Tao(°C)	31.00	32.00	32.20	32.50	29.40	28.50	29.20
Tai(oC)	37.00	34.20	33.10	33.70	32.50	34.70	32.60
Tso(oC)	33.20	34.50	34.20	33.80	32.80	30.20	31.00
Tsi(oC)	34.60	35.10	35.40	34.80	34.20	32.10	33.00
Tgs(oC)	34.50	34.60	35.60	35.00	34.60	33.90	34.20
Tgc(oC)	31.80	32.00	33.80	31.40	32.00	31.00	33.50

Rho(%) = relative humidity of atmospheric air
Rhi(%) = rel humidity silo headspace air
Tao(°C) = atmospheric air temperature
Tai(°C) = internal air temperature
Two(°C) = external wallsurface temperature
Twi(°C) = internal wall surface temperature
Tgs(°C) = temperature of grain near the surface
Tgm(°C) = grain temperature at the central portion

APPENDIX C

Table C1. Hourly temperature (°C) readings in the steel silo (3/10/00-26/11/00)

	TEMPERATURE °C								
Time	3-Oct	4-Oct	5-Oct	6-Oct	7-Oct	8-Oct	9-Oct	10-Oct	11-Oct
00.00hr		22.00	23.00	22.50	23.50	22.50	24.00	22.00	23.50
01.00hr		22.00	22.80	22.00	23.00	22.00	23.50	21.80	23.00
02.00hr		22.00	22.50	22.00	22.80	21.00	23.50	21.50	23.00
03.00hr		21.50	22.00	21.80	22.50	21.50	23.00	21.50	22.00
04.00hr		21.50	21.80	21.80	22.50	21.00	22.00	20.50	21.50
05.00hr		20.50	21.00	21.50	22.00	21.00	21.80	20.50	21.00
06.00hr		20.80	21.50	21.00	21.50	21.00	21.50	20.00	20.50
07.00hr		21.50	21.80	20.00	21.00	23.00	21.00	21.00	22.00
08.00hr		23.00	24.50	21.50	22.00	23.50	23.00	23.50	22.50
09.00hr		26.00	28.50	26.00	23.00	27.00	24.50	26.00	29.00
10.00hr		32.00	30.00	35.00	30.50	35.00	29.00	31.00	30.50
11.00hr	41.00	36.50	37.50	39.00	32.00	36.50	33.00	35.00	39.50
12.00hr	42.00	38.00	40.50	43.00	39.00	37.00	39.50	42.00	44.50
13.00hr	41.50	40.50	41.00	43.50	39.50	40.50	42.00	43.50	45.00
14.00hr	41.00	42.00	43.00	46.80	39.80	40.80	36.00	46.80	47.00
15.00hr	39.00	41.50	39.50	41.50	40.00	41.00	38.50	41.00	42.50
16.00hr	38.00	39.00	36.00	38.00	39.50	38.00	38.00	40.50	39.50
17.00hr	34.00	35.00	31.50	36.00	39.00	35.00	36.00	37.00	38.00
18.00hr	29.50	32.00	29.00	31.50	34.00	32.00	29.00	33.00	31.00
19.00hr	28.50	28.00	27.80	29.00	29.00	28.80	28.00	30.00	29.00
20.00hr	24.00	25.50	25.50	27.50	27.50	28.00	27.00	27.50	26.50
21.00hr	23.80	24.50	24.50	26.00	26.00	25.50	25.50	26.00	24.00
22.00hr	23.50	24.00	23.50	25.00	24.50	24.50	23.00	24.50	23.50
23.00hr	22.50	23.50	22.50	24.00	23.00	24.00	22.50	24.00	22.50
24.00hr	22.00	23.00	22.50	23.50	22.50	24.00	22.00	23.50	22.00

Table C1. cont;d

	TEMPERATURE °C								
Time	12-Oct	13-Oct	14-Oct	15-Oct	16-Oct	17-Oct	18-Oct	19-Oct	20-Oct
00.00hr	22.00	23.50	20.50	22.00	22.00	23.00	24.00	24.00	20.50
01.00hr	21.80	23.00	20.50	22.00	22.00	23.00	23.50	23.50	20.00
02.00hr	21.50	22.50	20.00	21.00	22.00	23.00	23.00	23.00	20.00
03.00hr	21.00	22.00	20.00	21.80	22.00	22.80	22.50	23.00	20.00
04.00hr	20.50	21.00	19.80	21.50	21.80	22.50	22.00	22.50	19.80
05.00hr	20.50	21.00	19.50	21.00	21.50	22.00	21.80	22.00	19.50
06.00hr	20.00	20.80	19.50	21.00	21.00	21.80	21.50	21.50	19.00
07.00hr	20.50	20.50	19.00	22.00	20.50	21.50	21.50	21.50	18.80
08.00hr	24.00	23.00	21.00	23.00	22.00	23.00	21.00	21.80	19.00
09.00hr	28.50	29.00	28.50	26.00	26.00	26.00	24.50	23.00	21.00
10.00hr	33.00	30.50	29.00	32.50	35.00	32.50	30.00	24.50	25.50
11.00hr	36.50	37.50	42.00	35.50	44.00	35.00	32.00	25.00	26.50
12.00hr	42.50	43.00	42.00	37.00	44.50	37.00	39.00	26.00	31.00
13.00hr	44.00	45.00	40.50	42.00	43.00	38.50	35.00	26.50	35.00
14.00hr	45.50	46.00	42.00	35.00	47.00	39.00	39.50	29.50	38.00
15.00hr	47.50	45.00	39.00	41.50	41.00	40.00	39.00	27.00	40.00
16.00hr	47.00	44.50	36.00	38.00	37.00	38.00	39.00	27.00	42.00
17.00hr	44.00	40.00	32.00	34.00	36.00	39.00	35.00	27.00	37.00
18.00hr	40.00	36.00	29.50	36.00	32.00	31.50	31.50	27.50	33.00
19.00hr	35.00	29.50	28.50	28.00	29.00	28.00	29.00	25.00	30.00
20.00hr	30.00	26.00	24.00	27.00	27.00	27.00	27.50	23.50	27.50
21.00hr	26.50	24.00	23.50	22.50	23.50	26.00	26.00	22.50	25.50
22.00hr	25.50	24.50	23.00	22.00	23.00	25.00	25.50	21.50	24.50
23.00hr	24.00	22.00	22.50	22.00	23.50	24.00	24.50	21.00	23.50
24.00hr	23.50	20.50	22.00	22.00	23.00	24.00	24.00	20.50	23.00

Table C1. cont;d

	TEMPERATURE °C								
Time/Date	21-Oct	22-Oct	23-Oct	24-Oct	25-Oct	26-Oct	27-Oct	28-Oct	29-Oct
00.00hr	23.00	21.80	22.50	23.00	23.00	22.50	25.00	25.00	28.00
01.00hr	22.00	21.00	21.50	21.50	22.50	22.00	24.00	24.00	27.50
02.00hr	21.50	20.50	21.50	21.00	21.80	20.80	23.50	23.50	26.00
03.00hr	21.00	20.00	21.00	21.00	21.00	21.00	23.00	23.00	26.00
04.00hr	20.80	19.80	20.80	20.80	20.50	20.00	22.00	22.00	23.50
05.00hr	20.50	20.00	20.50	20.50	20.00	19.00	21.00	21.50	22.50
06.00hr	20.00	19.50	20.00	20.00	19.50	19.00	21.00	21.00	22.00
07.00hr	20.00	18.00	20.00	19.50	19.00	18.50	20.80	20.50	19.50
08.00hr	20.00	18.50	20.50	19.80	19.00	17.80	20.50	19.50	20.00
09.00hr	20.50	23.00	26.50	22.00	20.00	19.50	20.00	19.00	22.00
10.00hr	23.00	28.00	35.00	26.00	26.00	22.50	21.50	23.00	22.50
11.00hr	29.00	39.00	38.00	35.00	34.00	28.00	24.00	23.50	27.00
12.00hr	34.00	43.50	44.50	43.00	40.50	40.00	30.00	25.00	31.50
13.00hr	35.00	45.00	46.50	44.00	43.00	43.50	36.00	31.00	38.00
14.00hr	38.00	46.00	47.50	46.50	45.00	45.00	40.00	38.00	41.50
15.00hr	39.00	45.00	48.50	48.00	44.80	45.00	43.00	43.00	44.00
16.00hr	42.00	45.00	47.50	47.50	47.00	47.00	43.50	42.00	45.00
17.00hr	41.50	40.00	47.00	42.00	45.00	46.00	45.00	44.00	43.00
18.00hr	34.00	35.00	38.50	36.50	37.50	40.00	44.00	36.00	43.00
19.00hr	30.00	31.00	35.00	31.00	33.00	35.00	40.00	34.00	37.00
20.00hr	26.00	27.50	28.00	28.00	28.50	30.00	35.50	29.00	33.00
21.00hr	24.00	26.00	26.50	26.50	25.00	27.00	33.50	28.50	30.00
22.00hr	23.50	24.50	25.00	25.00	24.00	26.00	29.00	28.00	28.50
23.00hr	23.00	23.00	24.00	24.00	23.00	25.00	27.00	28.00	27.00
24.00hr	21.80	22.50	23.00	23.00	22.50	25.00	25.00	28.00	27.00

Table C1. cont;d

	TEMPERATURE °C								
Time/Date	30-Oct	31-Oct	1-Nov	2-Nov	3-Nov	4-Nov	5-Nov	6-Nov	7-Nov
00.00hr		22.50	22.00	21.50	22.50	25.00	22.00	22.00	20.00
01.00hr		21.00	21.50	20.00	22.00	25.00	21.50	20.00	23.00
02.00hr		21.00	20.50	19.50	21.00	25.00	21.00	19.50	22.50
03.00hr		21.00	20.00	19.00	20.80	25.00	20.50	19.00	20.00
04.00hr		20.00	20.00	19.00	20.50	25.00	21.00	19.50	20.00
05.00hr		19.50	19.50	19.00	20.00	24.00	20.00	19.80	19.80
06.00hr		19.00	19.50	19.00	19.00	23.50	21.00	20.50	19.50
07.00hr		19.00	19.00	21.00	21.50	23.50	21.50	21.00	19.50
08.00hr		22.50	18.50	24.00	25.00	23.50	24.50	23.50	19.80
09.00hr		29.00	21.00	31.00	29.00	28.00	30.00	29.00	19.00
10.00hr	24.50	39.00	26.00	40.00	37.00	34.50	37.50	35.00	21.50
11.00hr	26.00	38.50	29.50	43.00	40.00	38.00	41.00	38.00	26.00
12.00hr	35.00	41.00	37.00	44.50	42.00	42.50	41.50	41.50	30.00
13.00hr	38.00	42.00	40.00	44.00	44.00	43.50	43.00	42.50	34.50
14.00hr	40.00	41.50	42.00	45.00	44.00	45.00	44.00	43.00	39.80
15.00hr	43.00	43.00	41.00	41.00	41.00	41.80	41.50	41.00	42.00
16.00hr	42.00	37.00	36.50	36.00	35.00	36.00	35.50	37.00	41.50
17.00hr	40.00	33.00	32.50	31.50	31.00	30.00	30.50	30.80	39.80
18.00hr	35.50	28.00	31.00	28.50	26.50	27.00	29.00	27.00	38.50
19.00hr	27.00	25.00	27.50	26.00	26.00	25.80	26.00	25.50	36.50
20.00hr	25.00	24.00	25.50	24.50	25.50	24.50	25.00	24.00	29.80
21.00hr	24.50	22.50	24.00	23.50	25.00	24.00	23.00	23.50	28.00
22.00hr	24.00	22.00	23.00	23.00	25.00	23.50	22.50	23.00	26.00
23.00hr	23.50	22.00	22.00	22.00	25.00	22.00	22.50	22.50	25.50
24.00hr	22.50	21.50	21.50	22.50	25.00	22.00	22.00	20.00	23.00

Table C1. cont;d

	TEMPERATURE °C								
Time/Date	8-Nov	9-Nov	10-Nov	11-Nov	12-Nov	13-Nov	14-Nov	15-Nov	16-Nov
00.00hr	23.00	24.00	23.00	22.00	22.50	22.00	22.00	20.50	21.50
01.00hr	22.80	24.00	22.00	22.00	21.50	21.50	21.50	20.00	20.00
02.00hr	22.50	22.50	22.00	21.50	21.00	21.00	20.00	19.80	19.80
03.00hr	21.50	21.00	21.00	20.00	20.00	20.80	19.80	19.00	19.50
04.00hr	20.50	20.00	20.00	19.00	19.50	20.50	20.00	19.00	19.00
05.00hr	20.50	19.50	20.50	19.50	19.50	21.00	20.00	19.50	19.00
06.00hr	19.80	18.80	19.00	20.00	20.50	21.50	20.50	19.80	19.80
07.00hr	19.50	18.50	20.00	20.50	23.00	21.80	22.00	21.50	20.00
08.00hr	21.00	21.00	23.00	21.00	23.50	24.00	23.50	25.00	23.00
09.00hr	24.80	28.50	29.50	25.00	30.50	31.00	27.00	28.00	29.00
10.00hr	30.00	29.00	36.80	31.00	38.50	37.50	35.50	35.00	34.00
11.00hr	36.00	39.50	41.00	39.00	41.00	40.50	39.00	38.50	40.00
12.00hr	40.00	40.00	41.50	42.50	41.50	42.00	41.50	42.00	41.50
13.00hr	41.50	41.50	44.00	43.00	43.00	43.50	44.00	43.00	42.50
14.00hr	44.50	43.50	44.00	43.50	45.00	44.00	44.50	44.00	43.00
15.00hr	43.00	41.00	42.00	41.50	41.00	41.00	44.00	41.50	41.00
16.00hr	40.80	41.00	36.00	41.00	35.50	35.00	36.00	35.00	37.50
17.00hr	36.00	36.00	30.00	35.00	30.00	30.00	31.00	31.50	30.00
18.00hr	31.00	31.50	28.50	31.50	26.00	26.50	25.00	28.00	28.50
19.00hr	27.00	29.00	26.00	28.50	25.80	26.00	24.50	27.00	26.00
20.00hr	25.50	27.50	24.50	25.50	24.50	25.00	24.00	25.50	25.00
21.00hr	25.50	25.50	23.00	24.50	23.50	24.00	23.50	24.00	24.50
22.00hr	25.00	24.50	23.00	23.50	23.00	24.00	22.50	23.00	23.50
23.00hr	24.50	24.00	22.50	23.50	22.50	23.50	21.50	22.00	23.00
24.00hr	24.00	23.00	22.00	22.50	22.00	22.00	20.50	21.50	22.50

Table C1. cont'd

TEMPERATURE °C					
Time/Date	22-Nov	23-Nov	24-Nov	25-Nov	26-Nov
00.00hr	22.50	21.80	21.00	21.50	21.00
01.00hr	21.00	20.00	21.00	21.00	22.00
02.00hr	20.00	19.80	20.00	20.50	21.00
03.00hr	20.00	19.50	20.00	20.00	20.50
04.00hr	19.80	19.80	20.50	20.80	20.00
05.00hr	21.00	20.00	20.80	20.50	19.00
06.00hr	21.00	20.50	21.00	22.50	19.00
07.00hr	21.50	21.00	24.00	23.00	19.80
08.00hr	23.50	21.50	25.00	24.50	20.00
09.00hr	30.00	29.00	29.00	25.50	21.00
10.00hr	37.00	36.50	39.00	32.50	25.00
11.00hr	40.00	39.50	41.50	39.50	26.00
12.00hr	44.00	41.00	41.80	40.80	33.00
13.00hr	44.00	40.00	42.00	41.00	39.00
14.00hr	44.00	41.50	42.50	41.50	39.80
15.00hr	40.50	40.50	39.00	41.50	40.00
16.00hr	34.50	39.00	36.00	40.00	39.50
17.00hr	33.00	29.80	32.00	34.50	40.00
18.00hr	29.00	27.50	27.50	29.00	35.00
19.00hr	24.00	23.50	25.50	25.50	29.00
20.00hr	23.50	23.00	24.50	25.00	26.00
21.00hr	23.00	22.00	24.00	23.80	27.50
22.00hr	23.00	21.80	23.50	23.00	23.00
23.00hr	22.50	21.50	22.50	22.00	22.50
24.00hr	21.80	21.00	21.50	21.00	22.00