PREDICTION OF BULK POTATO TEMPERATURE DURING FREE NATURAL VENTILATION STORAGE

BY

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A

THESIS

Submitted in Fulfilment for the Award of the Degree of
Doctor of Philosophy
of the University of Nairobi.

1999

DECLARATION

This thesis is my original work and has not been presented for a degree in any other university

26/ 09/ 2000

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This Thesis has been submitted for examination with my approval as University Supervisor for the Award of degree of Doctor of Philosophy in the Department of Agricultural Engineering in the Faculty of Engineering of the University of Nairobi.

26 / 9 / 2000

Lawrence Gumbe, PhD

SUPERVISOR

DEDICATION

To
my wife Jane, daughter Jacqueline and son Samuel,
in the
Precious Name of Our Saviour Jesus Christ
for their
prayers, encouragement and patience
during the research and thesis writing.

"Not only was the Teacher wise, but he also imparted knowledge to the people ..." (Ecclesiates 12 10a)

ACKNOWLEDGEMENTS

I am grateful to Prof. Lawrence Gumbe of the University of Nairobi (UoN), Kenya and Dr. Dean Burfoot of Silsoe Research Institute (SRI), Great Britain under whose guidance I did the research and wrote the thesis. Much thanks to Dr. Y. Xu of SRI for his support during the Computational Fluid Dynamics (CFD) modelling.

I am equally indebted to Egerton University for granting me study leave and the Commission for Higher Education of the Kenya Government for the scholarship which paid my tuition and part of the research. I am grateful to the British Council for funding my six months at SRI through the UoN-SRI Link; SRI for waving bench fees and funding my initial/trial experiments; PREPACE for funding the experiments through International Potato Center (CIP); and the Department of Agricultural Engineering of the UoN for paying my accommodation expenses in Nairobi during the thesis writing.

I wish to thank Mr. I. Otieno (of the Institute of Computer Science, UoN); Mr. K. Mawason of Sutton Potato Station (UK); Dr. P. Ewell of CIP and Dr. Lutaladio of PREPACE who helped me in one way or another, to finish this work. Finally, I thank all my friends, colleagues and family members without whose contribution through academic advice, material and moral support, this work would not have been completed.

Nyaanga D.M.
1999

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LIST OF SYMBOLS

Letters

A	surface area, m^2
B	body force
B	breadth, m
b	bottom
a	specific surface area, $m^2\ m^{-3}$ or m^{-1}
C	Celsius
c	specific heat, $J\ kg^{-1}K^{-1}$
c	centre
D	depth or height of potato stack, m
g	gram
H	total enthalpy, $J\ kg^{-1}$
H	total height, m
h	convective heat transfer coefficient, $J\ h^{-1}m^{-2}K^{-1}$

h	specific enthalpy, J kg^{-1}
h	hour
h	layer thickness, m
L	latent heat of vaporization of water, J kg^{-1}
L	length, m
J	Colburn J-factor
J	Joule, W s
k	constant; coefficient
k	kilo
K	Kelvin
m	moisture or water vapour
m	metre
n	index; number
P	pressure, Nm^{-2}
Q	heat exchange, J h^{-1}kg^{-1}
q	respiration heat release, Wkg^{-1}
t	time, s
T	temperature, deg C
U	(u, v, w) velocity tensor
V	total volume, m^{3}
v	velocity, ms^{-1}
v	layer volume, m^{3}
W	watts
w	weight, kg
w	water
Z	height, m
z	location or position within the bulk of potatoes at which temperature is measured, m

Subscripts

a	dry air

b	bulk; bottom
c	centre
h	heat transfer
m	moisture or water vapour
p	particle
t	potato tuber; top
s	solid
r	respiration
W	west
w	wall
E	east

Greek Symbols

Δ	difference
δ	thickness, m
ε	void fraction, dimensionless
θ	product or potato temperature, degrees (°) Celsius
μ	molecular viscosity, kg m^{-1}h^{-1}
ρ	density, kg m^{-3}
λ	thermal conductivity, Wm^{-1} K^{-1}
β	coefficient of thermal expansion, K^{-1}
τ	stress
Γ	effective diffusivity
ϕ	property, variable
σ	stress tensor
∇	divergence sign
ζ	bulk viscosity

LIST OF ABBREVIATIONS

AEA	Atomic Energy Authority.
ASAE	American Society of Agricultural Engineers.
Avg	Average
Burt	Burton
Cent	Centre
CFD-CFX	Computational Fluid Dynamics/Code, a commercial computer program.
CIP	International Potato Centre.
CTP	Computational Thermal Prediction
cpu	central processing unit
CO_2	carbon dioxide
deg	degrees (°)
diff	difference
dm	dry matter
ed	edition, editor
EG	Egerton
Eur. P. J.	European Potato Journal
FEM	Finite Element Method
HVAC	Heating, ventilating and air conditioning
HDS	Hybrid differencing
HUW	Higher-order upwind differencing
J. Agr. Engg	Journal of Agricultural Engineering
Max	maximum
mc	moisture content
Min	Minimum
Pa	pascal, Nm^{-2}
PMB	Potato Marketing Board (of Britain)
Pr	Prandtl number,
QUICK	Quadratic upwind differencing

sg	specific gravity
SAS	Statistical Analysis Systems
SRI	Silsoe Research Institute
Temp	temperature
Trans.	Transactions.
UDS	Upwind differencing scheme
UoN	University of Nairobi
vpd	vapour pressure deficit
Re	Reynold's number
rh	relative humidity
wb	wet basis

ABSTRACT

Prediction of Bulk Potato Temperature During Free Natural Ventilation Storage

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The broad objective of this research was to predict bulk potato temperatures at various locations and at different times of storage in boxes under free natural ventilation using both theoretical and physical experimental approaches. Mathematical modelling and simulation were done using available empirical and static models namely Burton (1989) and Nyaanga (1991) after the necessary modifications and a semi-dynamic and theoretical model [named Computational Thermal Prediction (CTP)] that was developed during the research. Experiments using potato storage boxes, thermocouple sensors and data loggers were conducted.

The Computational Thermal Prediction (CTP) semi-dynamic model was developed as a compromise between the specific, static and less precise empirical prediction expressions and the generalisable, very precise and highly dynamic models such as Computational Fluid Dynamics (CFD/CFX by AEA, 1996) which demand a lot of Central Processing Unit (CPU) memory and time; after the two were found inadequate for free natural ventilation which is neither fully static nor that dynamic as is the case of forced and other forms of controlled potato storage. CTP mathematical relationships involving the various parameters of the storage environment such as temperature; rate and amount of heat of respiration generated by the potatoes into the system and the amount lost by convection; and the physical characteristics of the bulk such as dimensions, porosity and density were developed based on the theories of free natural convection and results from experiments with appropriate assumptions. Finite element method of numerical analysis was used to determine the temperature at various locations (mainly along the vertical axis) within the bulk and at various time intervals.

Experiments were conducted on physical models using potato storage boxes and logging the data after being sensed by thermocouples. The data was used to test and verify the mathematical models and determine the temperature variations which the models could not reveal such as lateral temperature gradients.

The results of the research indicate that it is possible to predict the bulk potato temperature using empirical mathematical expressions using the modified Burton (1989) and Nyaanga (1991) models; develop a more generalisable Computational Thermal Prediction (CTP) model for the simulation of bulk potato temperatures; and experimentally determine various bulk potato temperatures in free natural ventilation potato storage. The empirical model predictions were not as accurate as the experiments but they gave accurate trends (history) of the bulk potato temperatures with the time of storage. The modified Burton (1989) model shows the temperature gradients in a bulk of potatoes although with slightly higher magnitudes and variations compared to the observed. The Nyaanga (1991) model simulations gave nearly the same values for all the major temperatures within a bulk of potatoes that is, the temperature at the bottom, centre and top were the same.

The Computational Thermal Prediction (CTP) simulations were more accurate than the empirical models and the computer program gives a wide range of options. The individual temperature trends, by various CTP options and at the different points of monitoring were the same at a probability of 1% using general linear model. Generally, the CTP predicted values are slightly higher than the observed. The small deviations could have resulted from assumptions and constants used in the mathematical model such as the major modes of heat and air exchange and their quantification. The CTP computer program using user information about the free ventilation potato storage, gives the user information and recommendations about the specified storage system with respect to bulk size, store temperature and time of storage. However, all the simulations showed that the bulk potato temperature varied with store specifications and ambient temperatures as expected.

"The heart of the prudent acquireth knowledge and the ear of the wise seeketh knowledge" (Proverbs 18:15).

CHAPTER 1: **INTRODUCTION**

1.1 Background

The term potato refers to an agricultural product from an Irish potato plant, *Solanum tuberosum* harvested as a tuber. The potato tubers are classified according to their use (depending on various characteristics and qualities) as ware or culinary or table potatoes which are used directly for human consumption; processing or industrial potatoes which are processed into other food or industrial products; and seed potatoes which are planted to propagate the potato crop.

Potatoes are the fourth most important staple food after rice, wheat and maize in developing countries (Booth and Rhodes, 1989). They contribute to human nutrition, create employment and generate income that contributes to the economy of individual households and the nation. The storage of potatoes is a process which goes on at all stages of potato handling, marketing and utilization until the tubers are consumed or processed or planted. A successful storage system should therefore contribute one or more of the following roles (Burton, 1955; Sparks and Summers, 1974; Ballestrem and Holler, 1977; Nyangito, 1986):

1. Food security at farm and national level
2. Reduction of wasteful disposal/usage of potatoes
3. Price stabilization; affordable prices for consumers during off season and good prices to farmers at peak harvesting
4. Constant supply of potatoes throughout the year for home and hotel consumption and processing
5. Reduction of transportation problems (bulk transportation, such as by rail possible rather than small vehicle transport due to lack of storage)
7. Seed for next crop

8. Reduction in over-reliance on cereals for starch
9. Possibilities of export

These roles of storage will only be realised when storage is accompanied by the reduction of post harvest losses (Durr and Lorenzl, 1980). Salunkhe and Desai (1984) have been quoted to say, "Losses of foods, especially of perishables such as vegetables and fruits in transit and storage must be halted to increase the world food supply.....a positive step towards a healthy and happy world".

Potato storage methods vary from simple unventilated heaps in or on the ground to computerised conditioned systems such as delayed harvest; unventilated and ventilated clamps; bulk storage in buildings with natural or forced draught ventilation; refrigeration; chemical treatment and controlled atmosphere storage (Sawyer *et al.* 1965; Cargill *et al.* 1989; Burton, 1989; Bishop and Maunder, 1980; Butcherbaker *et al.* 1967; Ryall and Lipton, 1972). Bulk storage systems include stores, bins, boxes, bags and heaps. The optimum method of storage in any particular case depends on individual circumstances including the local climate; health and type of the potatoes; the methods used to harvest, handle and move the potatoes; the finance, labour and management expertise available; and the market and the probable fluctuations in it during the storage season (Booth and Rhodes, 1989). The cost of large scale and expensive controlled storage systems may not be affordable in poor developing countries since the extra cost of storage cannot be paid by the extra price after storage and hence the inclination to the more viable alternatives such as cheap natural convective ventilation and uncontrolled storage systems (Hunt, 1982; Horton, 1987; Booth and Rhodes, 1989; Nyaanga, 1991).

Bulk potato temperature is used to refer to average temperature of both the bulk air and tuber temperatures of the air-potato medium. The phrase 'free natural ventilation or natural ventilation' is used in this thesis to refer to what has been termed 'unventilated' or 'uncontrolled' or 'free ventilation' or 'free draught' storage by a number of researchers (such as Burton, 1989; Burton *et al.* 1955; Nyaanga, 1991) to describe a storage system where the room/store conditions of temperature, humidity and air flow rate are not manipulated except by the walls, floor and roof of the structure defining the room/store in which the potatoes are held or stored. The conditions in this type of storage vary with a similar trend to that of the prevailing environmental ambient conditions unlike controlled storage where mechanical ventilation and artificial heating or cooling is used to maintain the desired environment often quite different from the ambient conditions.

The theories of heat and mass flow through a porous material and experiments can be used to predict the temperatures at various locations in stored potatoes (Greenkorn, 1983). The results of mathematical simulations that statistically agree closely with experimental data can be used for further predictions. The term prediction is used to imply the determination of the desired parameters of a system either theoretically or experimentally. Theoretically, prediction involves the use of the laws of physics and mathematics to calculate the dependent variables as a function of the independent variables of the system (a process termed mathematical modelling). Mathematical modelling uses governing equations which are solved numerically or analytically to quantify the pertinent parameters and hence theoretically describe a system. Mathematical models may be empirical (also termed static) using statistical observed data often from experiments or dynamic (also called mechanistic models) which are based on pure theoretical relationships about the system (Williams, 1997; Smith 1977a).

The use of physical (experimental) and mathematical (theoretical) models in the study of potato storage systems have merits and demerits. Experimental temperature determinations are slow, expensive, prone to many sources of error, limited to only a few data for every experiment while mathematical model simulations may be faster, more accurate and predictive but in some cases, they may be equally slow and expensive (Smith, 1977a; Holman and Gadja, 1984; Grahs *et al.* 1978). The identification of the parameters involved is crucial and must precede the theoretical prediction or experimental investigation (Brugger, 1979; Gumbe, 1987; Misener, 1973).

1.2 Problem and Justification

The potato tuber like most perishable and semi-perishable tubers and vegetables, experiences a high degree of post harvest deterioration caused by physical damage, microbial infection, endogenous physiological reactions, and fluctuating storage temperatures (Osuji, 1983). These losses are accelerated when potatoes are stored under uncontrolled tropical conditions of high temperatures, averaging about 20 °C in Kenya. In recent years potato production in these countries has spread out of the traditional mountainous, cool highland environments into warmer areas necessitating storage in a wide range of conditions (Booth and Rhodes, 1989). This calls for research in the design and management of the traditional less efficient, cheap and simple storage methods such as clamps and naturally ventilated boxes and bags in order to improve them (Shaw *et al.* 1982).

The storage temperature determines the length of storage, quantity and quality of stored potatoes since it influences the onset of disease incidence, chemical changes and physiological changes such as sprouting which are not desirable for ware potatoes (Burton, 1989). High temperature causes early sprouting, increased microbial activity, metabolism, disease incidence, water loss, sweetening and related physiological and mechanical losses (Schaper and Hudson, 1971; Schaper *et al.* 1967; Sparks, 1965; Rustowski, 1982; Singh and Mathur, 1938; Workman and Twomey, 1969). Accurate and prompt prediction of the occurrence of high temperature spots in any potato storage will help institute prevention measures against them to minimize losses and therefore maximize profits as well as increase food reserves.

Thus, the potato temperature is crucial in the design and management of storage systems, since it is an indicator of safe storage and therefore the length of storage, and is a signal of when to apply mechanical ventilation, cooling or terminate the storage. A number of design details such as the bulk size that should be used to ensure optimal storage temperature are not yet fully documented. For instance, Nyaanga (1991) and Nyaanga *et* *al.* (1994b) using slender experimental storage boxes (0.4 m by 0.4 m of heights varying between 0.6 m and 2.0 m) found the potato temperature to be lower than the ambient temperature while Burton *et al.* (1955) found the potato temperature to be higher than the average ambient temperature in large commercial unventilated stacks. The critical potato temperatures with respect to position in the stack and time of storage have not been established fully. Answers to questions such as which temperature (bulk or tuber temperature; at centre, top or bottom of the bulk); when to measure the temperature (at the start of storage or mid or end or continuously); and how to determine the temperature (experimentally and theoretically), are not evident from the available literature. The effects of the various factors of the storage of potatoes such as the bulk size, ambient conditions and the prevailing thermal processes, such metabolic heat release and evaporative cooling on the temperature of natural convective storage need to be investigated. These are some of the reasons why research on temperature prediction in natural potato storage should be conducted. While experimentation is the absolute way of establishing what happens in reality, it has a number of limitations hence the need for theoretical simulation. A number of theoretical studies have been done in controlled potato storage environments but not much has been done in uncontrolled natural storage conditions. Attempts to apply this approach to study natural ventilation crop storage is therefore important.

The difficulty in studying the natural convection storage including the prediction of the potato temperature is compounded by the many variables involved and its very nature of variation in response to the uncontrollable ambient conditions. Absolute conclusions about natural convection systems are virtually non existent, due to the fact that the study of such a system by experiments and even mathematical modelling remains still a formidable task. However, by making appropriate assumptions, a number of useful and valid inferences about the system can be made. Most models are verified with industrial data (from commercial storage) but more accuracy could be achieved using specific experimental data hence the need to conduct experiments alongside mathematical model simulations.

1.3 Objectives

The broad objective of this research was to predict potato temperatures at various locations and at different times of storage in boxes under free natural ventilation using both theoretical and experimental approaches.

The specific objectives were to:

1. Develop a mathematical model and algorithm to predict the potato temperature at various locations and times of storage

2. Experimentally verify the predictions in (1) above

"... Searched to find just the right words, and wrote what was upright and true." (Ecclessiates 12:10).

CHAPTER 2: LITERATURE REVIEW

This chapter covers the general requirements and characteristics of free natural ventilation potato storage systems; physical and thermal properties of potatoes and air around them; and mathematical modelling for the study of the crop storage and other porous environments.

2.1 General Potato Storage Requirements

A potato tuber has a cork-like skin with small pores through which moisture and heat exchange occurs. The tuber is a living organism containing about 75% to 80% water, wet basis (wb) (Glynne and Jackson, 1919; Charm, 1971; Johnston *et al.* 1968). The tubers can be stored for several months in controlled and uncontrolled environments with eventual termination by sprout growth, rotting, wilting and excessive chemical changes. Therefore, there are two main objectives in the storage of potatoes, namely, to prolong the storage life of the potato as an organism and to retain the quality of the potato as a food (Burton, 1963). Unfortunately, these objectives require different conditions, for instance, a very long storage life is possible at around 2 °C but at this temperature, potatoes become sweet and hence unacceptable as food. A compromise is to maintain a high relative humidity (above 75% to prevent wilting) and temperatures high enough to avoid sweetening (above 4 °C) but low enough to prevent other forms of deterioration such as rotting and sprouting (Schaper *et al.* 1967; Burton, 1955, 1963, 1973 and 1982a).

Methods of uncontrolled potato storage include field clamps, unventilated stacks and lately boxes. They cannot be expected to give ideal storage conditions, particularly where ambient temperatures are high, but they are the best alternatives in many situations in developing countries. Potato storage boxes have been found to be effective, cheap and adaptable to small scale potato producers and consumers in developing countries including Kenya (Hunt, 1987; Sparks, 1975; Horton, 1987). The boxes have been variedly referred to as 'pellet' or 'slatted' boxes due to the openings at the bottom and/or on the sides for ventilation and as crates when their main purpose is handling the potatoes (Hunt, 1987; Sparks, 1975; PMB, 1997; Horton, 1987). The boxes have better ventilation than sacks or bags and therefore will maintain the potato quality for relatively longer periods. Hunt (1982) gives the dimensions of a convectional storage box as 1 m by 1 m by 1 m, however, other dimensions have been used such as 0.4 m by 0.4 m with heights varying between 0.6 m and 2.0 m by Nyaanga (1991) and 1.84 m by 1.22 m by 1.44 m by PMB (1997). These methods are not suitable for prolonged storage but can be sufficient for up to three months and up to five months storage if chemical suppressants are applied even in the tropics (Nyaanga, 1991; Hunt, 1987).

Potato storage in boxes has similar characteristics as miniature unventilated stacks. In a 1 m^3 box, Burton (1989) notes that a ready convective air movement will maintain a maximum potato temperature within 1 °C of the average ambient temperature, and the minimum temperature a little different from average ambient temperature. Burton (1989) suggests that the boxes can be stack onto each other to a height only limited by the height of the building and safety considerations. The expected potato temperatures will be the same as those in a single stack of boxes. This could hold true if the gaps and clearances between the boxes are big enough such that each box behaves as a different thermal entity, otherwise this unlimited stacking will result in a large box whose increased height will increase resistance to airflow and heat removal thus cause overheating and mechanical damage (Abrams, 1984; Burton *et al.* 1955; Burton, 1963). The stacking of many boxes on top of each other is only possible in mechanised large storage. There is need to design boxes that can be used alone but large enough to take up to two tonnes of potatoes. Manual handling (stacking of boxes and loading of the potatoes) limits the use of more than one small box (<1 m high) on top of another. More experiments and mathematical modelling (using different potato stacks) are necessary to confirm whether the potato temperature is actually about the same as the ambient temperature in the tropics in line with what Burton *et al.* (1955) found in the temperate climates.

A successful storage process should be preceded with inspection (to remove rots, soil clods and other foreign materials), grading (where necessary) and curing the potatoes at 10-20 °C and 75-98% relative humidity to enhance wound healing and periderm formation in a process called suberization (Burton, 1989). If diseases such as skin spot are a problem, Burton (1989) recommends curing at 50% relative humidity. The storage system should ensure protection against the sun, rain, and external heat (frost or high temperature injury); minimize weight (moisture) loss, chemical changes, disease incidence and sprout growth; and enhance respiration heat and carbon dioxide removal. Potatoes exposed to direct or indirect sunlight will turn green (a process termed greening), becoming bitter in taste and poisonous thus rendering them unsuitable for human consumption. The main changes in composition during storage which are undesirable in culinary potatoes are sweetening and loss of ascorbic acid (Burton, 1963 and 1973). Water loss and peeling loss may be minimized by adequate suberization followed by maintaining a low water vapour pressure deficit in the air around the tubers and prevention of sprout growth. Restricted ventilation enhances self humidification of the bulk of potatoes accompanied with evaporation or condensation depending on the temperatures; increase in respiration heat and carbon dioxide accumulation which would raise the storage temperature and stimulate earlier break of dormancy respectively (Burton, 1963). If the relative humidity of the air surrounding potatoes falls below 90%, moisture will move from the tubers causing wrinkling and weight loss (Smith, 1977b; Villa and Bakker-Arkema, 1974; Villa, 1973; Sparks, 1973; Lerew, 1978; Iratani *et al.* 1977). A 5% weight loss affects quality while a 10% loss makes a potato unmarketable (Butcherbaker *et al.* 1973; Sparks and Summers, 1974).

Potatoes freeze at -1 °C (but the minimum safe storage temperature for long periods should be more than 2 °C) and break down at 35 C (but the maximum storage temperature should be 30 °C) (Burton, 1989). They require a high relative humidity, above 75%, to maintain a low vapour pressure deficit and prevent wilting and excessive weight loss. These limits are for the survival of potatoes not for fitness of use and storage. The climate in the tropics presents problems of high temperature; some areas having ambient temperatures approaching the upper potato limit and low humidity. However, at altitudes above 1850 m above sea level, where the mean minimum temperature is between 11 °C and 12.5 °C and the relative humidity is 90%, the climate is suitable for potato storage up to three months using simple storage systems such as the naturally ventilated box in a corner of multipurpose or potato store or dwelling house (Booth and Rhodes, 1989; Hunt, 1987).

Other requirements of effective free ventilation potato storage include selection of an appropriate stack and box size with sufficient openings at the bottom (false floor). From the above review of stacks and boxes, the optimal sizes are not clear but there are indications that size has an influence on the resulting temperature and therefore on the effectiveness of the system.

2.2 Properties of Air-Potato Porous Medium

The terms bulk or a pile or stack or heap of potatoes are used to refer to a number of tubers put together. A bulk of potatoes is considered a porous medium consisting of potatoes as the 'solids' and air as the fluid. The environmental, physical and thermal properties of the storage system that affect the potato temperature include time of storage, ambient and store or room temperature and air-potato porous medium properties such as size and density of potatoes; energy and moisture release and transfer with or without evaporation or condensation on the tuber and bulk surfaces. Specific tuber physical and thermal properties such as tuber dimensions, density and void ratio, moisture and weight loss vary with variety of potatoes and type and conditions of storage.

Most of the potato properties can be determined in the laboratory using standard procedures as in ASAE (1995) and Mohsenin (1970 and 1980) but some have no clear standards while a number can be predicted using established empirical and statistical models and expressions. Many reviews of potato properties exist including Smith (1977b), Burton (1989), Lerew (1978), Brugger (1979) Schippers (1971a; b), Bergh and

Lentz (1971) and Nyaanga (1991) while those for air properties include Bejan (1993) and Meyhew and Rogers (1970). Some of the important characteristics and properties of the bulk of potatoes and tubers are reviewed and discussed with reference to their influence on the bulk air-potato temperature.

2.2.1 Environmental Factors and Air Properties

The prevailing environmental conditions of ambient air flow, time (of storage), and the air properties such as temperature, relative humidity, velocity and inherent properties such as specific heat and thermal conductivity, have a great influence on the resulting temperature in a bulk of potatoes during storage. Some of these factors are discussed in this section while others are reviewed under other subsections of section 2.2 since these parameters are affecting an air-potato medium rather than the individual constituents of the medium.

The air properties are in turn determined by the climatic conditions of the locality and season of the year. Most of the ambient air properties do not vary widely and can be obtained from psychrometric tables and models and literature such as Brooker (1967, 1969) and Bejan (1993). The density of air decreases with an increase in temperature between 1.284 and 1.086 kg m^{-3} at 2 °C and 52 °C respectively, being about 1.177 kg m^{-3} at normal room temperature of 22 °C at atmospheric pressure. The specific heat of air varies slightly from 1.0038 to 1.0063 kJ kg^{-1} K^{-1} with temperatures varying from 2 °C to 50 °C at atmospheric pressure respectively with a value of 1.0049 kJ kg^{-1} K^{-1} at around normal room temperature of 22 °C both at constant pressure. The thermal conductivity of air varies slightly with the ambient temperature being 2.428 kW m^{-1} K^{-1} and 2.624 kW m^{-1} K^{-1} at about 0° C at 20° C at atmospheric pressure respectively (Brooker, 1967; Meyhew and Rogers, 1970; Bejan, 1993).

The properties of the storage air (store and 'pore' within bulk of tubers) are mainly a function of the potato-air storage environment principally determined by the building or store and the environmental control processes that may be applied. The air entering the bulk has different properties to those of the air within the bulk and since the rate of air movement through the bulk of potatoes is different due to the resistance to airflow, the temperature within the bulk will vary from one point to another both vertically and laterally with the former being more prominent (Burton *et al.* 1955; Burfoot *et al.* 1996a; Nyaanga, 1991).

Almost all forms of potato deterioration during storage are a function of time. The magnitude and rate of deterioration increases with the length of the storage time. Potatoes have a particular time span of dormancy during which the tuber activities of respiration are greatly reduced. After this period of dormancy the tuber metabolic processes are accompanied with greater moisture and heat losses especially after the potatoes start sprouting. The length of the storage period of ware potatoes is governed by the storage conditions and therefore the type of storage; store management and required quality of the potatoes. In most cases time determines the suitability of the storage system since long term storage with minimum loss in quality and quantity are the ultimate aims of storage.

However, most temperature predictions in naturally ventilated storage have often ignored the time factor. For instance Burton *et al.* (1955) and Nyaanga (1991) have given expressions for the determination of the potato temperature in this type of storage without the variation of time of storage. Burton *et al.* (1955) never gave any indication of the stage of storage when the expression was derived while Nyaanga (1991) derived the relation just after dormancy (six weeks of storage under tropical conditions). It is not clear whether these relationships can be used at any stage of storage or not hence the need for further research.

The rate of air flow through a bulk of potatoes is mainly a function of the temperature within the bulk, air density and buoyant acceleration as governed by the gravitational field strength and the thermal coefficient of expansion (Bejan, 1993; Greenkorn, 1983; ASHRAE, 1989). Although the temperature difference in small stacks of potatoes is not likely to be large, the air density difference created is sufficient to cause airflow and this will contribute to the distribution of the temperature throughout the stack.

2.2.2 Physical Properties of Potato Stacks and Tubers

The physical characteristics of potato stacks and tuber properties reviewed in this section include stack and tuber dimensions, surface area, density, voids ratio, and angle of repose with reference to their effect on heat and mass transfer and their eventual influence on the distribution of the potato temperature. Once potatoes are heaped together, they occupy space whose dimensions can be measured as length, width and height. These dimensions determine the volume enclosed and hence the amount of total heat that will be released by the stack. In practice the height of a potato stack has a much greater effect on its temperature than do its lateral dimensions. Nyaanga (1991) using boxes, found significant temperature differentials in the bottom-top direction unlike in the lateral plane confirming Burton *et al.* (1955)'s suggestion that natural convection flow is mainly from the bottom to the top. Under natural convective ventilation, Burton (1963) recommends a height of 2.0 m and 1.3 m for cool and warm climates respectively in order to minimize temperature differentials. With forced ventilation coupled with refrigeration, a pile depth of 3.5 m to 4.0 m is recommended as suitable with respect to safety against mechanical damage (Abrams, 1984). The walls of the store should be at least 1 m higher than the height of the pile to avoid adverse outside temperature influence (Jones, 1965; Cargill, 1989 and ASAE, 1989). Most of these height recommendations are made assuming the magnitudes of length and breadth have no significant influence on the system's thermal properties. But this assumption may not be correct.

The volume occupied by a tonne of potatoes varies with the amount of soil, size and shape of tubers, but averages 1.5 m^3 per tonne for reasonably clean tubers (Burton, 1989). The actual volume of potato tissue varies with the specific gravity of the tubers and thus depends upon their content of dry matter and is on average 0.92 m^3 per tonne. The difference between this and the volume occupied represents the volume occupied by the air, often termed porosity or voids volume which is 0.58 m^3 per tonne (38.6% voids ratio or fraction) but varies between 0.4 m^3 per tonne and 0.6 m^3 per tonne (Burton, 1989). The quantity of potatoes in any storage will determine the amount of heat generated and hence the potato temperature while the amount of air spaces will influence the rate of airflow. The volume of voids varies with the tuber dimensions (geometric mean diameter), shape; amount of soil and other foreign material in the bulk. Therefore, these two will affect the rate and amount of cooling or heating in the bulk and thus the potato temperature. Table 2.1 gives values of the potato densities and void ratios. The ratio of the volume of voids to total volume of the storage system is the bulk or bed void fraction, ε which is calculated from ratio of bulk (b) and tuber (t) densities as in equation (1).

Table 2.1 Potato densities (kgm^{-3}) and void ratios

Bulk density (ρ_b)	void ratio (ε)	Tuber density (ρ_t		Source
		Measured	Calculated	
597-603	0.43	-	1388-1402	Rao *et al.* (1975)
623	0.43	-	1448.8	Rice (1974)
714	-	-	-	Burton (1972)
650	0.40-0.45	-	1625-1444	Shirokov (1968)
625-667	0.38-0.47	-	1645-1419	Burton (1989)
700	0.33	-	2121.2	Ophius (1957)
593	-	-	-	Burton *et al.* (1955)
603-510	0.39-0.41	1096-1107	1546-1243	Nyaanga *et al.* (1994b)*

*the first and the last values in each column are for freshly harvested potatoes and after 11 weeks of storage respectively.

$$\varepsilon=\frac{\rho_b}{\rho_t} \tag{1}$$

where ε is the voids ratio

ρ_b is the bulk density of potatoes

ρ_t is the tuber potato density

The average bulk density, as per the cited sources, is 625.9 kgm^{-3} at an average voids ratio of 0.41 while the measured and calculated tuber densities 1101.5 kgm^{-3} and 1528.4 kgm^{-3} respectively hence the average tuber density can be taken to be 1315 kgm^{-3} implying that the measured bulk density is 639 kgm^{-3}. The overall average (calculated and measured) bulk density of potatoes is therefore 634 kgm^{-3}.

The surface area of air entry into a bulk of potatoes has a direct bearing on the amount of cooling or warming that occurs. The ratio of the surface area to the volume is an important design consideration of a store, stack or box potatoes since it affects the level of heat transfer. The shape with the most favourable ratio is the sphere but the most practical shape is the cube (Booth and Rhodes, 1989).

The tuber dimensions determine the surface area over which metabolic heat is released and heat and mass exchange takes place. Marvin *et al.* (1987) assuming the potato tuber as a prolate spheroid developed an expression for the surface area as function of the three dimensions (major, first- and second-minor diameters) of the tuber. Villa (1973) found their relationship inadequate and instead developed a relationship between the surface area (*A*) and mass (*W*) using one variety. Bergh and Lentz (1971) using data from five varieties developed a similar relationship as below:

$$A = 3.6x10^{-4} W^{0.713} \tag{2}$$

Burton (1989) has given the surface area of an individual tuber as varying between 6.5x10^{-3} m^2 for a 0.05 kg to 2.9x10^{-2} m^2 for a 0.5 kg tuber while the Berg and Lentz (1971) equation (2) would give 4.3x10^{-5} and 2.2x10^{-4} m^2 for the two sized tubers respectively. The area of contact between one tuber and the other once the tubers are bulked together is difficult to estimate but Burton (1989) gives a figure of about 75% as the exposed area for average sized tubers (0.2 kg). The total surface area in a unit volume (V) of storage is referred to as the specific surface area (a) and can be calculated by (Schumann, 1929):

$$a = \frac{(1-\varepsilon)A}{V} \tag{3}$$

where a is the specific surface area
V is the volume,
A is the total surface area, and
ε is the voids ratio.

If potatoes are heaped together without any retaining walls, the sides of the heap slope upwards at an angle (angle of repose) which depends on the size and shape of the tubers and amount of adherent earth, but lies between 30° and 40°, usually in the upper half of this range (Burton, 1989). The heap takes the form of a shallow cone, with the diameter of the base being about three times the height implying an angle of repose of 33.7°. If the potatoes are confined, they exert pressure on the walls of about 1.567 kN m^{-2} per metre height of stack at the base of walls (Burton, 1989 and Yaeger *et al.* 1987). But if potatoes are not confined, they will spread and reduce the height of stack hence affecting the shape and the surface area over which heat and mass exchange with the surrounding will occur and therefore influence the temperature variation/distribution in the stack.

All these stack properties such as bulk dimensions, volume, density, voids ratio and surface area affect the bulk potato temperature in one way or another.

2.2.3 Moisture Release and Weight Loss

One of the by-products of respiration is moisture whose release will depend on the age of the tuber, moisture content and condition of the periderm and the surrounding environment in terms of vapour pressure deficit between the air and the tuber and relative humidity. The moisture content of the tuber also affects its other physical and thermal properties although it is doubtful if this effect is significant (Mohsenin, 1970 and 1980). The average moisture content of potatoes from published values (as given in tables 2.2 and 2.3) has been computed to be 79%.

The rate of moisture loss from a bulk of potatoes has an effect on the rate of weight loss. The rate of weight loss has been reported by various researchers (Sparks, 1965, 1973; Schaper and Hudson, 1971; Ophius, 1957; Schippers, 1971a, b; Singh *et al.,* 1974; Burton, 1982b; Brugger, 1979; Fockens and Meffert, 1972; Schippers, 1971b; Iritani *et al.* 1977; Butcherbaker *et al.* 1973; Lerew, 1978; Nyaanga, 1991; Villa and Bakker-Arkema, 1974; Pratt and Buelow, 1978) as being dependant on the degree of sprouting; temperature; relative humidity; air velocity; variety and age of potatoes; length of time in storage; and vapour pressure deficit. Misener and Shove (1976b) have expressed moisture loss as a function of the voids ratio and density of the potatoes, the vapour pressure deficit and the time of storage with a regression as:

$$\frac{-m}{(1-\varepsilon)\rho_b} = 1.896x10^{-5}(vpd)^{-0.59}t^{-0.35} \qquad (4)$$

where m is moisture loss,

ρ_b is the bulk density of potatoes,

vpd is vapour pressure deficit, and

t is time.

ε is voids ratio

Misener and Shove (1976b) also measured weight loss from individual tubers under free convection at temperatures of 4.5, 15.5 and 28.4 °C and relative humidities ranging from 11.9 to 98.4%. Brugger (1979) found that weight loss drops from about $5.5x10^{-5}$ $kgkg^{-1}h^{-1}$ to a constant rate of about $1x10^{-5}$ $kgkg^{-1}h^{-1}$ within the first 2-3 weeks of storage under forced ventilation. Nyaanga *et al.* (1994b) found an accumulative weight loss of 10.6% at the end of 11 weeks of uncontrolled storage at room temperatures of about 20 °C.

Hylmo *et al.* (1978) have reported settling rates of 13 to 16 and 19 to 28 mm per month per m of pile height for low and high ventilation rates respectively. The major weight loss is caused by the inherent water loss and accompanying evaporation while respiration contributes about 0.12% in the first month after harvest, falling to 0.08% per month during most of the storage period (Burton, 1978 and Burton, 1982b). The percent dry matter (*dm*) of potatoes has generally been correlated with specific gravity (*sg*) as (Scheele *et al.* 1937):

$$dm = 24.18 + 211.04(sg - 1.099) \qquad (5)$$

with the variation of the constants being ±0.035 and ±3.3 respectively with an R^2 of 0.974.

Simmonds (1977) has found a similar relationship although with different coefficients. The initial moisture content (wet basis) of potatoes is found by subtracting percent dry matter from 100 and making moisture content (*mc*) the function of the equation (5) thus yielding:

$$mc = 75.82 - 111.04(sg - 1.099) \qquad (6)$$

Meigh *et al.* (1973) reported that 20 to 30 substances in addition to CO_2 are produced by potatoes at rates of the order of 10^{-9} $gkg^{-1}h^{-1}$ at 10 °C and concluded that this was negligible compared to the minimum rate of moisture release of 7.5×10^{-5} $gkg^{-1}h^{-1}$ per Pa vpd at the same temperature and vapour pressure difference (vpd). In general, total weight loss of components other than water amounts to less than 1% even after prolonged storage (Singh and Mathur, 1938; Burton, 1989; Smith 1977b).

The rate and amount of evaporative cooling depend on the amount of moisture evaporated, vapour pressure difference, surface area and temperature difference. If convection is accompanied by evaporative cooling then the prevailing temperature may fall below the average ambient temperature. The exact depression of the storage temperature due to this phenomenon has not been quantified but is expected to vary with the amount of moisture released, the prevailing relative humidities and hence the vapour pressure deficit, and the surrounding temperatures among other factors. Therefore, moisture release and loss (often indicated by weight loss) and the subsequent evaporation and/or condensation can be said to be directly and indirectly related to the temperature of the potato.

2.2.4 Thermal Properties of Potatoes

The thermal properties of potatoes reviewed here include specific heat, thermal conductivity and heat transfer coefficient. Several researchers have published values of these properties of potatoes as being dependent on moisture content.

Lerew (1978) expressed specific heat of tuber (c_p) as the sum of mass fraction of water (m_w) times its specific heat (c_w) plus mass fraction of dry matter (m_s) times its specific heat capacity (c_s).

$$c_p = c_w m_w + c_s m_s \tag{7}$$

where c_p is specific heat of tuber, kJkg^{-1} K^{-1}

m_w is mass fraction of water, percent

c_w specific heat, kJkg^{-1} K^{-1}

m_s is mass fraction of dry matter, percent

c_s is specific heat of dry matter, kJkg^{-1} K^{-1}

Yamada (1970) measured the variation of specific heat (c_p) with moisture content (m_s) and expressed it in two linear equations for moisture contents between 20% and 50% and another for more than 50% (wb). The latter, applicable to potatoes, is:

$$c_p = 904.3 + 3265 m_s \tag{8}$$

where c_p is specific heat of tuber, kJkg^{-1} K^{-1}

m_s is mass fraction of dry matter, percent

Table 2.2 compares the values published by various researchers with values calculated using Yamada's equation (equation 8).

Table 2.2 Specific heat capacity of potatoes

Moisture content (mass fraction)	Specific heat (kJkg^{-1} K^{-1})		Source of Literature Value
	Yamada's Equation Value	Literature Value	
0.79	3.48	3.52	Heldman (1977)
0.73-0.836*	3.29-3.63	3.50-3.75	Zak & Schauer (1976)
0.75	3.35	3.51	Charm (1971)
0.81	3.55	3.55	Lutz & Hardenburg (1968)
0.79 *	3.48	3.56	Shikorov (1968)
0.73-0.836*	3.29-3.63	3.42-3.78	Burton *et al.* (1955)
0.80	3.52	3.60	Burton (1989)
0.73-0.76	-	-	Nyaanga (1994b)

*Minimum, average and maximum moisture contents were adopted to enable computation of c_p using equation 8.

The average specific heat can therefore be taken as 3.48 kJkg^{-1} K^{-1} for a tuber with 79% moisture content. The specific heat of the potatoes, air and the porous medium determines the amount of heat transfer and therefore has a direct influence on the porous medium temperature.

Yamada (1970) using the analysis of unsteady state heat conduction and considering a potato tuber as sphere, reported a scattering of thermal conductivity values with changing moisture content but found no direct correlation. Rao *et al.* (1975) suggested that thermal conductivity varied with both moisture content and density. There is no sufficient expression of thermal conductivity from the suggested variables. Various values of thermal conductivity have been reported as in table 2.3.

Table 2.3 Thermal conductivity values of potatoes

Moisture content % wet basis	Thermal conductivity ($Wm^{-1}K^{-1}$)	Source
76.0	1.746	Yamada (1970)
81.2 - 83.6	1.919 - 2.056	Rao, et al (1975)
81.5	1.994	Heldman (1977)
-	2.135 - 2.261	Gromov and Krasovskaya (1967)

From these values it is true that the thermal conductivity is higher in potatoes with high moisture contents but the average thermal conductivity of potatoes can be taken as 2.09 $kJ\ h^{-1}m^{-1}K^{-1}$ at an average moisture content of 80.6%. The rate of heat exchange is directly related to the thermal conductivity of the system (being affected by that of the potatoes and the air) and therefore has a great influence on the temperature of the potatoes (potato-air medium).

Several studies on convective heat transfer coefficient for potato tubers or packed beds have been conducted and expressions proposed by Clary and Nelson (1970), Ophius, (1957) Watson and Staley (1963), Bird *et al.* (1960) and Hunter (1976). From the Colburn J_H formula of Bird *et al.* (1960), convective heat transfer coefficient (h) can be

$$h = \frac{J_H \rho_a c_a v}{Pr^{2/3}} \tag{9}$$

expressed as:

for $Re < 50$, $J_H = 0.91 Re^{-0.51}$ and for $Re > 50$, $J_H = 0.61\ Re^{-0.41}$

where

$$Pr = \frac{c_a \mu_a}{k_a} \qquad (10)$$

$$Re = \frac{\rho_a v l}{\mu_a} \qquad (11)$$

where ρ_a is the density of air,

Re is the Reynolds number,

Pr is the Prandtl number,

l is the characteristic length

c_a is the specific heat capacity of air

μ_a is the dynamic viscosity of air, and

v is the velocity.

K_a is the thermal conductivity

Brugger (1979) used Colburn J_h formula of Bird *et al.* (1960) and Hunter (1976) relationships to produce a graph of the coefficient of convective heat transfer as a function of superficial air velocities ranging between 30 m h^{-1} and 500 m h^{-1}. Since there are no values for this coefficient for natural convection (flows approaching zero) extrapolating the Brugger (1979) curve to zero gives 0.8 $Jh^{-1}m^{-2}K^{-1}$ and 0.6 $Jh^{-1}m^{-2}K^{-1}$ from the Bird *et al.* (1960) and Hunter (1976) curves respectively.

2.2.5 Heat Exchange and Temperature Distribution

Potatoes respire and release heat energy termed heat of respiration or metabolism. The heat of respiration depends on the age of potatoes, the stage of storage and tends to be higher when the potatoes sprout and temperatures are high (Boe *et al.* 1974; Burton *et al.* 1955 and Burton, 1982b). The rate of heat generation by tubers is measured directly or indirectly by conversion from the rate of CO_2 production using a factor of 12.1 mg CO_2

$\mathrm{kg}^{-1}\mathrm{h}^{-1}$ as being equivalent to 1 $\mathrm{Jkg}^{-1}\mathrm{h}^{-1}$ (Bergh and Lentz, 1972). However, few researchers have attempted to develop a mathematical expression for this heat generation. Brugger (1979) attributes this partly to the difficult shape of the respiration curve (Grahs *et al.* 1978) which shows a decay decrease from 50 to 30 $\mathrm{Jkg}^{-1}\mathrm{h}^{-1}$ between 0 and 3-4 °C before increasing exponentially to above 70 $\mathrm{Jkg}^{-1}\mathrm{h}^{-1}$ as the temperature approaches 15 °C. Burton (1955) reported values of 251.2 $\mathrm{Jkg}^{-1}\mathrm{h}^{-1}$ for freshly harvested immature tubers, 167.5 $\mathrm{Jkg}^{-1}\mathrm{h}^{-1}$ for mature fresh potatoes and 41.9 $\mathrm{Jkg}^{-1}\mathrm{h}^{-1}$ for tubers under refrigeration. Boe *et al.* (1974) developed a fifth degree regression polynomial to predict respiration rates and published only the resulting curves without the coefficients. Misener and Shove (1976a) and Lerew (1978) give the respiration rate (q_r) as:

$$q_r = 6.99T_p - k \qquad (12)$$

where q_r is the respiration rate in $\mathrm{Jkg}^{-1}\mathrm{h}^{-1}$

T_p is the potato temperature in °C

k is a constant representing the rate at 0 °C, which has been given to be 17.7 and 12.5 by Misener and Shove (1976a) and Lerew (1978), respectively .

A pile of potatoes produces sensible metabolic heat which raises the temperature of the air within the pore spaces of the tubers. Convection currents so created, force the heated, less dense air out of the pile and replaces it with an equal volume of cooler, denser air. The more the temperature rises the faster the air movement. If the convection so activated removes the heat as rapidly as it is generated, there would be no rise of the potato temperature and the potato would be in a state of dynamic equilibrium with the surrounding temperature. The establishment of a dynamic equilibrium assumes that the production of metabolic heat does not outstrip the ability of natural convection to catch up with it and evaporative cooling is negligible. But if heat generation outstrips loss by convection, then overheating is imminent. Burton *et al.* (1955) have expressed this as being the case when:

$$\left(\frac{T_D+1}{T_D}\right)^{1.55}=\left(\frac{Q_r+\delta Q_r}{Q_r}\right) \tag{13}$$

where T_D is the temperature difference between the potatoes and the ambient, K
Q is the metabolic heat production before the rise in temperature T_D+1, and
δQ is the increase in heat production caused by 1 °C rise in temperature.

The convectional heat loss due to thermal and mass effects in buildings due to infiltration (random and unintentional air exchange) has been given by Porges (1995) as:

$$Q_v=c\rho NV\Delta T \tag{14}$$

where c is the specific heat of air
ρ is the density of air
N is the number of air changes
V is the volume of room
ΔT is the temperature difference between the inside and outside

The number of air changes per hour (N) of conventional structures varies with prevailing environmental conditions but it averages 1 and 6 for stores and human living rooms respectively (Awbi, 1991; Porges, 1995).

During natural dormancy, physiological activity is lower and the induced ventilation is also low. The distribution of the heat energy will be indicated by the temperature differentials within the bulk of potatoes and its environment.

The potato temperature tends to follow fluctuations in store temperature but with minimised magnitudes due to the thermal inertia of the potatoes which dampens down the response to the external temperature changes. Therefore, the potato temperature does not follow rapid and wide diurnal variations. It does however, follow the trend of the average daily temperature fairly closely though again with a dampened response (Burton, 1989). The exact closeness and quantification of this trend could not be found in the literature reviewed.

Temperature differentials varying in all any of the three axes in a box or store of potatoes have been shown to exist in forced convective ventilation and controlled storage conditions by a number of researchers including Butcherbaker *et al.* (1967), Rice (1974), Bakker-Arkema and Lerew (1974), Misener (1973), Misener and Shove (1976a), Burfoot and Xu (1997) and Burfoot *et al.* (1996a) using both experimental and theoretical approaches. Rice (1974) notes that there is no satisfactory theoretical basis for free convection heat transfer and therefore, results from physical experiments are commonly used to predict the temperature.

Burton *et al.* (1955) found that using natural convection ventilation, the temperature of a large stack of potatoes settled down at an average of the ambient night and day temperatures in the temperate climate. When air entry was allowed into an insulated stack only at night, the potato temperature became 1 °C to 2 °C below the average ambient temperature. The dimensions of the stack were not reported (Burton, 1982a). Nyaanga (1991) found a similar trend where the potato temperature settled at 1 °C to 1.2 °C below the average ambient temperature and 1.7 °C to 1.9 °C below the average store temperature when the potatoes were stored in slender boxes (small stacks with lateral dimensions of 0.4 m by 0.4 m and the height varying between 0.6 m and 2.0 m) in a mudwalled-ironsheet roof structure in Nairobi, Kenya.

The temperature differentials in natural convective ventilation may be decreased by reducing the height of the pile or by decreasing the base dimensions of the pile so as to create a faster chimney (stack or thermal buoyancy) effect (Brockett and Albright, 1987; Bruce 1978 and 1982). Placing pans of water or water soaked charcoal or sacks in the path of the ventilating air can increase the air moisture content during dry conditions and consequently lower the temperature and increase the relative humidity thus reduce moisture and weight loss (Burton, 1982a).

The entry of heat into the potato store through the roof and walls tends to increase the storage temperature and should therefore, be reduced by using good insulating materials such as thatch, earth or air-cavity walls in warm climates. An overall heat transfer coefficient of 1.0 Wm^{-2} per° C for walls and 0.5 Wm^{-2} per° C for roofs have been recommended (Burton, 1982a; Jones, 1965; ASAE, 1989). In very hot places, with temperatures above 25 °C, 50% more insulation should be added to the roof (Booth and Rhodes, 1989).

The air enters the stack saturated at ambient/store/room temperature and leaves it saturated at exit/top temperature. Burton (1989) suggests that in large commercial stacks with negligible conductive heat loss through the sides (and hence in boxes with solid walls), free convection is mainly from the bottom to the top. Occasionally, this flow is reversed if the surrounding temperature rises above that of the potatoes. This is the main reason why the convectional currents and temperature distribution patterns are not as simple as above in heaps and stacks of potatoes under free convection.

The rate of free convection depends on the rate of heat production by the potatoes, the height of the stack and the amount of air voids in the bulk. Burton *et al.* (1955) found an average overall rate of convection to be 6-8 m^3h^{-1} per tonne. The average rate consists of higher rates in regions of low resistance at the entry and exit, and lower rates with a higher temperature difference in the centre of large commercial stacks or at a distance three quarters from the entry in small storage boxes (Burton *et al.* 1955; Nyaanga, 1991). At the periphery or entry and exit, the temperature of the top potatoes differs little from store temperature. Every m^3 of air (about 1.25 kg) which leaves the stack at a temperature 1 °C above that at which it entered, removes about 1.25 kJ of heat and 0.5-0.6 g of water vapour by evaporation (Burton, 1989) thus, cooling the potatoes. Taking latent heat of evaporation of water at potato storage temperatures (10-20°) as 2.49 kJg^{-1}, Burton (1989), estimates that evaporative cooling removes 1.25-1.5 kJm^{-3} for every °C rise and together with the direct removal of about 1.25 kJ this gives a total of about 2.5-2.75 kJm^{-3} per °C rise.

The resistance to air flow varies considerably because of varying tuber sizes and hence voids, amounts of adherent soil, and absence or presence of sprouts. The general equation for airflow through a potato stack has been modelled after the Henderson and Perry (1980) expression for flow through porous materials by equating the pressure activating flow (P) to the product of approach velocity raised to an index (n), the height of the stack (z) and a coefficient of resistance to airflow (k). Using an index of 1.8 as has been used by Burton *et al.* (1955) and which is within the range found by Neale and Messer (1976), the coefficient of resistance to air flow can be expressed as:

$$k = \frac{P}{zv^{1.8}} \tag{15}$$

where P is the pressure activating flow (equivalent to the resistance to flow), kPa or mm of water

z is the height of the stack (proportional to the length of flow path)

v is the velocity of airflow in mh^{-1}

k is the coefficient of resistance of potatoes to airflow.

If P is in kPa or mm water and v in mh^{-1}, k for clean potatoes, derived from the results of Ophius (1957) has been calculated by Burton (1989) to be 5.4×10^{-7} or 5.5×10^{-5} respectively.

Evidently, many variables affect the bulk potato temperature during free natural ventilation storage. Complete and accurate quantification is a difficult exercise. The use of published and experimental data in mathematical models and computer simulations does reduce this difficulty and hence the current study to predict the potato temperature by use of both theoretical and experimental models.

2.3 Mathematical Modelling

Mathematical modelling of any system involves the formulation of mathematical equations that adequately describe its physical setup into which known inputs (independent variables) are cast and by use of computational techniques outputs (dependent parameters) are achieved upon which decisions on system design and control are based. An ideal mathematical model should:

- Have a sound mathematical and physical basis
- Not have limitations with regard to the geometry, shape and physical composition of the domain
- Be easy to input parameters which describe the required conditions (environment); have ability to handle transient and buoyant conditions
- Have sufficient accuracy; flexible enough to allow the choosing of a desired degree of approximation without reformulating the entire problem
- Involve a systematic procedure that can be automated for use on digital computers (Brugger, 1979; Reddy, 1984; Smith, 1977a)

The two main classes of the very simple empirical models of low precision and the precise dynamic theoretical models have their own limitations. While the very simple are not precise, the precise dynamic ones are unsuitable for use over long periods and are too complex to be of much practical use outside the developed world research and academic institutions. The solution of the equations for energy, mass and momentum transfer in three dimensions through a bulk of stored potatoes is extremely cumbersome (Brugger, 1979). The simplification of the problem to one dimension (Misener, 1973; Hunter, 1978; Lerew, 1978) has been found to be sufficient in describing the temperature and air flow distribution throughout a potato pile. Though this is often not the case (Schaper *et al.* 1976), the one-dimensional model does permit a study of the temperature and airflow through the pile in a direction that is parallel to the direction of airflow.

The steps involved in the development of a mathematical model include making appropriate assumptions, setting up the necessary mathematical formulation and settting procedures of solving the resulting equations.

2.3.1 Importance of Theoretical Modelling

System simulation may arise from one or a combination of the following (Smith, 1977a):

- The need to conduct a low cost study or design of a system whose complex nature precludes development in a laboratory or field experiment or as a scale model
- To verify that a system of mathematical modelling equations which are to be used in a control system is valid or to gain insight into the system
- To forecast the response of a system to complex controls or policies as a means of evaluating the consequences of control, design or policy alternatives

The main stages in modelling problems in real world engineering include:

1. Formulating real model, that is, describing the system in physical terms
2. making appropriate assumptions about the system hence inputs for the model
3. Formulating a mathematical problem/model for the system
4. Solving the mathematical problem and getting outputs
5. Interpreting the solution, that is, simulated outputs
6. Validating the model by its agreement with physical observations
7. Using the model to explain, predict, decide or design a better system (Smith, 1977a)

Items 1, 6 and 7 refer to the physical (real) world; 2 and 5 involve the interpretation while 3 and 4 involve the physics or mathematics of the problem. This comprises the simulation design process. The model is validated by ensuring that the theoretical simulations are in good agreement with observations from the real situation (experiments). The seven stages can be summarised in four, as:

1. Formulation - the expression of the problem in mathematical language based on the appropriate physical laws governing the process

2. Solution - appropriate mathematical operations are accomplished so that logical deductions may be drawn from the mathematical model
3. Interpretation - the development of relations between the mathematical results (simulations) and their meaning in the physical world
4. Refinement - the recycling of the procedure to obtain better predictions as indicated by experimental checks (Smith, 1977a; Zienkiewicz, 1991; Reddy, 1984)

The formulation step often results in algebraic or difference or differential or integral equations or a combination of these after the pertinent variables have been identified and the relationships between them postulated. These mathematical models always arise from statements of physical laws such as the law of mass, momentum and energy conservation. Many general laws are expressed by differential equations. Specific phenomena are then singled out from the infinity of solutions of these equations by assigning the individual boundary or initial conditions which characterise the given problem such as a boundary value for equilibrium or propagation problems respectively. The solution must satisfy the initial conditions plus any 'side' boundary conditions. The problem is described physically (dimensions, observations and what needs to be predicted) and by suitable mathematical equations after making a number of simplifying assumptions which must be as appropriate to reality (boundary conditions) as possible (Smith, 1977a). These would be considered dynamic models while those developed from experimental data and statistical analysis are termed empirical models (Williams, 1997; Lipson and Seth, 1973).

Theoretical models often use laws of conservation of mass, momentum and energy. They are all expressed as functions of time; in one-, two- or three- dimensions and therefore as partial differential equations. The resulting equations are simplified by appropriate and accurate assumptions by applying exact boundary conditions and appropriate solution techniques and solved by numerical methods since analytical methods are limited due to their nonlinearity (Reddy, 1984; Brooker, 1961; Zienkiewicz, 1991; Dorn and McCracken, 1972; Cook, 1981). The most common approach used is the Finite Element

Method (FEM) variational formulation and approximation.

Numerous processes involving actively respiring agricultural products have been described mainly in biological terms which are difficult to translate into mathematical expressions. However, mathematical models that have been applied in the study of potato storage environment may be classified into two groups, namely, fully theoretical or dynamic or mechanistic models and statistical correlations or empirical relationships or static models (Smith, 1977a; Williams, 1997). Most of the current dynamic models for the study of the potato storage environment have been based on commercial storage systems using forced ventilation often combined with artificial cooling. The use of these models in small free natural ventilation systems appears not to have been published. A combination of these dynamic and empirical model approaches with relevant experiments would reveal inherent characteristics and processes that may help reduce costs in energy and ways of maintaining lower bulk potato temperatures thus prolong storage life and retain quality.

A theoretical prediction works out consequences of a mathematical model, rather than those of an actual physical model. Simulation must conform to reality for it to be reliable. Therefore an ample understanding of the real situation by experiments is vital. The most reliable information about a physical process is often given by actual measurement. This can be done using full-scale or small-scale tests; but the former are prohibitively expensive and often impossible (Smith, 1977a; Holman and Gadja, 1984). The information from the small scale tests, however, must be extrapolated to full-scale, and general rules for doing this are often unavailable. Further, the scale models do not always simulate all features, thus reducing the usefulness of the results. Finally, there are serious difficulties of measurement in many situations, and instruments are not free from errors.

Brugger (1979) notes that recommendations from experimental results for controlled potato storage management vary widely; the major controversy being on the temperature and relative humidity that should be maintained during storage. The same should be true in the design and management of uncontrolled potato storage that could give the minimum absolute temperatures and temperature differentials in any stack. For instance, Nyaanga (1991) using small potato experimental piles, recommends slender tall boxes without any control of the ventilation while Burton *et al.* (1955) using large commercial stacks, recommend shallow short stacks with night ventilation only. Temperature variation in free naturally ventilated potato storage with position in the bulk and time have not been well documented nor is there any proven theoretical approach to predict it. This justifies the use of mathematical modelling in the prediction of the potato storage environment.

Brugger (1979), Gumbe (1987) and Patankar (1980) are among the researchers who agree that with the identification and quantification of all variables (such as airflows, sources of energy and water vapour in the current study) and the use of the laws of energy and mass conservation are crucial in the study of any system.

For the prediction of heat and hence temperature, the mathematical models consist of sets of differential equations. There is little hope of meaningful prediction by use of classical mathematics - the solutions often contain infinite series, special functions, transcendental equations for eigen-values, and so on, so that their numerical evaluation may present a formidable task (Smith, 1977a). Fortunately, the development of numerical methods such as the FEM and the availability of digital computers now can give implications of a mathematical model for almost any practical or engineering problem. One approach is to subdivide the domain into grids or control volumes and to make computations at discrete points at the grid points. Algebraic equations are formed and solved for the unknown parameters at these points. The simplification inherent in the use of algebraic equations rather than differential equations makes numerical methods so powerful and widely applicable (Reddy, 1984; Segerlind, 1976; Cook, 1981; Bajpai *et al.*1983; Zienkiewicz, 1991).

Aurelius (1926) and Schumann (1929) independently published the pioneering significant work on heat transfer through porous beds of solids. They used conservation equations on conditions of a uniform one dimensional air flow at a constant inlet temperature, uniform solid temperature and no thermal gradient in the solids. The final analytical solutions for the cooling or heating of the solids were:

$$\frac{\partial T}{\partial t} = -v_a \frac{\partial T}{\partial x} - \frac{h_a}{\rho_a \varepsilon c_a}(T - \theta) \qquad \textbf{(16)}$$

and

$$\frac{\partial \theta}{\partial t} = \frac{h_a}{\rho_t c_t (1 - \varepsilon)}(T - \theta) \qquad \textbf{(17)}$$

where T is the temperature of air (°C)

θ is the product temperature (°C)

h is the convective heat transfer coefficient ($Jh^{-1}m^{2}K^{-1}$)

ρ is the density (kgm^{-3})

ε is the voids fraction (percent)

subscript $_a$ is the dry air

$_t$ is the tuber

c is the specific heat, $Jkg^{-1}K^{-1}$

t is the time (h)

V is the velocity of air (mh^{-1})

Schumann (1929) expressed the solution in the form of modified Bessel function. These solutions account for only sensible heat and are exact for systems where thermal conductivity of the solid particles is large and their size small. They have been modified, extended and used in combination with other relationships to study flow through various porous media (materials and products) by various researchers and scientific writers such as Patankar *et al.* (1993), Greenkorn (1983), AEA (1996), Beukema (1980), Ergun (1952) and Lee (1986).

In free natural ventilation modelling is based on buoyancy effects which occur in any variable-density and gravitational field. Their importance increases with density gradient and may be characterized by the size of the Richardson number:

$$Ri = \frac{\Delta\rho}{\rho}\frac{gh}{u^2} \tag{18}$$

where $\Delta\rho$ is the density difference that occurs over a typical (usually vertical) length scale h in a flow of velocity u in a gravitational field g.

Significant buoyancy effects can occur if either $\Delta\rho/\rho$ is significant, as in small scale plumes, or if gh/u^2 is significant, as in large-scale geophysical flows (Cebeci and Bradshaw, 1988). The range of buoyant flows that occur in nature and engineering practice is large and has been extensively reviewed by Jaluria (1980).

2.3.2 Governing Equations

The governing equations used for the prediction of various parameters of the porous media including crop storage and potatoes in particular are outlined below. The individual differential equations express a certain conservation principle of laminar fluid flow and heat and mass transfer. Each equation employs a certain physical quantity as its dependent variable and implies that there must be a balance among various factors that influence the variable. The dependent variables are usually specific properties, that is, quantities expressed on a unit-mass basis for example specific enthalpy, velocity (momentum per unit mass). Temperature is often used as a dependent variable in most of these equations instead of specific internal energy or enthalpy (AEA, 1996; Patankar, 1980).

The basic set of governing equations called the Navier Stokes or transport equations include equations for conversation of mass (continuity) and momentum and, in a non-isothermal flow, energy.

The continuity equation is:

$$\frac{\partial\rho}{\partial t}+\nabla.(\rho U)=0 \tag{19}$$

where ρ is the density of fluid

U is the velocity tensor, the u, v, w of the fluid velocity

∇ is the divergence sign

t is the time

The momentum equation is:

$$\frac{\partial(\rho U)}{\partial t}+\nabla.(\rho UU)=\boldsymbol{B}+\nabla.\sigma \tag{20}$$

where σ is the stress tensor, expressed as:

$$\sigma=-\boldsymbol{p}\delta+(\zeta-\frac{2}{3}\mu)\nabla.U\delta+\mu(\nabla U+(\nabla T)=\frac{\partial \boldsymbol{p}}{\partial t} \tag{21}$$

where B is the body force,

ζ is the bulk viscosity,

p is the pressure,

μ is the molecular viscosity, and

λ is the thermal conductivity.

The energy equation is:

$$\frac{\partial\rho H}{\partial t}+\nabla(\rho UH)-\nabla.(\lambda\nabla T)=\frac{\partial p}{\partial t} \tag{22}$$

where T is the temperature

H is the total enthalpy, given in terms of the static (thermodynamic) enthalpy (h) by:

$$H=h+\frac{1}{2}U^2 \tag{23}$$

These equations represent the five transport equations in seven unknowns u, v, w, p, T, ρ, h. They are completed by adding two algebraic equations from thermodynamics, namely the equation state relating density to temperature and pressure and the constitutive equation relating static enthalpy to temperature and pressure. These equations and their modifications combined with additional scalar equations have been used in various forms and solved numerically including for the study of mass and heat flow through potatoes. The use of the above equations in the commercial Computational Fluid Dynamics (CFD) computer software coded CF3D (for preprocessing the input geometry, grid, sets of equations) and CFX4.4/5 (for solving the equations and post postprocessing the outputs) has been used to study heat and mass flow in potatoes (Burfoot *et al.* 1996a; Burfoot and Xu, 1997; Xu and Burfoot, 1997). These equations are integrated and discretised and solved by FEM techniques using appropriate boundary conditions.

2.3.3 Boundary Conditions

Boundary conditions are defined at the inlets into the control volume in terms of velocity, temperature and other system parameters. Velocity boundary conditions may be specified (as in the CFD-CFX code) by (AEA, 1996; Versteeg and Malalasekera, 1995):

$$A_iU+B_i\tau_i=C_i \tag{24}$$

where τ_i is the wall shear stress, often without slip i.e. constants $A_i = 1$, $B_i = 0$ and $C_i = 0$. If $B_i = 0$ and $C_i \neq 1$ a moving wall is defined while if $A_i = 0$, then the shear stress is specified.

with

$$\tau_i = (\mu \frac{\partial U_i}{\partial y})_w \tag{25}$$

Many of the variables vary rapidly in the near-wall regions of the flow and thus necessitating the use of extremely fine grids in these regions or additional wall functions called scalar conditions resulting in Neumann or Dirichlet boundary.

The boundary conditions for heat transfer can be specified in terms of temperature, as in the CFD code as (AEA, 1996; Versteeg and Malalasekera, 1995):

$$AT_w + BQ_w = C \tag{26}$$

with

$$Q_w = (\lambda_b \frac{\partial T}{\partial n})_w \tag{27}$$

where Q_w is heat flux at the wall

∂T is the temperature difference normal (n) to the wall (w)

λ_b is bulk thermal diffusivity

At the solid-fluid boundary (wall, solid boundaries), there are two interface conditions: the temperature is continuous and the normal heat-flux is continuous.

A flow boundary is, by definition, a boundary where a fluid can enter (inlet) or leave (outlet) the domain. All variables (temperature, energy, velocity, pressure and or work, and additional scalars) are specified at the inlet while outputs are described at any point of interest including the outlet. The global mass conservation law (mass in = mass out) must be obeyed at all control volumes. A periodic boundary has periodicity, that is, a mathematical simple boundary condition which ensures that all variables, and hence also all coefficients, have the same value at both ends of the computational or physical domain (Versteeg and Malalasekera, 1995; Patankar, 1980).

These Navier Stokes (transport) equations have not been widely used in the study of free natural ventilation systems due to the low fluid flow rates that characterize these systems and that make the manipulation of the equations difficult. This therefore justifies the need for other equations.

2.3.4 Discretization and Solution Techniques

The general equations of conservation of energy and mass that describe the environment within a potato pile are too complex for analytical solutions and therefore, the variable is solved for each general or specific equation as a function of one or more independent variable by a numerical method. The numerical method treats as its basic unknown the value of the dependent variable at a finite number of locations (grid points) in the calculation domain (Bejpai *et al.* 1983; Versteeg and Malalasekera, 1995; Patankar, 1980). The method includes the tasks of providing a set of algebraic equations for these unknowns and prescribing an algorithm for solving the equations. The continuous values at the grid points (of exact solution) are replaced with discrete values. This class of numerical methods are referred to as discretisation methods (Reece, 1986; Smith, 1985; Smith, 1977a).

A discretization equation is an algebraic relationship connecting values of a dependent variable for a group of grid points, expressing the same physical information as the differential equation. As the number of grid points becomes very large, the solution approaches the exaction solution (Ritchmyer and Morton, 1967; Mitchell, 1969). There are two alternative versions of the discretisation method, that is, finite-difference and finite-element methods. The distinction between the two results from the ways of choosing the profiles and deriving the discretization equations. Often the two are used together, though numerical computations mostly have a finite-difference appearance. Both methods require the division of the region over which the solutions are desired into small elements by a grid system. The techniques give values at the intersection points of the grid lines or nodal points that enclose the control/solution volumes/cells. The values are calculated either directly by an explicit method or indirectly by an implicit method which usually requires solving a set of independent linear equations. The nature of the differential equations to be solved and the region to which they are applied, affect the choice of the method (Reddy, 1984; Mitchell, 1969).

The finite element method is newer and has been applied successfully to several forms of differential equations (Segerlind, 1976; Merchant, 1976a, b; Hunter 1978). It handles irregularly shaped boundaries, nonhomogeneous properties and regions with varying element sizes (often necessary to save CPU time and get more detail at certain regions of the computational domain). More stringent stability requirements for the transient models and lack of techniques to handle hyperbolic equations are two of its drawbacks.

Finite difference schemes have been developed to successfully handle both linear and non linear hyperbolic, parabolic and elliptical equations (Mitchell, 1969; Singh *et al.* 1993). Some form of central, forward, and/or backward difference is used to approximate the differential equations. A difference approximation that gives accurate results with minimum of calculations is preferable. This may be different to the difference approximation that is used to develop differential equations. The limit on the accuracy of the finite difference approximation to the actual equation is related to the scheme used. The schemes are related to series approximations which are a function of the increasing powers of the grid spacing and time step. The accuracy of the scheme is related to the number of terms incorporated. It is usually expressed in terms of the order of the grid spacing, H as H, H^2, etc. Most approximations are either H or ${}^{2}H$ (double precision). Additional accuracy may be achieved by adding more terms to the approximation but this increases the complexity of the solution (Mitchell, 1969; Merchant, 1976b).

Besides accuracy, the stability of the method is a major concern. This is generally a function of the time interval, position, grid spacings and the equation coefficients (Richtmyer and Morton, 1967). A finite element method should converge to the exact answer/value as the time approaches infinity and this should be any given time when the grid spacing and time step approach zero, that is, very large number of cells and very small time steps - this requires a lot of CPU work space and memory. Stability criteria have been developed for finite difference approximations for simpler equations but it is very difficult if not impossible to have detailed analyses for complicated equations developed. Implicit schemes are often employed to overcome some of these stability problems (Mitchell, 1969; Brooker, 1969).

A conservative finite-difference, or finite-volume method with all variables defined at the centre of control volumes which fill the physical domain is usually used in computer models such as CFD-CFX code uses (AEA, 1996). Each equation is integrated over each control volume to obtain a discrete equation which connects the variable at the centre of the control volume with its neighbours. In the CFD-CFX code, all the equations apart from the continuity equation have the same form (Versteeg and Malalasekera, 1995):

$$\frac{\partial(\rho\phi)}{\partial t}+\nabla.(\rho \boldsymbol{u}\phi)-\nabla.(\Gamma\nabla\phi)=S \qquad \textbf{(28)}$$

where Γ is the relevant effective diffusivity for the variable ϕ.

Integrating over the control volume gives:

$$\int\frac{\partial(\rho\phi)}{\partial t}dv+\int\rho u\phi.\boldsymbol{n}dA-\int\Gamma\nabla\phi.\boldsymbol{n}dA=\int Sdv \qquad \textbf{(29)}$$

All terms in all the equations are discretized in space using second-order centred differencing apart from the advection terms and the convection coefficients obtained using the Rhie-Chow interpolation formula.

The diffusion term (from one face) of the control volume (to the other) is discretized as (Patankar, 1980; Smith, 1985):

$$\int_E^W \Gamma\nabla\phi.ndA = \frac{\Gamma A_W}{h_W}(\phi_p - \phi_W) \qquad \textbf{(30)}$$

where subscript $_W = D_W(\phi_p - \phi_W)$ represents west face of volume

A is the area of the face

h is the distance between the west and central (P) node at centre of volume

D is the diffusion coefficient.

The treatment of the advection terms (by different differencing schemes) determines the accuracy of the solutions of the model equations. More accurate schemes tend to be less robust and slower (Smith, 1985; AEA, 1996). However, a range of discretization methods from diffusive, simple upwind schemes through bounded, quadratic upwind schemes are available and sufficient.

Using upwind differencing scheme (UDS), the advected (due to the velocity force) value of the variable ϕ is taken to be ϕ_w so that at the west face

$$\int_E^W \rho\phi.ndA = \rho U_W A_W \phi_W \equiv C_W \phi_W \qquad \textbf{(31)}$$

where C_w is the convection coefficient at the west face.

This gives a matrix coefficient for the west point of

$$A_W = MAX(C_W, 0) + D_W \qquad \textbf{(32)}$$

This scheme is first order accurate.

A modification of the above gives a hybrid differencing scheme (HDS) in which central differencing is used if the mesh Peclet number (C/D) is less than 2, and upwind differencing but ignoring diffusion is used if C/D is greater than 2. Then equation 32 becomes

$$A_W = MAX(\frac{1}{2}C_W, D_W) + \frac{1}{2}C_W \tag{33}$$

This scheme is slightly better than UDS, because second-order central differencing is used across streams and in regions of low flow. It is commonly used in many CFD-CFX4 computations (AEA, 1996; Smith, 1985). Other schemes are briefly described below.

1. Central differencing scheme (CDS), where

$$\phi_W = \frac{1}{2}(\phi_W + \phi_P) \tag{34}$$

is second-order accurate but not robust, often requiring very small under-relaxation factors or giving non-physical solutions.

2. Higher-order Upwind differencing (HUW), where

$$A_W = MAX(C_W, 0) + \frac{1}{2}MAX(C_E, 0) + D_W \tag{35}$$

and is second-order accurate but less compact than the previous schemes.

3. Quadratic Upwind differencing (QUICK), where

$$\phi = \frac{3}{8}\phi_P + \frac{3}{4}\phi_W + \frac{1}{8}\phi_{WW} \tag{36}$$

and is third order accurate for advection and uses two upstream points. In this case

$$A_W = \frac{5}{8}MAX(C_W, 0) + \frac{1}{8}MAX(C_E, 0) + D_W \tag{37}$$

Modifications of the above schemes are possible and they are used in many computer programs to solve the transport equations (Smith, 1985).

Discretization equations should obey the following four basic rules to ensure physical realism and overall balance (Patankar, 1980):

1. Consistency at control-volume faces: When a face is common to two adjacent control volumes, the flux across it must be represented by the same expression in the equations for the two volumes

2. Positive coefficients: An increase in the value at one grid point should, with other conditions remaining constant, lead to an increase (and not a decrease) in the value at the neighbouring point

3. Negative-slope linearization of the source term must always be less than or equal to zero

4. Sum of the neighbour coefficients should be equal to the centre point coefficient for situations where the differential equation continues to remain satisfied after a constant is added to the dependent variable

The commonest time stepping procedure is the backward difference whereby, if the equations are written in the form (Smith, 1985):

$$\frac{\partial\phi}{\partial t} = F(\phi) \tag{38}$$

the discretised form is

$$\frac{\phi^n - \phi^{n-1}}{\Delta t} = F(\phi^n) \tag{39}$$

The terms on the left hand sides can be absorbed into the sources and sinks for each equation and the resulting equations at the n^{th} time step look like the discrete steady state equations. These are then solved using standard steady state techniques. Another procedure is the time centred Crank-Nicolson treatment where the discrete time stepping equation is

$$\frac{\phi^{*}-\phi^{n-1}}{\Delta t/2}=F(\phi^{*}) \tag{40}$$

Once ϕ^* has been calculated (as in backward treatment) then ϕ^n may be evaluated. This in effect, is a two step procedure, the first step being to use a backward difference procedure over the first half step, and then an extrapolation to give the solution at the end of the time step. This is equivalent to the mid-point rule for solving ordinary differential equations.

2.3.5 Model Validation

Before a model can be accepted as being valid and used, it must be demonstrated that the model does an accurate job of simulating the actual events to an acceptable degree (Brugger, 1979). The proof that a model is completely accurate and will handle all cases can only be done when all possible situations have been tried but this is unattainable. Even this is no assurance that the model could successfully handle yet another case that might come along. Therefore a proof of validity consists of trying to prove that the model will handle a specific case for which the model was developed.

2.3.6 Theoretical Crop Storage Model Results

Hougen and Marshall (1947) developed differential equations for the time-position-temperature-concentration condition in both gases and solids during the adsorption of dilute gases flowing through granular beds. Analytical solutions and modified Schumann-Furnas charts and graphical techniques were used to solve the linear and nonlinear relationships respectively. The isothermal requirements preclude the use of this analysis for predicting moisture loss from biological products.

Businger (1954) applied the Schumann-Furnas analysis to heat transfer during forced aeration of bulk agricultural products (such as onions) for one dimensional airflow. Both moisture loss and heat generation or loss were neglected. This could explain discrepancies between the reported experimental and theoretical results.

Arsdel (1955) developed partial differential equations for simultaneous heat and mass transfer in a non-isothermal system. Equations for batch and continuous flow drying configurations operating in low moisture ranges were published. Fluid film and internal resistances to heat transfer were the only transfer mechanisms incorporated. Since the model was for dehydration and not temperature control, no heat generation and latent heat gain/loss were considered. The system of equations was solved using the predictor-corrector method and a difference-equations method without the aid of a computer. Comparisons of predicted and measured values were not made due to lack of valid experimental data; a strong indication for the need of experimental data for model validations.

Ophius (1957) applied Businger (1954) analysis to potato bed to determine air flowrate. Substantial agreement between the calculated and measured trend was claimed but data to verify this was not presented.

Bakker-Arkema *et al.* (1977) have reviewed many grain drying models. They are mainly one dimensional models and concentrating on airflow through non-respiring products within adiabatic walls. These assumptions are not valid for accurate modelling of the potato environment.

Watson and Staley (1963) studied heat transfer rates in a laboratory scale potato bin. The data was analysed using Furnas method for the temperature history of the air and solids.

Apparent values for the heat capacity of the solids and surface coefficient of heat transfer (thus including effects of latent heat of vaporisation, respiration/generation excluding condensation) as functions of air velocity were obtained. A number of environmental and bulk characteristics which affect the heat transfer to and from the potato are not specified.

Bakker-Arkema and Bickert (1966) and Bakker-Arkema *et al.* (1967) developed deep bed cooling equations and solved them numerically for simultaneous heat and mass transfer with varying inlet conditions. These works were used by Bakker-Arkema (1970), Bakker-Arkema and Lerew (1974) and Rosenau *et al.* (1970) for simplified and realistic cooling models, for agricultural products. Rosenau's model included internal temperature gradients within irregularly shaped products. Heat generation and latent heat removal was not accounted for in either model.

Murata (1971) extended Schumann's theory to include solids with low thermal diffusivities. The solution of the one-dimensional heat conduction equation with radiation was used for determining the surface temperature in place of the uniform solids temperature assumption. Approximate analytical and numerical solutions were presented. Good agreement was reported between the theoretical and experimental results in the cooling of a column of eggs. Heat generation and/or removal by evaporation or condensation due to moisture loss were not included.

Misener (1973) developed a model of temperature and weight loss from a bed of potatoes which was a variation of some grain drying model with the following assumptions: one dimensional airflow of the plug-flow type; adiabatic walls; temperature and moisture gradients in a horizontal layer of potatoes in the pile are negligible and temperature equilibrium is obtained during the calculation time interval. An enthalpy balance which included heat generation and latent heat of vaporization was taken over a differential layer during the time interval. This balance was solved for the equilibrium temperature. Similarly a mass balance was used to solve for the temperature and humidity ratio at saturation. The assumption of thermal equilibrium precluded any effect of air velocity or heat and mass transfer. This effect can be significant in forced ventilation though it is good for natural ventilation if latent energy transfer is included. The comparisons of the model results and experimental data were published by Misener and Shove (1976a). The model results and experimental data were not always in good agreement and no explanation was offered. Its applicability in free natural ventilation potato storage is unknown.

Rice (1974), using equations similar to Bakker-Arkema (1970), modelled one-dimensional heat and mass transfer in potato storage. Terms for heat generation and latent heat were added. While the equations contained several errors and no attempt was made to justify several assumptions implicit in the equations, reasonable agreement was claimed with experimental data.

Hylmo *et al.* (1975 a, b) developed a model for temperature distribution in bulk stored potatoes based on the heat balance equation. Heat generation, sensible heat change and latent heat were included in the equation. The expected weight loss was proportioned over the entire period instead of using a specific relationship for moisture loss as a function of potato and air properties. This model was based on a steady state condition, air at 100% relative humidity and uniform one-dimensional airflow.

Hunter (1976, 1977) simulated the heat and mass transfer within a potato pile with an implicit solution of the energy balance of the potatoes within a layer. This model equated the latent heat of vaporization with the heat generation and convective heat transfer between the air and the potato but/and did not include sensible heat changes especially if the store air and potato temperatures were not the same at the start. The solution of layer acted as input for the next, thus giving a steady state profile. The model is not capable of handling condensation, heating or cooling but may be acceptable for long term steady state condition.

Lerew (1978) developed a one-dimensional transient model of temperature and humidity within a potato storage. He solved a set of partial differential equations for the conservation of energy and mass by finite difference methods. He used most of the assumptions Misener (1973) used. Moisture loss and convective heat transfer were related to the velocity of airflow by the Colburn J_H factor. He showed good agreement between predicted results and his experimental data. The assumptions of one-dimensional airflow and adiabatic walls may prevent the model from predicting areas of condensation and/or hot spots. He found that the uniform potato temperature assumption was sufficiently accurate to be valid for normal storage conditions. It is not known whether this can be true for free convective ventilation. He expressed concern over the limitations of the models for variation of moisture loss and heat generation rates during the wound healing period, with respect to time. These relationships were similar to those found experimentally by Pratt and Buelow (1978) for one variety of potatoes and one flowrate.

Hunter (1978) developed a cooling model for bulk potatoes based on the amount of heat and mass transfer that can occur in a layer of potatoes during the time required for air to flow through the layer. He used his earlier heat and mass transfer relationships of steady state (Hunter, 1976, 1977). The applicability of his model in free natural ventilation storage could be difficult since it was developed for fast air flows. He approximated the heat transfer from the potato by a single step conduction term from the centre to the mean air temperature. The total conductance included the thermal conductivity within the flesh and a surface convective heat transfer coefficient. The sensible heat and latent heat and mass transfer were used to determine the air state entering the next layer. The 1D model was based on forced air flow, adiabatic walls, but did not cater for condensation during pile warming.

Brugger (1979) developed a model using assumptions used in the Lerew (1978) model but included non-adiabatic walls (insulation and its contribution to condensation) and made it 2D. The model was to simulate potato storage environments and perform a sensitivity analysis of independent variables since any attempt to evaluate experimentally the effect of one variable by holding others constant results in numerous problems and reduces the result to being an approximation of the conditions.

Beukema (1980) used the energy balance equations to study the heat and mass transfer during cooling and storage of agricultural products as influenced by natural convection.

Lee (1986) computed numerically heat and mass transfer in highly porous media using four idealised models by computer. Temperature profiles within the porous layer were computed for highly porous media such as forests and grain fields. Heat transfer by radiation was included but comparisons with measured values were made for cases of negligible radiation field only. The theoretical results were reported to correspond well with experimental results.

Bibby (1997) has used CFD package to simulate three-dimensional, transient temperature distributions by solving time dependent nonlinear system of Navier-Stokes equations which describe air and heat flow through a grain silo. The silo geometry was divided into 52,000 control volumes over which the equations, converted into algebraic form, were solved for the domain of interest. Assumptions included: laminar incompressible flow; no internal heat generation (none from mould growth, respiration or moisture condensation); adiabatic silo with wall and roof at a constant temperature of 10 °C while the initial uniform bulk temperature was 30°C. He used a time step of 1 hour for the simulations and the following wheat properties: density 758.5 kgm^{-3}, bulk thermal conductivity 0.133 Wm^{-1}K^{-1}, specific heat 1970.5 Jkg^{-1}K^{-1}, horizontal resistance coefficient 2688.0, vertical resistance coefficient 4208.0 and volume porosity 0.41 (ASAE, 1995). Assuming no leakages, air movement in the silo was driven by natural convection. The predicted pattern indicated hot spots at the centre and top of bulk as had been shown by other numerical models (Khankari, 1995; Singh *et al.* 1993).

Burfoot *et al.* (1996a), Burfoot and Xu (1997) and Xu and Burfoot (1997) have used the transport equations in the commercial CFD computer program to simulate mass and heat flow through a 45-tonne store potato store. The potatoes were in boxes and were mechanically ventilated and cooled as required. The D. simulated results of air flow and temperature were reported to be in good agreement with measurements taken at the store. Predictions of high (6 ms^{-1}) and low velocity (0.003 ms^{-1}) regions were reported. They assumed turbulent flow though some flows may have been laminar-transitional flows because no credible transitional model was available in CFD. They assumed the heat to be transferred by the movement of the air, by conduction through the air and by conduction from potatoes in one cell to potatoes in neighbouring volumes. The model included moisture transfer between neighbouring cells by the movement of the air and by diffusion. The results were reported to be in good agreement with measured temperature. Burfoot *et al.* (1996b) has also used the transport equations to model the distribution of isopropyl N-(3-chlorophenyl) carbamate [CIPC] in box potato stores successfully.

2.3.7 Empirical Potato Temperature Prediction Models

A limited number of empirical relationships to model a few potato storage environmental parameters were available. Those that are relevant to the current study are Burton et al. (1955) and Nyaanga (1991) and Nyaanga *et al.* (1994a) as reported in the following paragraphs.

Burton *et al.* (1955) studying unventilated large commercial stacks of potatoes have developed an empirical expression for predicting temperatures and height at which overheating would occur. They assumed the effective area for the entry of air in a large unventilated stack to be equivalent to half the top surface area. Burton (1989) has given the equation in SI units (taking the bulk density of potatoes to be 1.5 m^3 per tonne) as:

$$(\Delta T)^{2.8} = 80k(q_r H)^{1.8} \tag{41}$$

where ΔT is the difference between the potato temperature and the average air temperature (K)

q_r is metabolic heat ($kJt^{-1}h^{-1}$)

k is the coefficient of resistance to airflow (constant), and

H is the height of the stack (m)

This prediction ignores the effect of evaporative cooling which Burton (1989) argues may have been compensated for by an over-estimate of the area available for the entry of air. The results were also presented in form of a graph of air temperature against average potato temperature for various pile depths of clean, dirty, mature, immature and sprouted potatoes. The main utility of the expression is to determine the maximum height or depth to which a given sample of potatoes could be stored at a given ambient temperature under free natural ventilation without overheating (inducing thermal and other forms of deterioration).

Nyaanga (1991) argues that Burton *et al.* (1955) equation omits the effect of lateral dimensions and the values of Q and k can be held constant for given potatoes while a number of other characteristics (such as the stage of storage, which air (ambient or store) temperature and centre, bottom or top potato temperature and void ratio) should be specified since these would have an effect on the prediction. Nyaanga (1991) and Nyaanga *et al.* (1994a) applying the theory of similitude and using experimental storage boxes developed the expression:

$$\frac{(T_r - T_p)}{T_r} = -0.094\left(\frac{D^2}{BL}\right)^{-0.003}\left(\frac{Z}{D}\right)^{-0.005} \tag{42}$$

where T_p is the potato temperature, ° C

T_r is the room temperature, ° C

D is the depth or height of pile or potato stack as defined by the box, m

B is the breadth of the box, m

L is the length of the box, m

Z is the point from bottom (within the bulk of potatoes) at which the potato temperature is measured, m

Nyaanga (1991 and Nyaanga *et al.* (1994a) using the above expression (42) and experimental data suggested that the optimal bulk size of naturally ventilated potato piles should be narrow but long which could induce convectional thermal currents causing a fast rate of heat removal from the bulk of potatoes. It is not clear whether this can be true for other ambient conditions.

More modelling and experiments on free natural ventilation potato storage systems are needed in order to be able to answer a number of the issues raised in this review. The knowledge so gained, will help improve the design and management of cheap but effective technologies/systems suited for developing economies.

"… pondered and searched out and set in order in many ways..." (Ecclessiates 12:10)

CHAPTER 3: METHODOLOGY

Prediction of temperature can be obtained by mathematical simulation (modelling) and/or physical observations (experimentation). Both mathematical and experimental approaches were used to predict the potato temperature during natural convective potato storage. The temperature of potatoes can be predicted using simple statistical correlations or complex differential and integral mathematical methods.

3.1 Empirical Predictions

The empirical prediction expressions used in this study include those proposed by Burton (1989) and Nyaanga (1991). They are applied with the necessary modifications for the prediction of temperature in free natural potato storage.

3.1.1 Burton Predictions

Taking the Burton (1989) equation 41 and substituting k with $5.5\text{x}10^{-5}$ mm water (Burton, 1989) for clean mature potatoes it becomes:

$$(\Delta T)^{2.8}=4.4x10^{-3}(q_rH)^{1.8} \qquad (43)$$

where ΔT= Tp-Ta with Tp being the bulk potato temperature and Ta being the ambient temperature.

Substituting, simplifying and rearranging, the equation 43 becomes

$$T_p=0.144(q_rH)^{0.643}+T_a \qquad (44)$$

The value of the heat of respiration (q_r) varies with temperature and seems to vary with different researchers. Table 3.1 gives respiration rates as generated using equation 12 for the Misener and Shove (1976a) Lerew (1978) values while those for Burton have been extracted from his graph (Burton 1989).

Table 3.1: Heat of respiration ($kJt^{-1}h^{-1}$) at tropical temperatures

Temperature (°C)	Lerew (1978)	Misener and Shove (1976a)	Burton (1989)	Average
15	117.35	87.15	51	85.17
16	124.34	94.14	53	90.50
17	131.33	101.13	58	96.82
18	138.32	108.12	62	102.81
19	145.31	115.11	70	110.14
20	152.30	122.10	80	118.13
21	159.29	129.09	96	128.13
22	166.28	136.08	101	134.45

The average of the three researchers' respiration rates can be expressed by linear regression equation (with $R^2 = 0.9924$), in $kJt^{-1}h^{-1}$ as:

$$q_r = 7.195Tp - 24.84 \qquad \textbf{(45)}$$

and as a power function (with $R^2 = 0.9939$) as:

$$q_r = 3.096Tp^{1.2175} \qquad \textbf{(46)}$$

where q_r is the rate of respiration rate in $kJt^{-1}h^{-1}$

Tp is temperature in °C

If qr is $W\,kg^{-1}$ equation 45 becomes

$$q_r = (1.998Tp - 6.9) * 10^{-3} \qquad \textbf{(47)}$$

Using modified Burton equations for q_r, and H (values of 0.01Z, 0.25Z, 0.50Z, 0.75Z and 0.99Z for the different height positions from the bottom to the top of the potato stack with a total height of Z) and the ambient/room temperatures collected during experimentation, the potato temperatures were simulated and compared with the observed potato temperatures.

3.1.2 Nyaanga Predictions

The Nyaanga (1991) equation 42 can be simplified for various box dimensions and temperature monitoring positions. The two ratios (terms on the right hand side) raised to small negative powers are equal to about 0.99 and 1.00 respectively for almost any dimension of box and position of measuring the temperature. Substituting the two values and rearranging the Nyaanga (1991) equation yields:

$$Tp = kTr \qquad \textbf{(48)}$$

where k is a constant equal to 1.094 on average for the Egerton 1.2 by 1.2 by 1.2 m experimental box and taking the measuring points at the bottom, centre and top of the bulk, the k constants become 1.0940, 1.0943 and 1.0946 respectively.

Using this modified Nyaanga (1991) equation (48) with the relevant k values, various potato temperatures were simulated for given room (store) temperatures and compared to actual measured temperatures. Computational Fluid Dynamics (CFD) modelling by use of the commercial CFD-CFX4 computer program developed by AEA (1996) was tried but was found too slow; demanding too much CPU memory and time due to the very slow rate at which the environmental variables change in free natural ventilation potato storage. A less robust semi-dynamic fairly generalisable, precise and easy to apply model named Computational Thermal Prediction (CTP) was therefore, developed to fill the gap between the very complex precise theoretical models such as CFD-CFX and very simple restrictive static empirical models such as that of Nyaanga (1991).

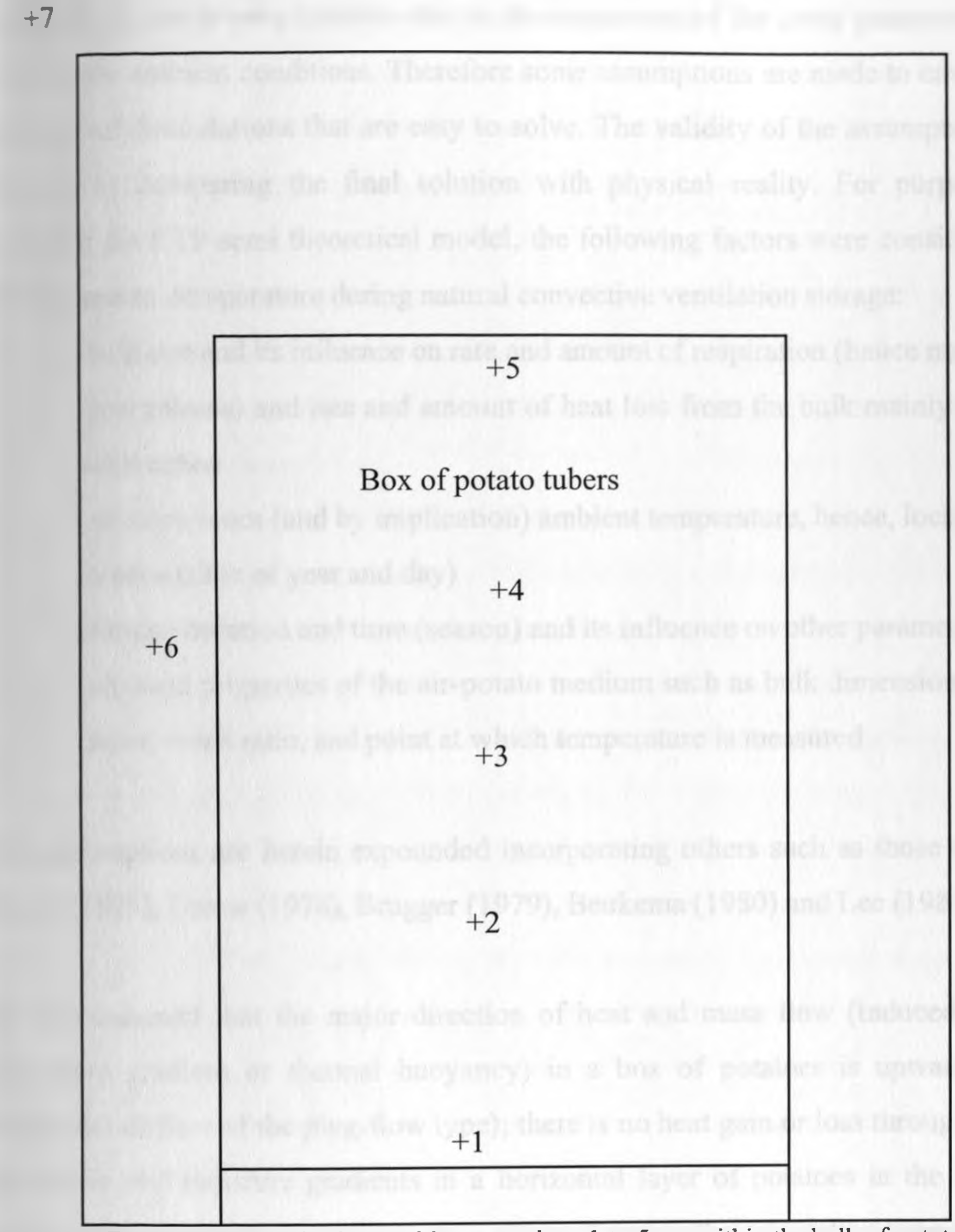
3.2 Computational Thermal Prediction (CTP) Model

The CTP model was developed based on a rectangular bulk size defined by a box of potatoes, using theoretical relationships, finite difference approximation and a computer program that produces the simulations. The computer program allows numerous input options and guidance so that the user only needs to understand the physical phenomena which enables the user to exhaustively describe the system in order to simulate the system.

3.2.1 Physical Formulation

Physical formulation involves identifying and defining quantitatively all the relevant and inherent properties and characteristics of the system. The basic physical system under investigation was a box of potatoes to represent a pile or stack of potatoes stored under conditions of natural convection in given room conditions of temperature among others. The setup was such that the required parameters (in this case temperature) are monitored at all points of interest as in figure 3.1.

The box (with a rectangular base and top) was chosen because of the ease of defining its dimensions quite precisely both physically and theoretically. The dimension of great interest was the height of the box and therefore the depth of potatoes. The system studied involved a bulk of potatoes in a box with a false floor raised at least 150 mm above the ground. The box dimensions will determine the volume enclosed and hence the amount of total heat that will be released by the stack. The sizes used in experiments were 1.2x1.2x1.2 m for the Egerton box and 1.83x1.22x1.44 m for the SRI box. The layer thickness set by the locations at which the potato temperature were measured: at the base (bottom) of the box, a quarter up, at the centre, three-quarters from bottom and at the top of the stack.



+Temperature monitoring positions, numbers 1 to 5 are within the bulk of potatoes while 6 and 7 are in the store and outside the store respectively.

Figure 3.1 1-D Physical setup for mathematical model development (Not to scale).

3.2.2 Basic Assumptions

The potato storage environment consists of a number of factors as discussed in section 2.2 above. The physical environment of a potato storage (especially the free natural ventilation) system is very complex due to the interaction of the many parameters that vary with the ambient conditions. Therefore some assumptions are made to enable the mathematical formulations that are easy to solve. The validity of the assumptions are evaluated by comparing the final solution with physical reality. For purposes of developing the CTP semi theoretical model, the following factors were considered to affect the potato temperature during natural convective ventilation storage:

- bulk size and its influence on rate and amount of respiration (hence metabolic heat release) and rate and amount of heat loss from the bulk mainly by free convection
- air store/room (and by implication) ambient temperature, hence, locality and season (time of year and day)
- storage duration and time (season) and its influence on other parameters
- physical properties of the air-potato medium such as bulk dimensions, tuber sizes, voids ratio, and point at which temperature is measured

These assumptions are herein expounded incorporating others such as those used by Misener (1973), Lerew (1978), Brugger (1979), Beukema (1980) and Lee (1986).

1. It was assumed that the major direction of heat and mass flow (induced by the temperature gradient or thermal buoyancy) in a box of potatoes is upwards (one dimensional airflow of the plug-flow type); there is no heat gain or loss through walls; temperature and moisture gradients in a horizontal layer of potatoes in the pile are negligible and temperature equilibrium is obtained during the calculation time interval. Therefore it was assumed that there was no variation in air flow, temperature or humidity in a direction that was perpendicular to the upward airflow.

2. It was assumed like Burton *et al.* (1955), that the amount of heat transfer between the bulk of potatoes and its surroundings by radiation and conduction are negligible compared to convection due to the dull surfaces and low thermal conductivities. Therefore, (like Hunter, 1976, 1977), the metabolic heat generated by the potatoes (Qr) is lost by

convective heat transfer (Qv) between the room and the potato stack. It was assumed that condensation and evaporation do not occur in free natural ventilation storage where the environmental conditions between the bulk and its surrounding (store/room) are not that different in terms of temperatures and relative humidity.

3. It was assumed that there is a temperature equilibrium between the air and the tubers in the porous medium. There exists a uniform bulk temperature with finite convective heat transfer between vertical potato layers. Therefore, heat energy (Q) can be expressed in terms that contain temperature.

4. The region modelled was assumed to be uniform in spatial characteristics. This implies that no settling, deformation or volumetric shrinkage occur and the bed void volume is uniformly distributed. This assumption may be hard to justify especially for tubers with large amount of adhering soil or excessive weight loss during storage but is fair for clean and same grade (size) of potatoes which are stored for short periods especially before sprouting sets in.

5. The physical and thermal properties of air such as specific heat, density, convective heat transfer coefficient, thermal conductivity and latent heat of evaporation do not vary significantly and are therefore assumed constant. Therefore, the dry-air vapour stream behaves as an incompressible fluid. Water vapour in the air is in constant thermal equilibrium with the dry air. The bulk temperature is nearly uniform due to low velocities that occur within the potato pile.

6. Potatoes emit a variety of gases due to their metabolic activity which represents the mass transfer from the potato. This transfer however is very small in comparison to that of water vapour hence it is assumed that: The generation and transport of gases other than water vapour is negligible. Changes in the mass and composition of the dry matter of the product are negligible. This may be difficult to justify in long term storage and therefore would require development of step functions with different coefficients to cater for this

variation but this makes the mathematical formulation very complex to develop. The net exchange of mass and energy associated with dry gases and composition is very small and therefore negligible for short term storage before the potatoes sprout.

7. The potato consists of individual cells where water is in liquid phase and intercellular spaces where water is in either a liquid or vapour phase. A rapid rate of evaporation and a slow thermal response may cause major temperature variation within the tuber. However, due to low airflow rates in natural convection, the tuber temperature is assumed to be the same. Furthermore, the interest was to predict the bulk layer temperature, which can be assumed to be same potato-air temperature as discussed in section 1.1. It is only affected by the overall evaporation surface area of the layer of potatoes rather than individual tubers.

It is assumed that moisture released is only in the form of water which evaporates as soon as it is released. In spite of the high humidity within the pile the little fluctuations in temperature and slow heat exchange between the pile and the room or its environment results in gradual evaporation of a continuous film of uniform thickness of the moisture released by respiration over the top or bottom of the layer under consideration. The water released onto the layer surface is in thermal equilibrium with the air stream.

3.2.3 Mathematical Formulation

Theoretically, temperature can be computed from the heat energy balance between the room/store and bulk such as :

$$Q_s+Q_r=Q_v+Q_e+Q_c+Q_R \qquad (49)$$

where Q_s is the heat stored

Q_r is the heat generated by respiration

Q_v is the heat lost by ventilation

Q_e is the heat lost to evaporation

Q_c is the heat lost by conduction

Q_R is the heat lost by radiation

Neglecting all forms of heat exchange modes in line of assumption 2, equation (49) becomes:

$$Q_r = Q_v \tag{50}$$

Hence this enthalpy balance when taken over a differential layer during the time interval and put in differential form as:

$$\frac{\partial Q_r}{\partial t}\Big|_z = \frac{\partial Q_v}{\partial t} \tag{51}$$

where subscript z indicates the thickness of the bed layer

Equation (51) was then discretised using the backward difference procedure so that it is of the form:

$$\frac{Q_{r_{z_2}} - Q_{r_{z_1}}}{\Delta t} = \frac{Q_{v_{z_2}} - Q_{v_{z_1}}}{\Delta t} \tag{52}$$

Taking the time interval to be constant, thus computing the heat energy balance within a given layer of a bed/bulk of potatoes and equating the amount of heat of respiration (Qr) to the amount of heat removed by infiltration (Qv) given by equation 14 yields:

$$Q_r = c\rho N v \Delta T \tag{53}$$

Substituting for specific heat © with 1.01 $kJkg^{-1}\ K^{-1}$, air density (ρ) with 1.21 $kg\ m^{-3}$, temperature difference (ΔT) with Tp_i-Tp_{i-1}, (N as air changes per hour and v as the layer volume), on rearranging yields:

$$Tp_i = Tp_{i-1} + \frac{Q_r}{0.3395 N v} \tag{54}$$

The total heat produced by each layer (Q_{ri}) is found by multiplying the rate of metabolic heat production (q_r) using equation (46) with the mass of potatoes which is the product of the layer volume (v) and density of potatoes (ρ_t) which yields:

$$Q_{ri} = 10^{-3}\rho_t(1-\epsilon)(1.998Tp-6.9)v \tag{55}$$

Substituting for Qr in equation 54 yields:

$$Tp_i = Tp_{i-1} + \frac{10^{-3}\rho_t(1-\epsilon)(1.998Tp_i-6.9)}{0.3395N} \tag{56}$$

Letting:

$$c_i = \frac{10^{-3}\rho_t(1-\epsilon)(1.998Tp_i-6.9)}{0.3395N_l} \tag{57}$$

Equation (56) reduces to:

$$Tp_i = Tp_{i-1} + c_i \tag{58}$$

with the initial condition that

$$Tp_1 = Tr + c_0 \tag{59}$$

where

$$c_0 = \frac{10^{-3}\rho_t(1-\epsilon)(1.998Tr-6.9)}{0.3395N_b} \tag{60}$$

where Tp_i is the potato temperature at a given position with 1 being at the bottom of the bulk (°C)

Tr is the room/store temperature

c_i is a constant that caters for evaporative, respiration, ventilation and conduction heat exchange between the layers and can be calculated using equation 57

c_0 is a constant that caters for difference between the room and bottom (layer 1) potato temperature, and can be computed by equation 60

Q_n is the total heat produced by the mass of potatoes in the layer

v is the volume of layer of potatoes

N_b is the number of air changes in and out of the box of potatoes computed by equation 61

N_l is the number of air changes in each layer of potatoes computed by equation 62.

The number of air changes through the slatted half-open floor of the potato box (N_b) is much higher than that reported and recommended for stores. This N_b increases from the centre of the bulk (the remotest point) to the pheriphery of the bulk that is, the bottom and top of the box of potatoes as in equation 61

$$N_b = \frac{V_s}{\epsilon V_b} N_s \qquad \textbf{(61)}$$

where N is the number of air changes

V is volume

s is the store

b is the box

Taking the recommended value of N_s as 1 (Porges, 1995), equation 61 can be used for the air changes for every computational layer as per the equation below:

$$N_l = \frac{V_s}{\epsilon z V_b} \qquad \textbf{(62)}$$

where N_l is the number of air changes through given layer

z is the depth of the layer of potatoes

ϵ is the voids ratio of the potatoes

The assumptions leading to equations 62 are based on the fact that a storage box is a number of times smaller than a convectional room/store and has intended openings at the bottom while the top is fully open. N is also affected by resistance to air movement up the porous medium varying with the voids ratio (ϵ) which in turn is a function of the size of the potatoes.

The constants c_0 and c_i vary with ambient conditions, thickness of a potato layer (and to some extent the lateral dimensions in that these will determine the surface area over which air enters). These constants vary with locality (prevailing ambient conditions), size of bulk/box, time of storage among other factors. In general, c_0 expresses the structure's effect on the store/room temperature (Tr) and the resulting initial or boundary (first layer) bulk potato temperature (Tp1).

The CTP program uses equations 57, 60 and 62 to calculate the constants c_0 and c_i by prompting the user to supply the required variables. The equations are solved for each layer using the previous results as input for the next, thus constituting a finite element approach thus giving a steady state profile. The program also gives the option of generating random values for the constants based on the experience and statistical data of former similar storage systems. However, this option is only applicable for specified conditions and systems and the program cautions the user accordingly.

The ambient (Ta) or weather station (Taw) and room/store temperatures (Tr) have to be supplied from experiments or computed by the sinusoidal relationships (as in figure 3.2) and linear regression relationships developed such as the one below from the Egerton data:

$$Tr=-8E^{-8}t^{6}+E^{-5}t^{5}-5E^{-4}t^{4}+1.08E^{-2}t^{3}-1.12E^{-1}t^{2}+4.247E^{-1}t+20.702 \qquad (63)$$

with R^2 value of 0.764 and where t is time in days

or

$$Tr = 0.7613 Tae + 5.142 \quad (64)$$

with an R^2 of 0.7186

Equations 63 and 64 (given as options in CTP) were based on 45 days' readings which

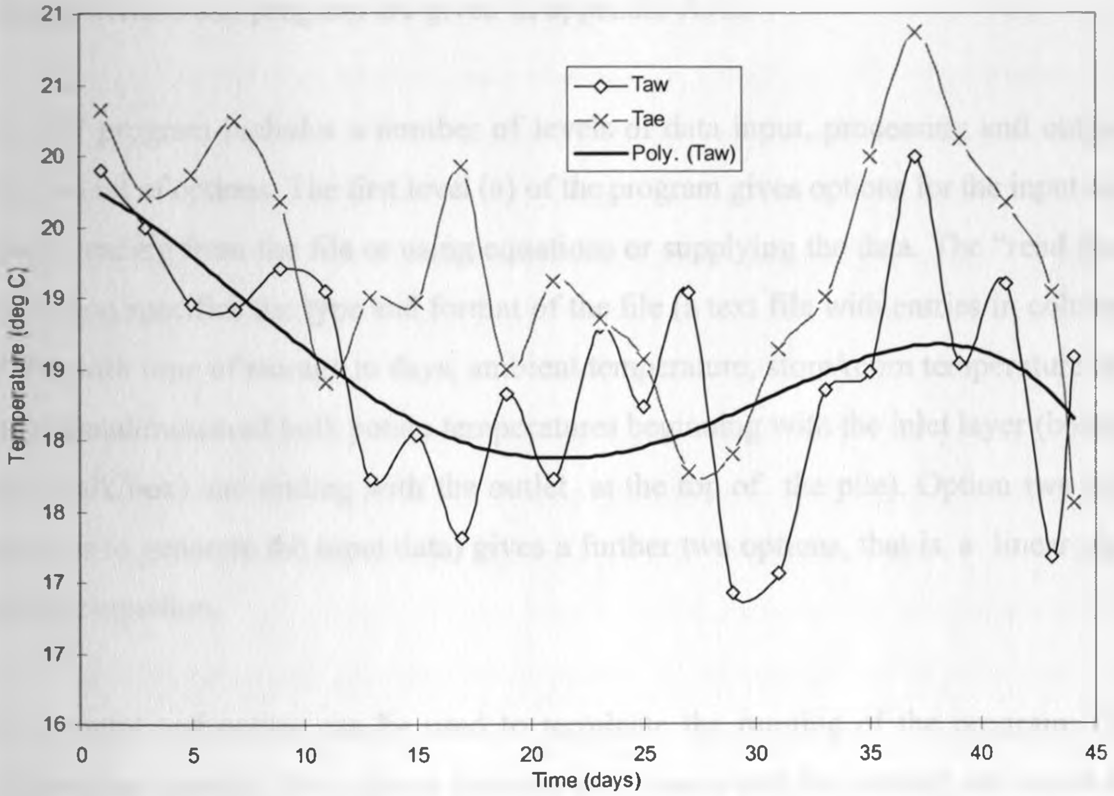


Figure 3.2 Egerton weather station (Taw) and experimental (Tae) ambient temperature variation with time (April/May 1998)

were averages of the six readings per day. The program allows the user to supply appropriate coefficients while using those in the two equations (63; 64) as default. Similar relationships are possible between the room temperature and the ambient temperature from the weather stations (Taw). The coefficients vary with season (time of year), locality (latitude on the globe) and type of building and structure used as a store.

3.2.4 Computational Thermal Prediction (CTP) Computer Program

The computer program coded Computational Thermal Prediction (CTP) was written in Pascal for use on a personal computer. The program guides the user and interactively acquires inputs from the user through prompts, solving the mathematical formulae developed (in section 3.2.3) thus simulating the required potato temperature. Figures 3.3 and 3.4 give the summary and details of the program in flow charts. The symbols used in the flowcharts and program are given in appendix A1.2.

The CTP program includes a number of levels of data input, processing and outputs through a set of options. The first level (a) of the program gives options for the input data namely reading from the file or using equations or supplying the data. The "read from file" option specifies the type and format of the file (a text file with entries in columns starting with time of storage in days, ambient temperature, store/room temperature and experimental/measured bulk potato temperatures beginning with the inlet layer (bottom of the bulk/box) and ending with the outlet at the top of the pile). Option two (use equations to generate the input data) gives a further two options, that is, a linear or a quadratic equation.

Each prompt and option can be used to terminate the running of the program. The equations are specific for a given location and season and the default are based on standard medium potato properties stored at normal room temperatures. The number of time readings and temperatures to be simulated are specified by the user. The number of potato temperatures (with respect to the internal box or bulk dimensions) determines the number and size of layers.

The program computes the bulk potato temperature using equations 58 and 59. The CTP also gives an option whereby the random c_0 or c_i values are added to or subtracted from an earlier temperature depending on the condition of whether the ratio of the square of the height to the product of the length and width of the bulk is less or greater than two respectively, based on Nyaanga (1991).

Equation 55 was adopted for the computation of the rate of respiration heat release and a default value of 0.033 W/kg was used assuming the room temperature of 20 °C and a bulk density of 634 kgm^{-3}.

The random c_0 and c_1 values were determined by using the minimum and maximum differential temperatures between the store/room and first layer potato temperature and the lowest bulk potato temperatures respectively. The variables used in the computation of c_0 and c_1 include the number of air changes in each layer per hour (N), the bulk density of the potatoes (ρ_b) and voids fraction (ϵ), volume of the layer (V_l) and total bulk/box (V_b) and the rate of metabolic heat release (qr). The program prompts the user to supply the variables or use one of the three options for supplying or computing the same.

The ambient, room and observed potato temperatures for each day of the stated storage period are either read from a text file or supplied interactively by the user at the computer terminal. If the user decides not to use the file or supply the data the other option is to use the inbuilt equations to simulate the room/store (Tr) and ambient (Ta) temperatures. The number of potato layers are specified as the number of temperatures to be simulated. The program computes the potato temperatures for each layer using the formulae developed above by use of finite element method. The solution for the first layer is used as an input for the next layer. The program allows the specification of the box or size of potato stack in terms of length, breadth and height in a row. The subsequent potato temperatures for the layers are generated using constants k and c either supplied by the user or calculated using the formula.

The output data generated by the program is stored in a text file which includes the input data and can be opened in a spreadsheet package like MsExcel to perform some further analysis on the data. The program analyses the data generated and displays it in a graph comparing the experimental and simulated potato temperatures. The graph shows the first three experimental and three simulated temperatures for comparison purposes. The program also gives the user an option of viewing alternate simulated data against the experimental data values.

The program determines and displays a numerical summary of the key temperatures and recommendations of what should be done in case the limits are exceeded. The analysis and summary from the output file include:

- determining and displaying the maximum and minimum store/room (Tr) and potato (Tp) temperatures for each time reading (day)
- checking whether any ambient temperature exceeds 30 °C or the storage room and potato temperature exceeds 25 °C
- indicating the maximum differential potato temperature of 1.5 °C
- indicating whether the maximum difference between potato and store temperatures exceeds 2 °C, and the time when this occurs
- giving recommendations in event of exceeding the limits

The remedy options are:

- terminate the storage process
- redesign the box or stack by reducing the dimensions especially the height, bottom clearance, floor and side openings
- institute some management practise such as forced ventilation and cooling or passive humidification

The major procedures of the program are given in the Appendix 1 and its full listing is at the University of Nairobi.

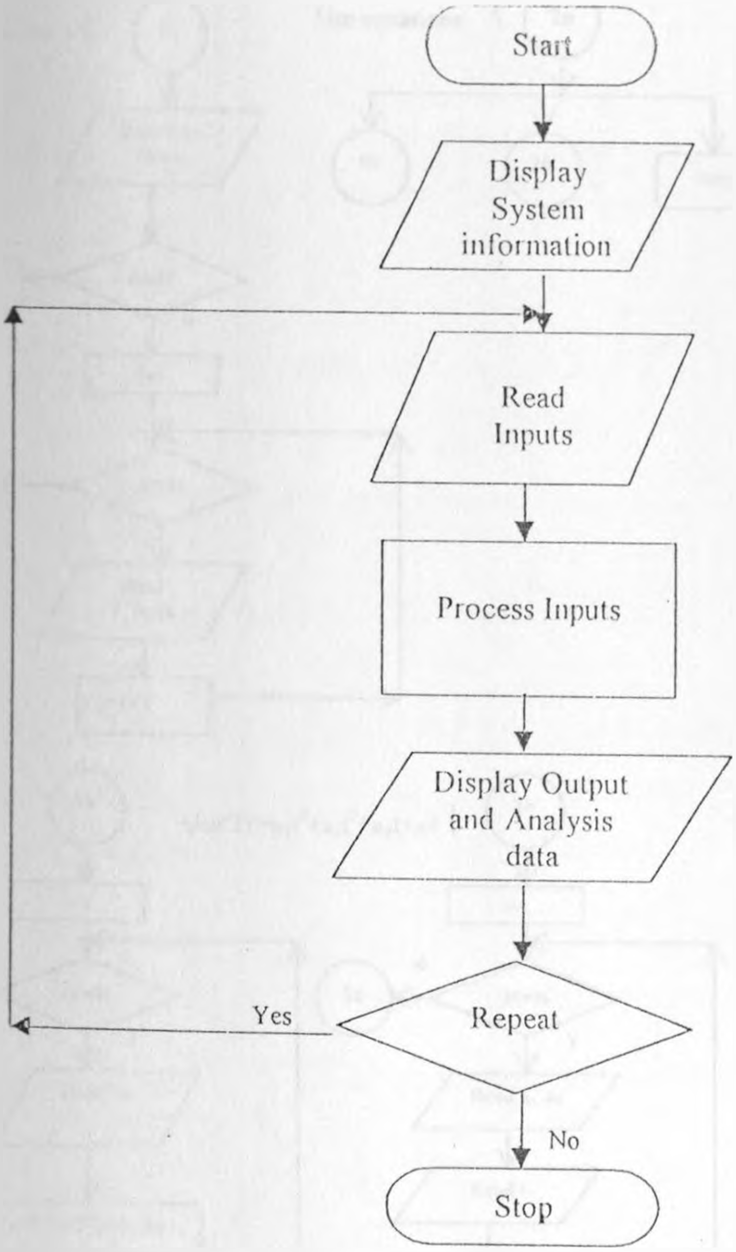


Figure 3.3 Computational Thermal Prediction (CTP) System flowchart

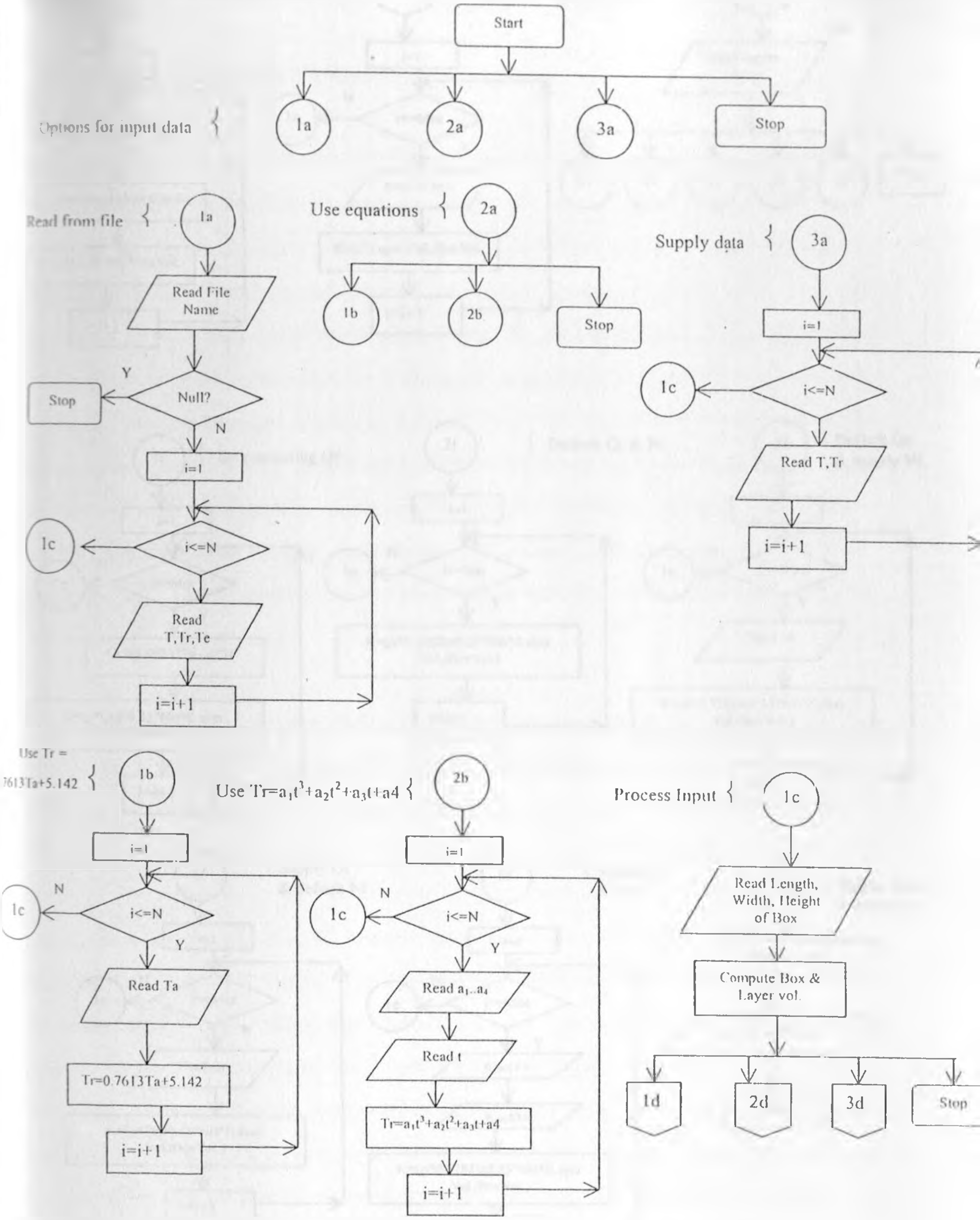


Figure 3.4 Computational Thermal Prediction (CTP) detailed flowchart

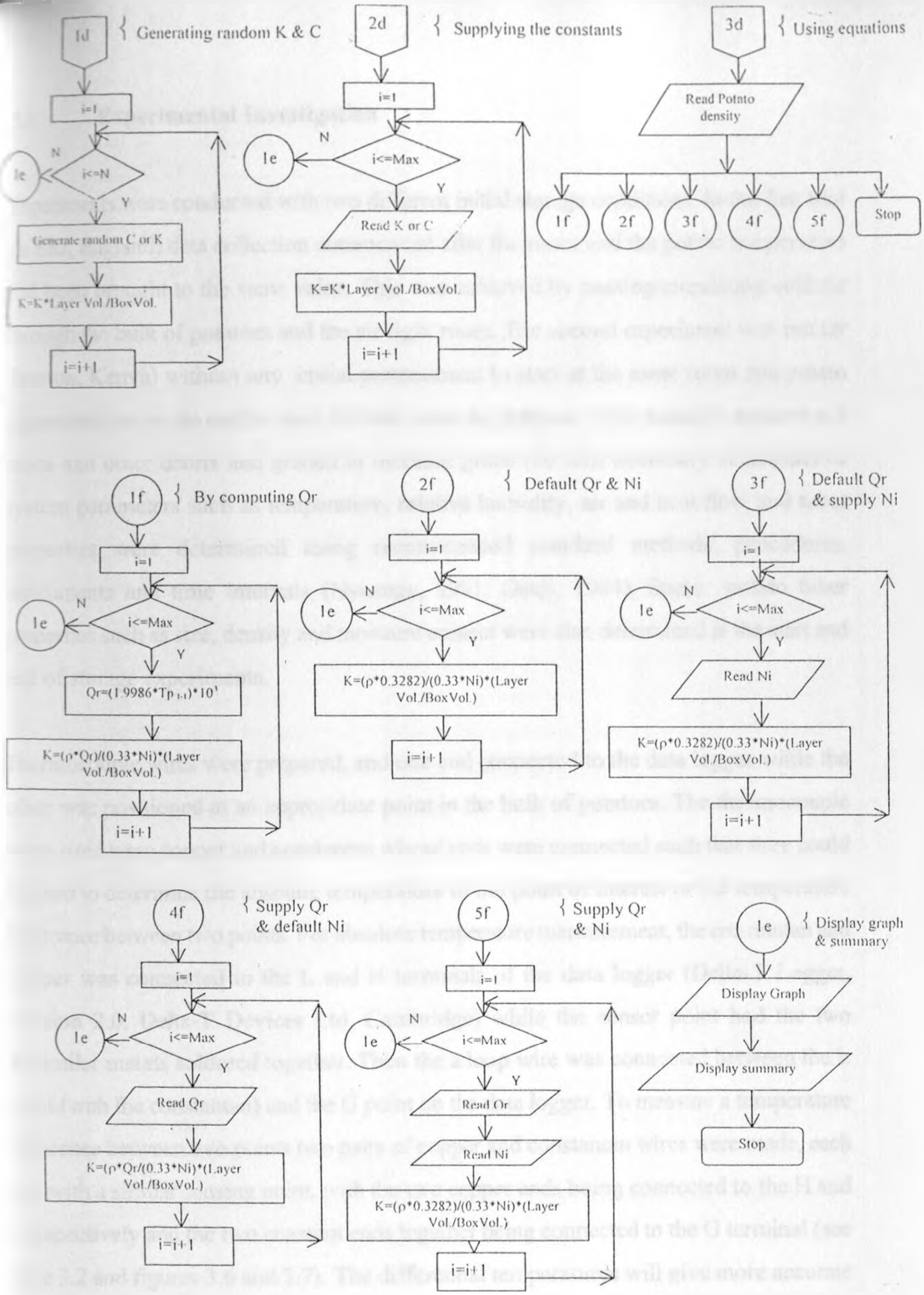


Figure 3.4 contd

3.3 Experimental Investigation

Experiments were conducted with two different initial storage conditions. In the first trial (at SRI, England) data collection commenced after the room and the potato temperature had been brought to the same value. This was achieved by passing/circulating cold air through the bulk of potatoes and the air tight room. The second experiment was run (at Egerton, Kenya) without any initial pretreatment to start at the same room and potato temperature as in the earlier case. In both cases the potatoes were sorted to remove soil clods and other debris and graded to medium grade (50 mm diameter). A number of system parameters such as temperature, relative humidity, air and heat flow and tuber properties were determined using recommended standard methods, procedures, instruments and time intervals (Nyaanga, 1991; Osuji, 1984). Some potato tuber properties such as size, density and moisture content were also determined at the start and end of storage experiments.

Thermocouple wires were prepared, and one end connected to the data logger while the other was positioned at an appropriate point in the bulk of potatoes. The thermocouple wires used were copper and constantan whose ends were connected such that they could be used to determine the absolute temperature of the point of interest or the temperature difference between two points. For absolute temperature measurement, the constantan and copper was connected to the L and H terminals of the data logger (Delta-T Logger, Version 2.0, Delta-T Devices Ltd, Cambridge) while the sensor point had the two dissimilar metals soldered together. Then the a loop wire was connected between the L point (with the constantan) and the G point on the data logger. To measure a temperature difference between two points two pairs of copper and constantan wires were made, each pair with a similar sensing point, with the two copper ends being connected to the H and L respectively and the two constant ends together being connected to the G terminal (see table 3.2 and figures 3.6 and 3.7). The differential temperatures will give more accurate results than the difference between two absolute temperatures.

Table 3.2 SRI Thermocouple Locations

Channel	Location	Type of Temperature measured
1	H -centre, L - room	Differential between centre of bulk and room
2	H-top, L- room	Differential between top of bulk and room
3	H-1/4 to topc, L-room	Differential: quarter to top of bulk and room
4	h- wall, l- centre	Differential temperature between centre of bulk and wall at same height
5	h- centre, l - ½ to wall	Differential temperature between centre of bulk and halfway to wall at same height
6	h-1/4 to bottom, L- room	differential between quarter way to bottom of bulk and room
7	h-1/4 to bottom, L- ½ to wall	differential between quarter way to bottom of bulk and half way to the wall at same height
8	h- in tuber, l - surface of it	differential between centre of a tuber and its surface in the centre of the bulk
9	h-bottom, L -room	differential between bottom of bulk and room
10	h-1/4to topc, l- wall	differential between quarter way to bottom of box and half way to the wall at same height
11	h-1/4to topc, l-half to wall	differential between quarter way to top of bulk and half way to the wall at same height
12	h-topcentre, l - wall	differential between top centre of bulk and the wall at same height
13	h-topc, l-half to wall	differential between top centre of bulk and the half to the wall at same height
14	h-centre, l- corner	differential between top centre of bulk and the corner of the box at same height
17	bulk centre	Absolute temperature at the centre of bulk of potatoes in the box
18	bulk top absolute temp	Absolute temperature at the top of bulk of potatoes in the box
19	room absolute temp	Absolute temperature in the insulated room
20	Lab/ambient absolute temp	Absolute temperature in the laboratory housing the insulated room

The thermocouple wires were calibrated at two known temperatures (melting ice, 0°C and boiling water, 100 °C). The thermocouples were placed in the water at the two temperatures for more than one hour and logged continuously. The mean calibration constants (deviations) from 0°C and 100°C were later added to or subtracted from the all temperature readings in the experiment after down loading the data from the logger.

The temperatures were measured at various locations within the bulk of potatoes defined by a box and its immediate surroundings during the experiments conducted at Silsoe Research Institute (SRI), Great Britain and Egerton (EG), Kenya as indicated in figures 3.6 to 3.9.

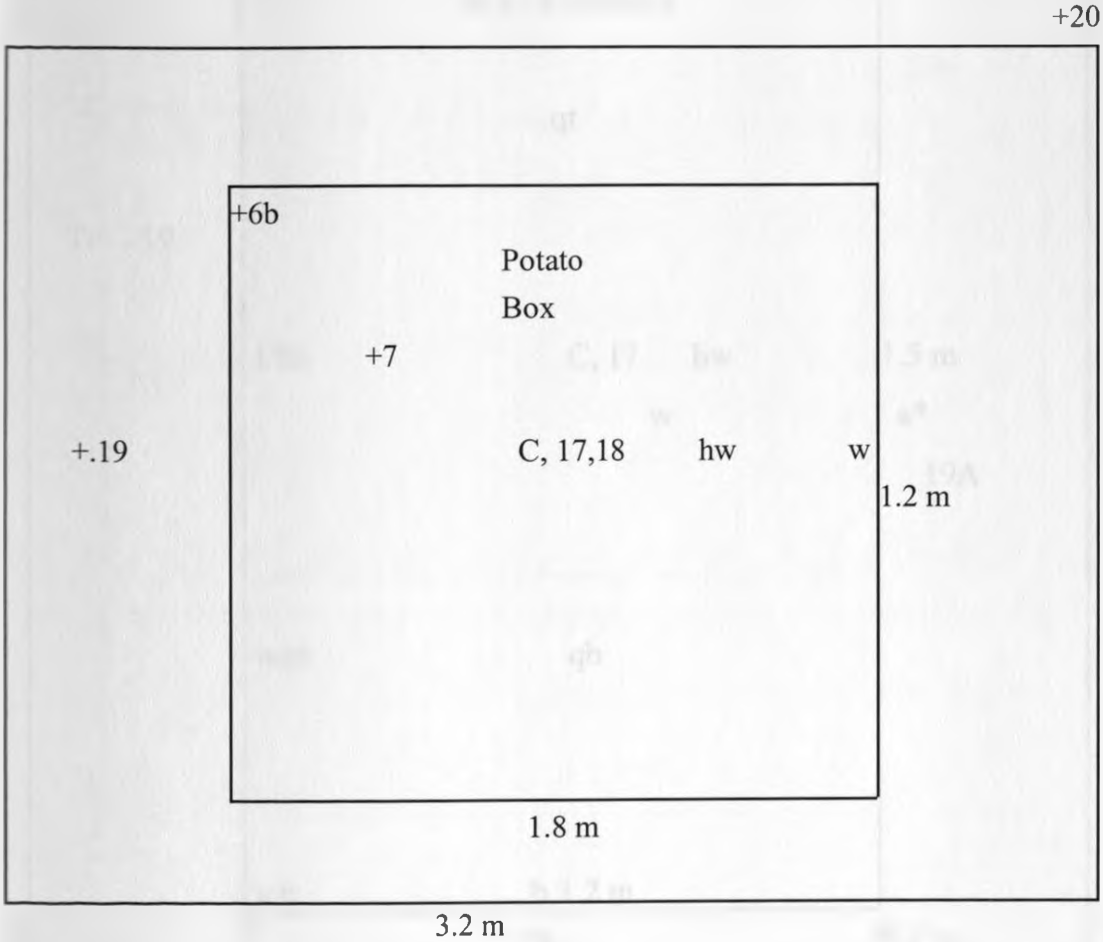


Figure 3.5 Layout plan of SRI potato box in a room and location of sensors. (Not to scale)

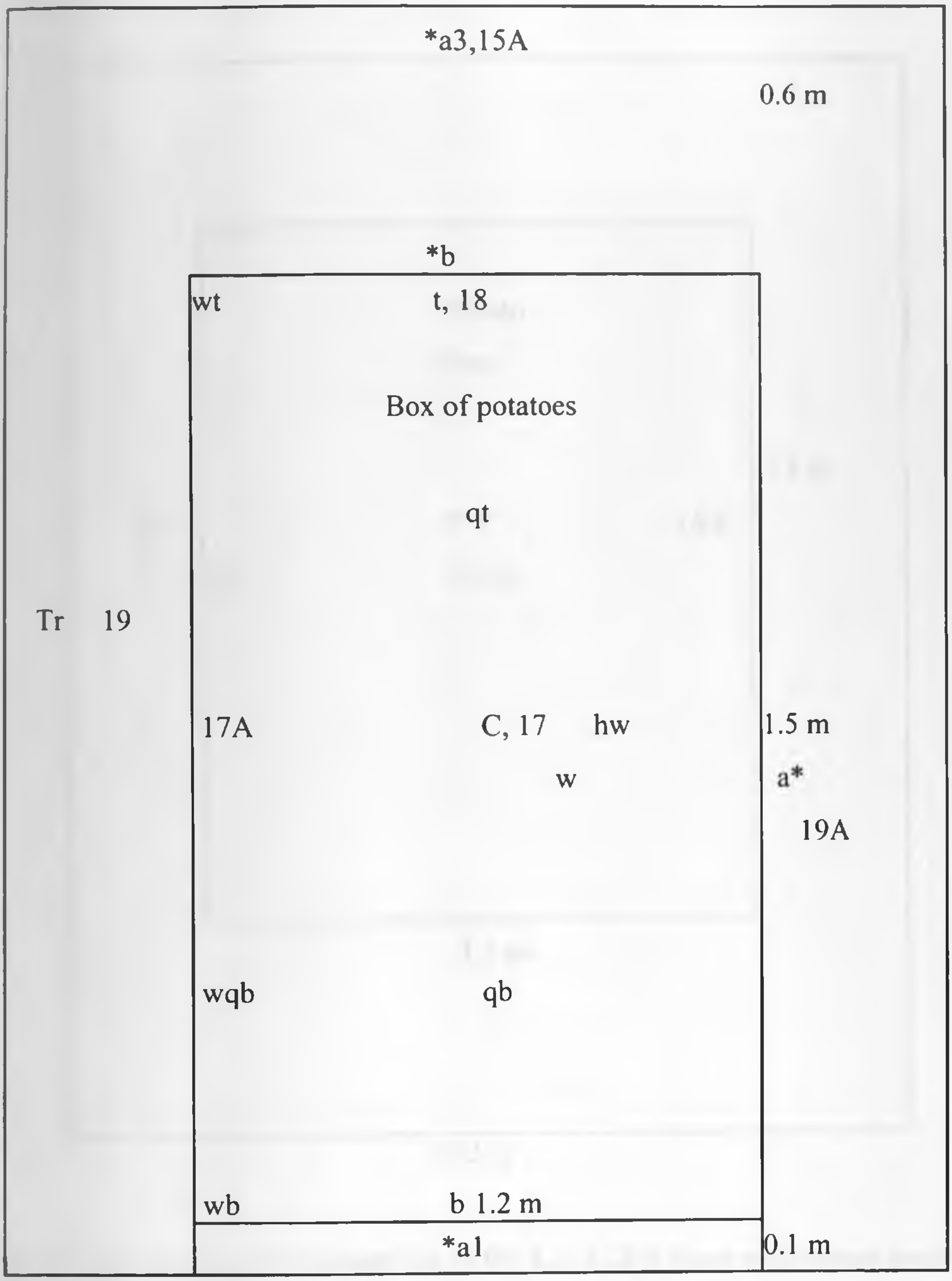


Figure 3.6 Section of SRI room and box of potatoes with sensor locations.

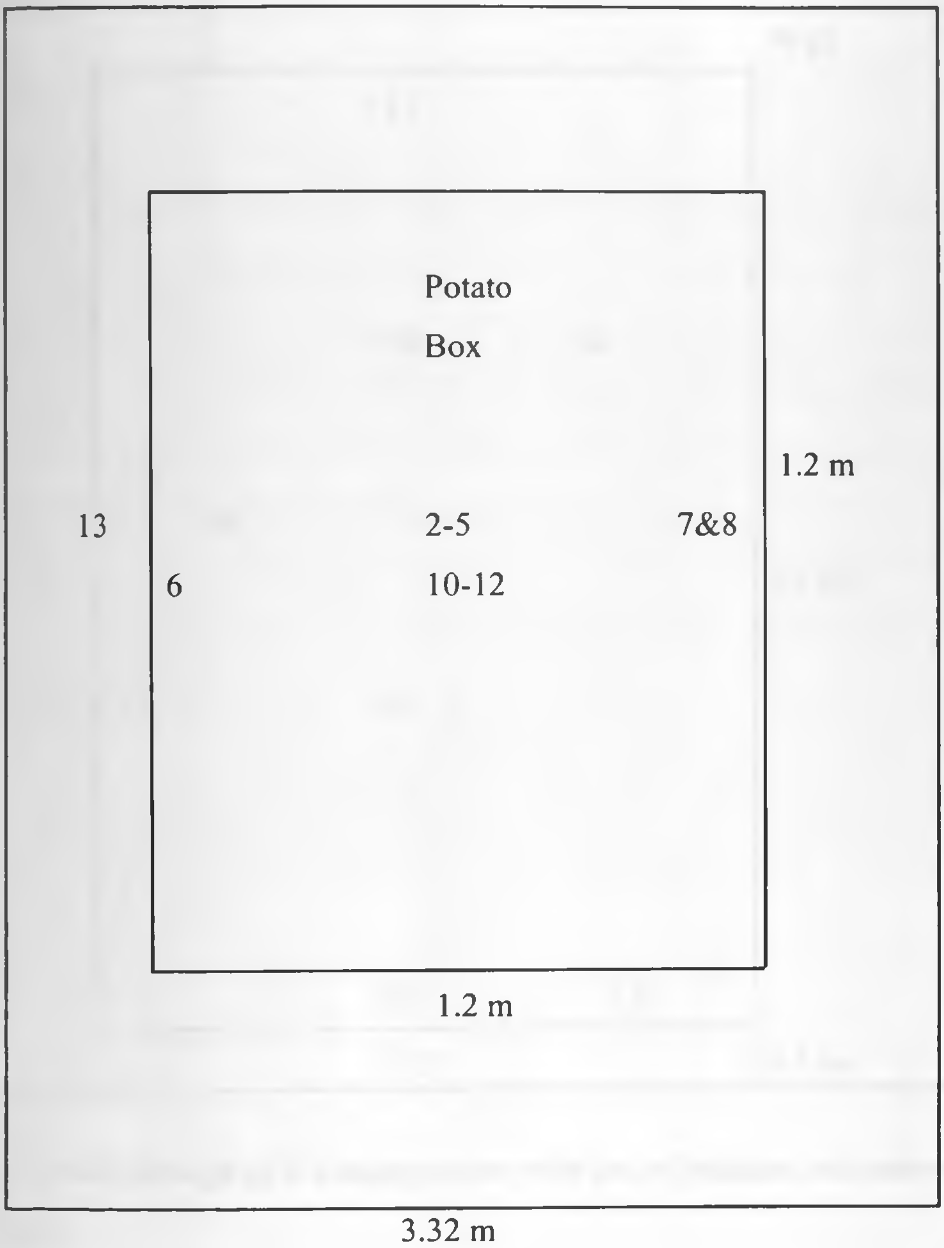


Figure 3.7 Layout plan of EG potato box in the 4.2x3.32 m store with sensor positions.

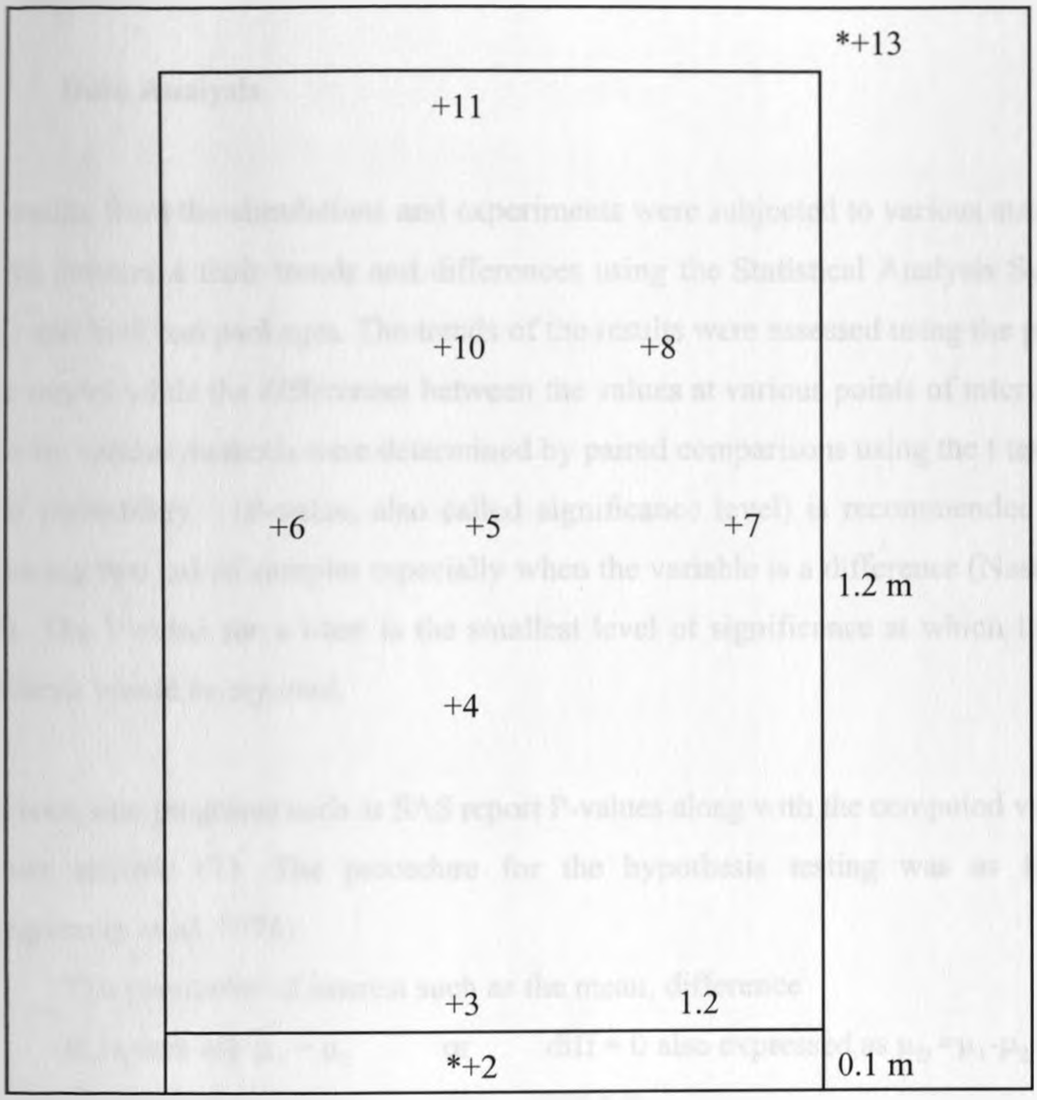


Figure 3.8 Section through of EG storage room with box of potatoes and sensors (Not to scale).

The positioning of the differential and absolute temperature sensors for the SRI experiment is as described in table 3.2. Differential temperatures were determined by sensors between two points of interest, the logger automatically stored the differences at the specified time intervals. The modified PMB box was deemed large enough to reveal differences in lateral temperatures (in all the three dimensions) unlike in the model development which assumed one dimensional variation. Dewpoint temperatures were determined at the centre of the bulk and store using dewpoint meters (Delta-T Dewpoint Meter, Version 1.0, Delta-T Devices Ltd, Cambridge).

3.4 Data Analysis

The results from the simulations and experiments were subjected to various statistical tests to determine their trends and differences using the Statistical Analysis Systems (SAS) and MsExcel packages. The trends of the results were assessed using the general linear model while the differences between the values at various points of interest and results by various methods were determined by paired comparisons using the t test. The use of probability (P-value, also called significance level) is recommended when comparing two paired samples especially when the variable is a difference (Nassiuma, 1999). The P-value for a t-test is the smallest level of significance at which the null hypothesis would be rejected.

Most computer programs such as SAS report P-values along with the computed value of the test statistic (T). The procedure for the hypothesis testing was as follows (Montgomery *et al.* 1998):

1. The parameter of interest such as the mean, difference
2. H_o: (such as) $\mu_1 = \mu_2$ or diff = 0 also expressed as $\mu_D = \mu_1 - \mu_2 = 0$
3. H_o: (such as) $\mu_1 \neq \mu_2$ or diff $\neq 0$
4. P = 0.05 (probability)
5. The test statistic is

$$T = \frac{x - \mu_0}{s/n^{1/2}} \qquad \textbf{(65)}$$

or

$$T = \frac{d}{s_d / n^{1/2}} \quad (66)$$

where diff is the difference; x is the sample mean;

μ is the standard mean deviation

s is standard deviation

d is the sample average, and

s_d standard deviation of the differences.

6. Reject H_0 or accept based on results
7. Computations of the variables
8. Conclusions and meaning of analysis

CHAPTER 4 RESULTS AND DISCUSSIONS

The results of temperature predictions by modified Burton (1989), Nyaanga (1991), semi-theoretical Computational Thermal Prediction (CTP) model and experiments are presented by tables, graphs and discussed in line with the earlier sections of the thesis.

4.1 Empirical Simulation

Using modified Burton (1989) and Nyaanga (1991) equations 44 and 49, the average respiration rate equation 46 and the height (H) as 0.01, 0.25, 0.50, 0.75 and 0.99 of the bulk height (for the different height positions from the bottom to the top), potato temperatures can be computed.

Table 4.1 gives the measured laboratory (labelled ambient), store (room), centre of bulk and top of bulk potato temperatures and the same bulk temperatures as calculated at the centre (0.72 m from bottom) and top of the bulk of potatoes in the SRI box using the modified Burton (1989) and Nyaanga (1991) empirical expressions for predicting the potato temperatures during free convection storage.

Figures 4.1 gives the experimental and Burton empirically simulated centre and top bulk potato temperatures during the 4 days of free ventilation holding. The ambient (laboratory and room/store temperatures are also included for comparison. It is evident that the both experimental and simulated temperatures increased although the store temperatures remained nearly constant confirming that there was internal warming up which has been attributed to the metabolic heat release by the tuber by many researchers. The temperature at the top of the bulk is higher than that at the centre by both methods. This is in agreement with the effects of buoyancy in free ventilation such that cool air enters through the bottom of the stack/box of potatoes and leaves at the top carrying the heat of respiration. The observed temperatures are lower than the simulated temperatures. The average measured centre and top temperatures are 14.94 °C and 15.66 °C respectively while those predicted by the modified Burton (1989) expression are 17.66 °C and 19.16 °C respectively.

Table 4.1 SRI Experimental versus empirically simulated bulk ambient, room and centre and top of bulk potato temperatures (°C)

			Experimental		Burton (1989)		Nyaanga (1991)	
Days	Ta	Room	Centre	Top	Centre	Top	Centre	Top
0.00	21.50	18.91	13.82	14.44	16.36	17.72	17.91	17.90
0.21	21.13	18.46	13.90	14.57	16.46	17.87	18.02	18.01
0.25	21.22	16.74	13.93	14.66	16.50	17.99	18.06	18.05
0.50	21.82	16.56	14.10	15.26	16.70	18.70	18.27	18.27
0.75	21.75	16.50	14.31	15.62	16.93	19.12	18.53	18.53
1.04	21.78	16.49	14.59	15.86	17.26	19.40	18.88	18.88
1.29	22.07	16.57	14.77	15.99	17.47	19.56	19.12	19.12
1.50	22.00	16.65	14.97	16.10	17.70	19.69	19.37	19.37
1.75	21.66	16.60	15.18	16.21	17.93	19.82	19.63	19.62
2.00	22.15	16.42	15.38	16.30	18.17	19.93	19.88	19.88
2.25	22.52	16.45	15.49	16.34	18.29	19.97	20.02	20.01
2.50	21.83	16.66	15.68	16.40	18.52	20.04	20.27	20.26
2.75	22.03	16.53	15.69	16.41	18.53	20.06	20.28	20.27
3.00	22.25	16.39	15.80	16.48	18.65	20.14	20.41	20.41
3.25	22.18	17.47	15.87	16.46	18.73	20.12	20.50	20.49
3.50	21.81	15.34	15.33	14.87	18.11	18.23	19.82	19.82
3.71	21.88	15.09	14.92	14.78	17.64	18.12	19.31	19.30
3.75	22.09	15.11	14.80	14.76	17.50	18.10	19.16	19.15
4.00	22.29	15.05	14.37	14.71	17.01	18.04	18.61	18.61
Average	21.89	16.23	14.94	15.66	17.66	19.16	19.33	19.32
Maximum	22.81	19.07	15.89	16.50	18.76	20.16	20.53	20.52
Minimum	20.55	14.60	13.82	14.18	16.36	17.41	17.91	17.90
Range	2.26	4.47	2.08	2.32	2.39	2.75	2.62	2.62

Generally, the Burton prediction overestimates the temperatures by 2.72 and 3.5 °C for the centre and top temperatures respectively. The difference between the observed and calculated temperature is a bit smaller for centre prediction maybe because the expression may have been developed using centre temperatures (Burton *et al.* 1955 who originally developed the relationship do not give these details). Statistically, the differences between the experimental and the Burton predicted temperatures are significant ($P<5\%$). This implies that the Burton expression may not be accurate although for this SRI data reducing the simulated values by an average of about 3.11 °C could suffice in the absence of any better prediction model.

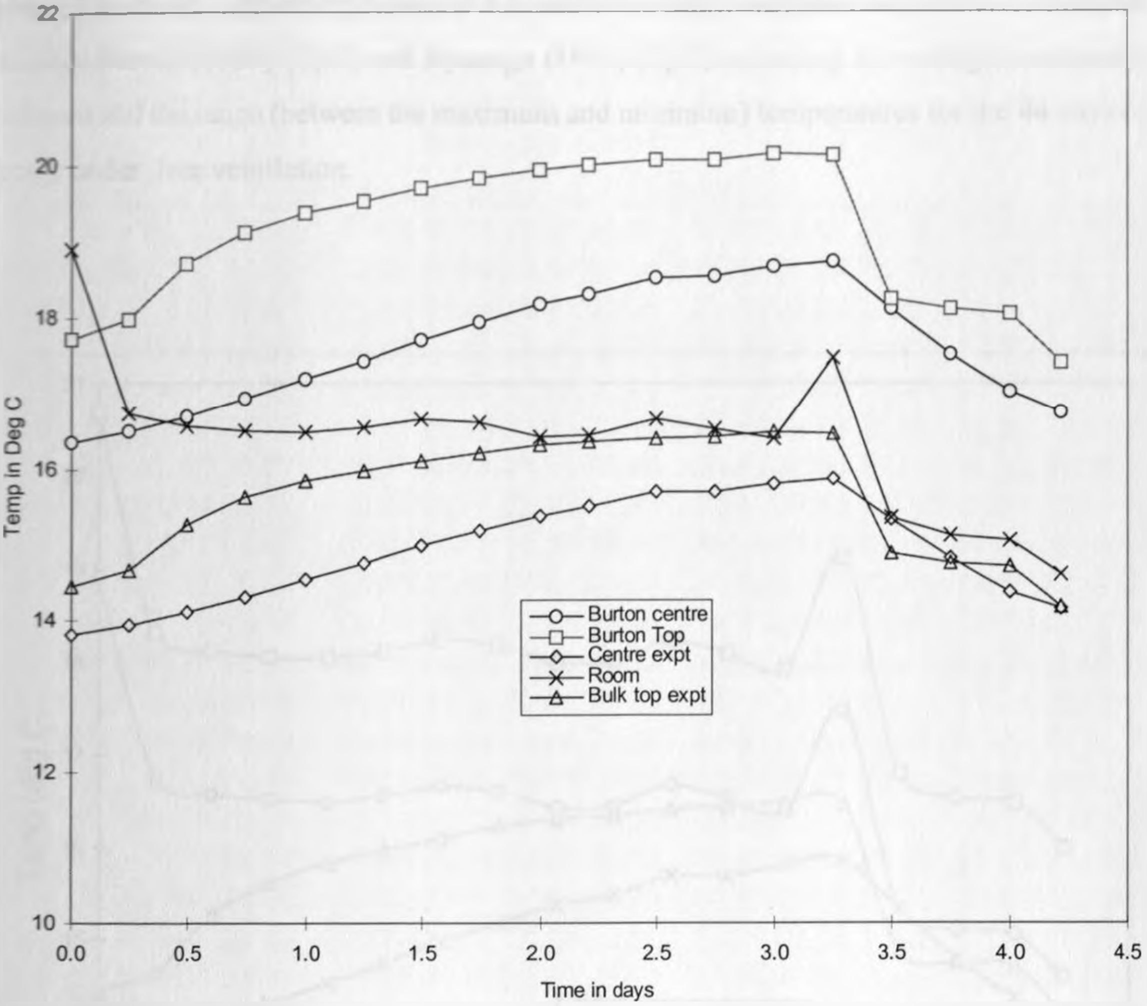


Figure 4.1 SRI Experimental and Burton (1989 mod) predicted bulk potato centre and top bulk potato temperatures

Figure 4.2 compares the SRI experimental with Nyaanga (1991) simulated centre and top bulk potato and store temperatures. Like in the foregoing analysis on figure 4.1 on the Burton (1989) simulation the average Nyaanga (1991) model prediction gives 19.33 and 19.32 °C for the centre and top temperatures respectively. This model is not able to give differences between various bulk temperatures. In this SRI case it overestimates the centre and top temperatures by 4.39 and 3.66 °C respectively. These are much bigger margins than those by Burton model for the same data. This could be attributed to the fact that Burton expression was developed using temperate temperature ranges as those of the SRI data while Nyaanga model was developed using tropical temperature ranges.

Table 4.2 gives the Egerton experimental data and empirically simulated temperatures using the modified Burton (1989) (TpB) and Nyaanga (1991) (TpN) including the average, maximum, minimum and the range (between the maximum and minimum) temperatures for the 44 days of storage under free ventilation.

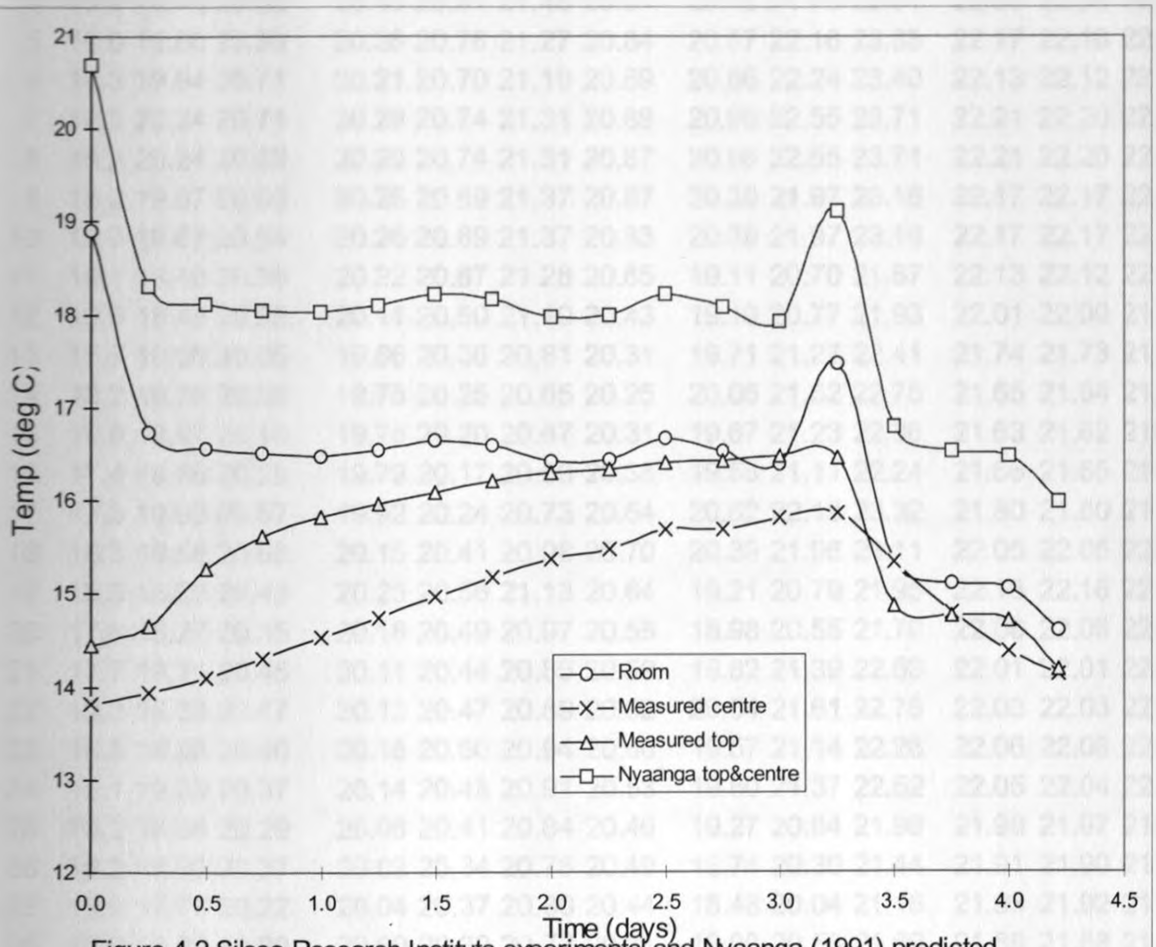


Figure 4.2 Silsoe Research Institute experimental and Nyaanga (1991) predicted centre and top bulk potato temperatures

Table 4.2 Egerton* experimental and empirically simulated temperatures (in °C)

Measured/Exptl				Temperatures				Simulated			Temperatures		
Time	Environmental			Experimental Potato				Burton model			Nyaanga model		
days	Taw	Tae	Tre	Tpbe	Tpce	Tpte	Tpme	TpbB	TpcB	TptB	TbN	TcN	TtN
1	19.9	20.32	20.84	20.72	20.76	20.99	21.10	21.05	22.63	23.76	22.68	22.67	22.66
2	19.8	19.67	20.73	20.81	21.06	21.37	21.13	20.40	22.00	23.15	22.78	22.77	22.76
3	19.5	19.72	20.64	20.62	21.04	21.43	21.05	20.45	22.05	23.21	22.57	22.56	22.56
4	19.9	19.43	20.52	20.43	20.91	21.40	20.91	20.15	21.75	22.91	22.36	22.36	22.35
5	19.0	19.86	20.53	20.26	20.76	21.27	20.84	20.57	22.16	23.33	22.17	22.16	22.16
6	19.3	19.94	20.71	20.21	20.70	21.19	20.89	20.66	22.24	23.40	22.13	22.12	22.11
7	18.9	20.24	20.71	20.29	20.74	21.31	20.89	20.96	22.55	23.71	22.21	22.20	22.20
8	19.2	20.24	20.69	20.29	20.74	21.31	20.87	20.96	22.55	23.71	22.21	22.20	22.20
9	19.2	19.67	20.69	20.26	20.69	21.37	20.87	20.39	21.97	23.16	22.17	22.17	22.16
10	19.7	19.67	20.54	20.26	20.69	21.37	20.83	20.39	21.97	23.16	22.17	22.17	22.16
11	19.1	18.40	20.38	20.22	20.67	21.28	20.65	19.11	20.70	21.87	22.13	22.12	22.12
12	19.0	18.48	20.03	20.11	20.50	21.10	20.43	19.19	20.77	21.93	22.01	22.00	21.99
13	17.7	19.00	20.05	19.86	20.36	20.81	20.31	19.71	21.27	22.41	21.74	21.73	21.73
14	18.2	19.36	20.09	19.78	20.25	20.65	20.25	20.06	21.62	22.75	21.65	21.64	21.63
15	18.0	18.97	20.10	19.76	20.20	20.67	20.31	19.67	21.23	22.36	21.63	21.62	21.62
16	17.4	18.86	20.29	19.79	20.17	20.63	20.38	19.56	21.11	22.24	21.66	21.65	21.65
17	17.3	19.92	20.57	19.92	20.24	20.73	20.54	20.62	22.18	23.32	21.80	21.80	21.79
18	18.3	19.68	20.68	20.15	20.41	20.98	20.70	20.39	21.96	23.11	22.05	22.05	22.04
19	18.3	18.50	20.43	20.25	20.56	21.13	20.64	19.21	20.79	21.95	22.16	22.16	22.15
20	17.6	18.27	20.35	20.16	20.49	20.97	20.58	18.98	20.55	21.70	22.06	22.06	22.05
21	17.7	19.11	20.45	20.11	20.44	20.85	20.59	19.82	21.39	22.53	22.01	22.01	22.00
22	19.3	19.33	20.47	20.13	20.47	20.89	20.62	20.04	21.61	22.75	22.03	22.03	22.02
23	18.8	18.86	20.46	20.16	20.50	20.94	20.60	19.57	21.14	22.28	22.06	22.06	22.05
24	18.1	19.09	20.37	20.14	20.48	20.91	20.53	19.80	21.37	22.52	22.05	22.04	22.04
25	18.2	18.56	20.29	20.08	20.41	20.84	20.46	19.27	20.84	21.98	21.98	21.97	21.97
26	19.2	18.03	20.37	20.02	20.34	20.76	20.49	18.74	20.30	21.44	21.91	21.90	21.90
27	19.0	17.77	20.22	20.04	20.37	20.80	20.44	18.48	20.04	21.18	21.93	21.92	21.92
28	17.3	18.29	19.99	20.00	20.32	20.72	20.31	19.00	20.56	21.69	21.89	21.88	21.88
29	16.9	17.90	19.86	19.89	20.21	20.49	20.19	18.61	20.16	21.27	21.77	21.76	21.76
30	17.0	18.09	19.87	19.81	20.11	20.30	20.13	18.79	20.34	21.43	21.69	21.68	21.67
31	17.1	18.63	19.99	19.78	20.05	20.26	20.14	19.33	20.88	21.97	21.65	21.64	21.64
32	18.0	18.49	20.06	19.79	20.04	20.32	20.19	19.20	20.74	21.84	21.66	21.65	21.65
33	18.4	19.00	20.10	19.81	20.07	20.37	20.19	19.70	21.25	22.36	21.69	21.68	21.68

Table 4.2 Contd.

days	Taw	Tae	Tre	Tpbe	Tpce	Tpte	Tpme	TpbB	TpcB	TptB	TbN	TcN	TtN
34	17.4	19.52	20.23	19.81	20.08	20.44	20.27	20.22	21.76	22.88	21.68	21.68	21.67
35	18.5	19.99	20.45	19.85	20.14	20.61	20.40	20.69	22.24	23.38	21.73	21.72	21.71
36	18.9	19.62	20.83	19.97	20.26	20.82	20.62	20.33	21.88	23.03	21.85	21.85	21.84
37	20.0	20.87	21.00	20.17	20.46	21.15	20.85	21.58	23.15	24.32	22.08	22.08	22.07
38	19.1	20.36	20.94	20.41	20.69	21.38	20.97	21.08	22.66	23.84	22.34	22.33	22.32
39	18.5	20.12	20.82	20.47	20.81	21.47	20.98	20.84	22.43	23.61	22.40	22.40	22.39
40	19.1	20.51	21.05	20.33	20.72	21.39	21.12	21.23	22.81	24.00	22.25	22.24	22.24
41	19.1	19.67	21.19	20.41	20.81	21.55	21.13	20.39	21.98	23.17	22.35	22.34	22.33
42	18.5	18.48	21.02	20.53	20.95	21.72	21.15	19.20	20.80	22.00	22.48	22.47	22.46
43	17.2	19.03	20.83	20.58	20.98	21.60	21.07	19.76	21.36	22.54	22.53	22.52	22.51
44	18.6	17.55	20.47	20.49	20.90	21.47	20.64	18.27	19.87	21.05	22.43	22.42	22.42
Avg	18.52	19.21	20.47	20.16	20.51	21.00	20.64	19.92	21.49	22.64	22.06	22.06	22.05
max	19.99	20.87	21.19	20.81	21.06	21.72	21.15	21.58	23.15	24.32	22.78	22.77	22.76
min	16.93	17.55	19.86	19.76	20.04	20.26	20.13	18.27	19.87	21.05	21.63	21.62	21.62
Range	3.06	3.32	1.33	1.05	1.02	1.46	1.01	3.31	3.28	3.28	1.15	1.15	1.15

* T is the temperature, a represents ambient, w represents weather station, r represents room, e represents experimental or measured, p represents potato, b represents bottom of bulk, c is the centre, t is the top of bulk. B represents Burton model simulation and N represents Nyaanga

Figure 4.3 shows the trends of the centre observed (Egerton data) versus the modified Burton (1989) predicted bulk potato temperatures in relation to the ambient temperature. The bulk temperature at the centre is higher than the ambient temperature throughout the 44 days of storage. The simulated temperature has the same trend as the ambient temperature, rising and falling at nearly the same time. The simulated temperature is higher averaging 21.49 °C with a higher variation (3.28 C) unlike the measured temperature (average 20.51 with a smaller variation, 1.02 ^{0}C.

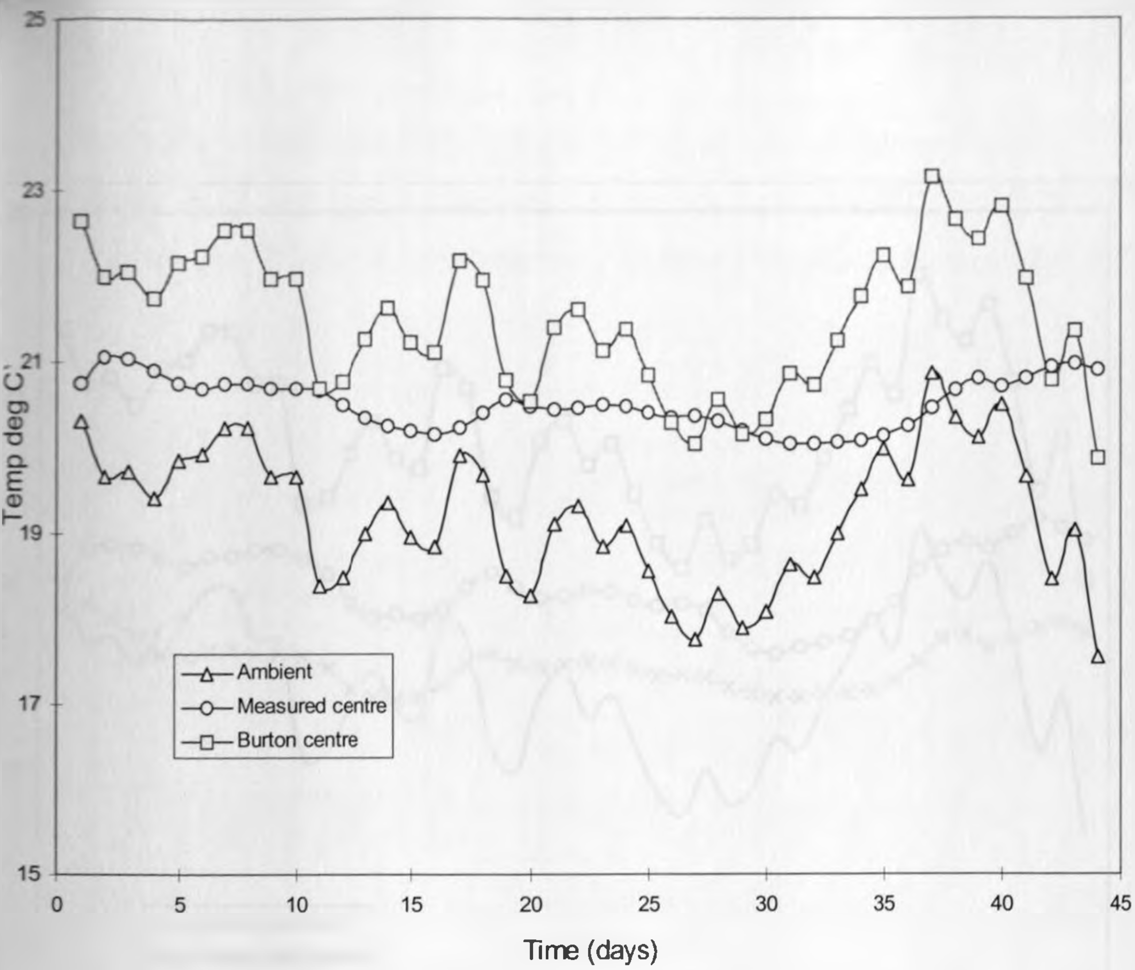


Figure 4.3 Egerton measured and modified Burton (1989) predicted centre bulk potato and ambient temperatures

Figure 4.4 compares the Burton simulated with the Egerton measured temperatures at the top and bottom of the bulk. The results show that the Burton (1989) simulated potato temperature varies and fluctuates with the same trend as that of the ambient temperature but the potato (particularly centre) temperature is fairly stable throughout the storage period. The measured top and bottom temperatures are fairly uniform though not equal. The top temperature is consistently higher than the bottom temperature as expected due to self warming of the bulk due to the heat of respiration. The maximum temperature gradient is about 0.85 °C between the top and the bottom of the bulk from the observed values. On average, the bottom Burton simulated temperatures are slightly lower by about 0.25 °C, than the actual bottom observed temperatures. However, the simulated Burton top potato temperature (average 21.00 °C) are consistently higher by an average of 1.64 °C than the actual observed temperature (averaging 22.64 °C).

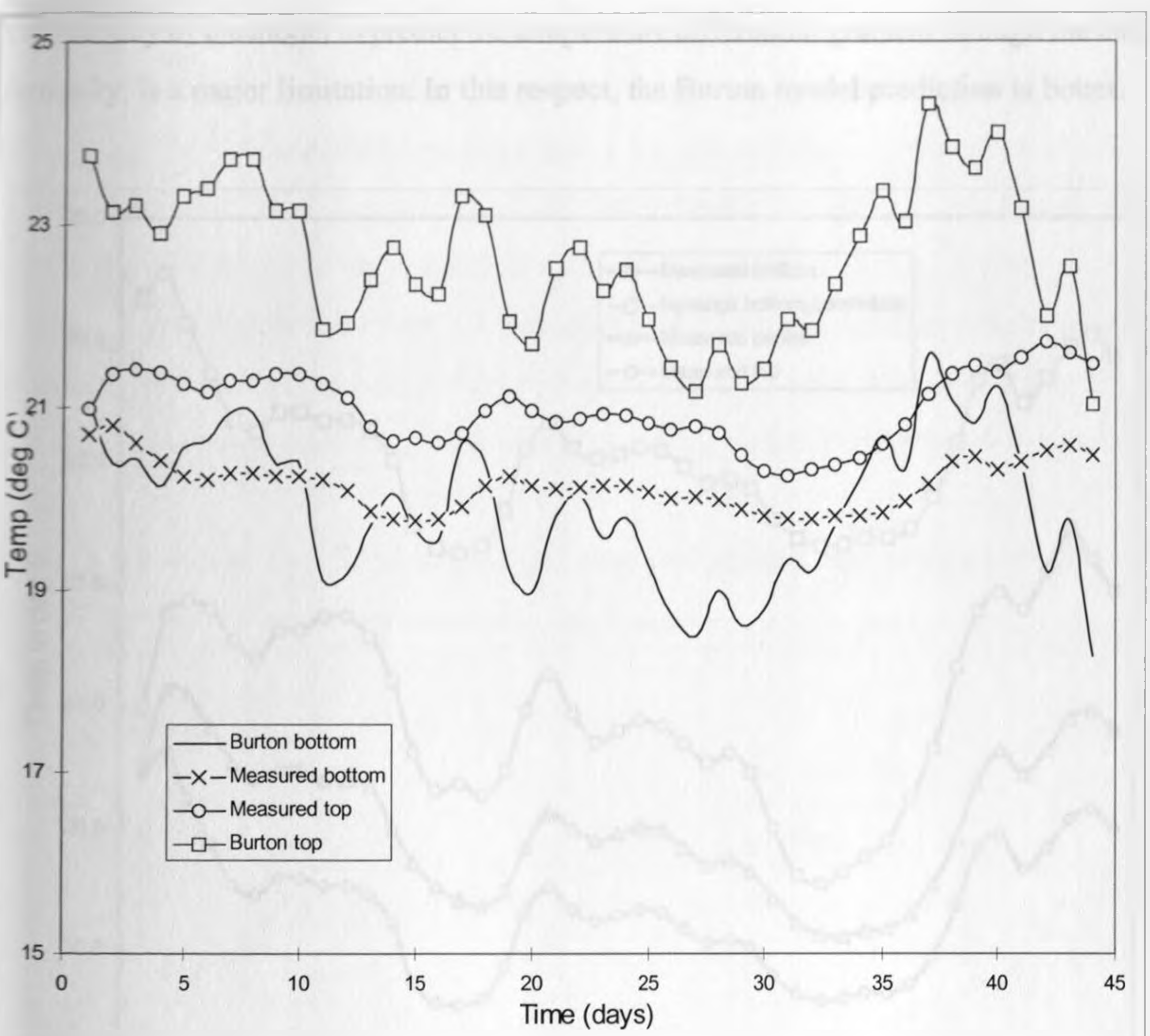


Figure 4.4 Egerton measured and Burton (1989) predicted bottom and top bulk potato temperatures

Figure 4.5 gives the observed and Nyaanga (1991) model simulated bulk potato temperatures. From the figure, it is clear that the Nyaanga (1991) prediction model gives the same bottom, centre and top potato temperature which is consistently higher than the measured temperature although with exactly the same trend. This similarity could be attributed to the fact that the model just increases the room temperature by a multiplying factor of 1.094. This also confirms that the potato temperature is a function of the storage/room temperature. The Nyaanga (1991) potato simulated temperature averages about 22.06 °C with a variation of 1.15° C thus predicting an average top, centre and bottom temperatures which are 1.06, 1.55 and 1.90 °C above the observed respectively. The inability of the model to predict the temperature differential gradient through the bulk vertically, is a major limitation. In this respect, the Burton model prediction is better.

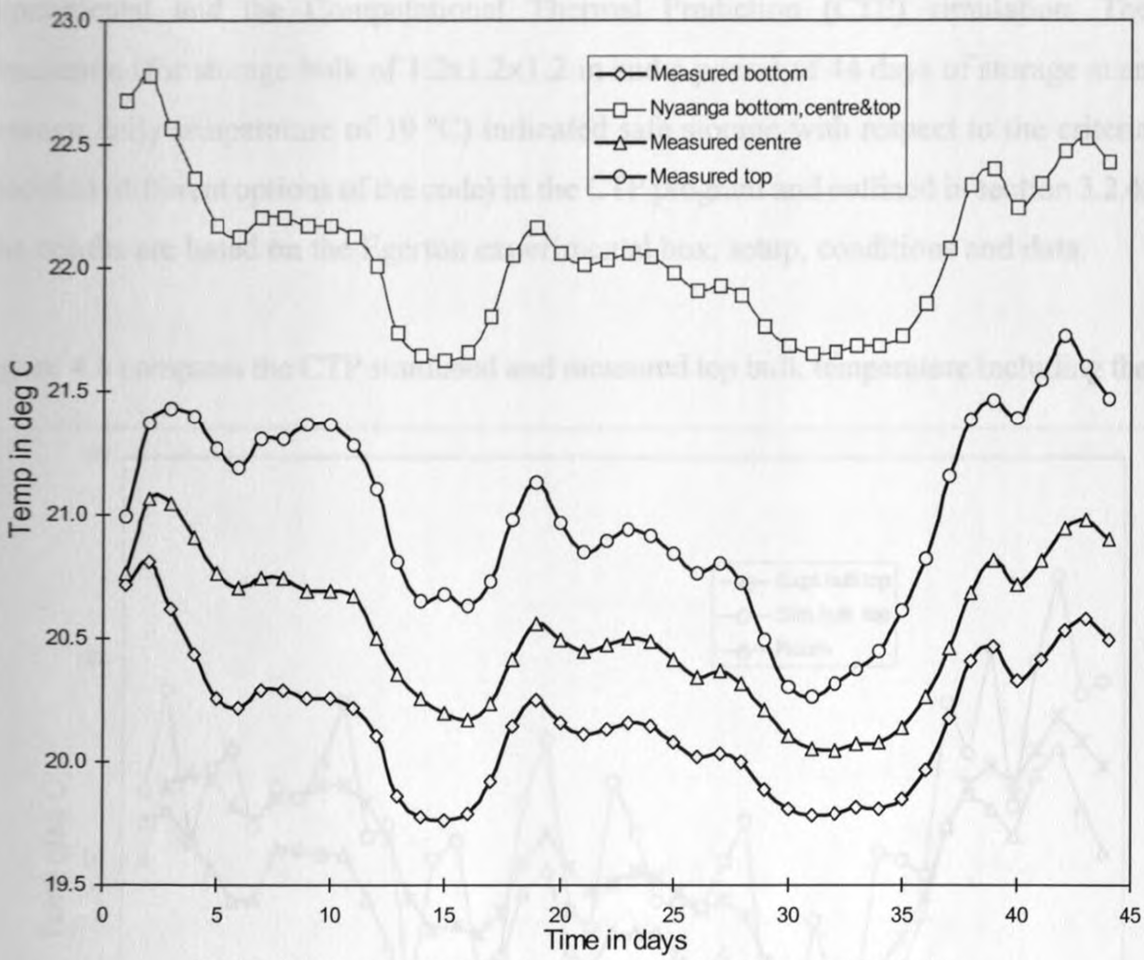


Figure 4.5 Egerton measured and Nyaanga (1991) predicted potato temperatures

The most important observation in the two empirical prediction equations and simulations is that the potato temperature is directly related to the room and ambient temperatures and therefore the prediction of the bulk potato temperature is mainly determined by the prevailing room or ambient temperature. With appropriate factors the equations could be used to predict the bulk potato temperature to some accuracy.

4.2 Computational Thermal Prediction (CTP) Simulation

Tables A2.2 (in the appendix) and 4.3 were used to produce the graphs (figures 4.4 to 4.6) table A2.3 (in the appendix) was the basis for the statistical comparisons on the experimental and the Computational Thermal Prediction (CTP) simulation. The simulation (for storage bulk of 1.2x1.2x1.2 m and a period of 44 days of storage at an average daily temperature of 19 °C) indicated safe storage with respect to the criteria specified (different options of the code) in the CTP program and outlined in section 3.2.4. The results are based on the Egerton experimental box, setup, conditions and data.

Figure 4.6 compares the CTP simulated and measured top bulk temperature including the

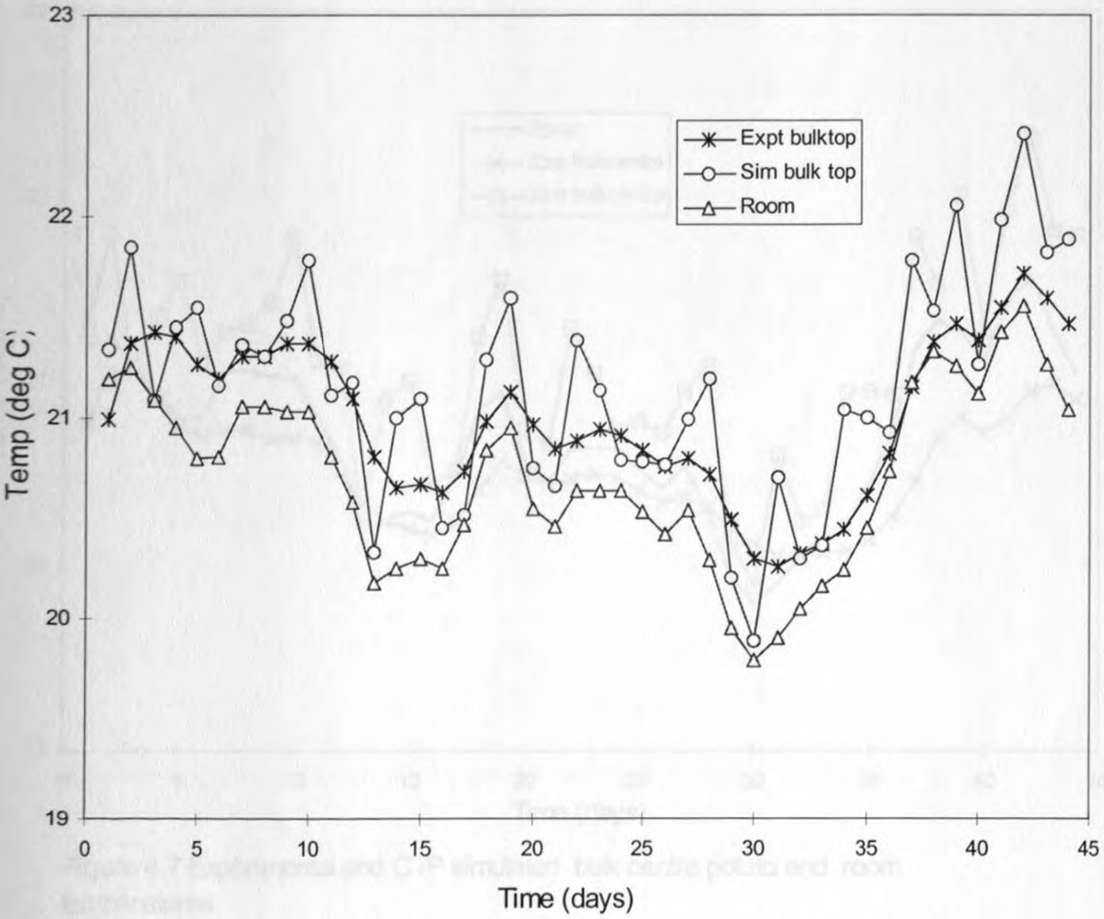


Figure 4.6 Experimental and CTP simulated bulk top potato, room and ambient temperatures

room and ambient temperatures. The CTP simulated and observed top temperatures closely follow each other in trend and magnitude although the simulated temperature (averaging 21.15 °C) curve has daily deviations of about 0.5 °C from the mean trend. The observed overall mean bulk top temperature was 21.00 °C. The average room temperature (20.71 °C) is lower than both the potato temperatures (21.00 °C) throughout the 44 days of storage and data collection. This can be attributed to the heating effect due to release of metabolic heat by the potatoes. The average store/room temperature (20.47 °C) was higher than the ambient (weather station) temperature (19.21 C) due to the greenhouse effect of the structure housing the storage room.

Figure 4.7 compares the CTP simulated and measured centre bulk temperature including

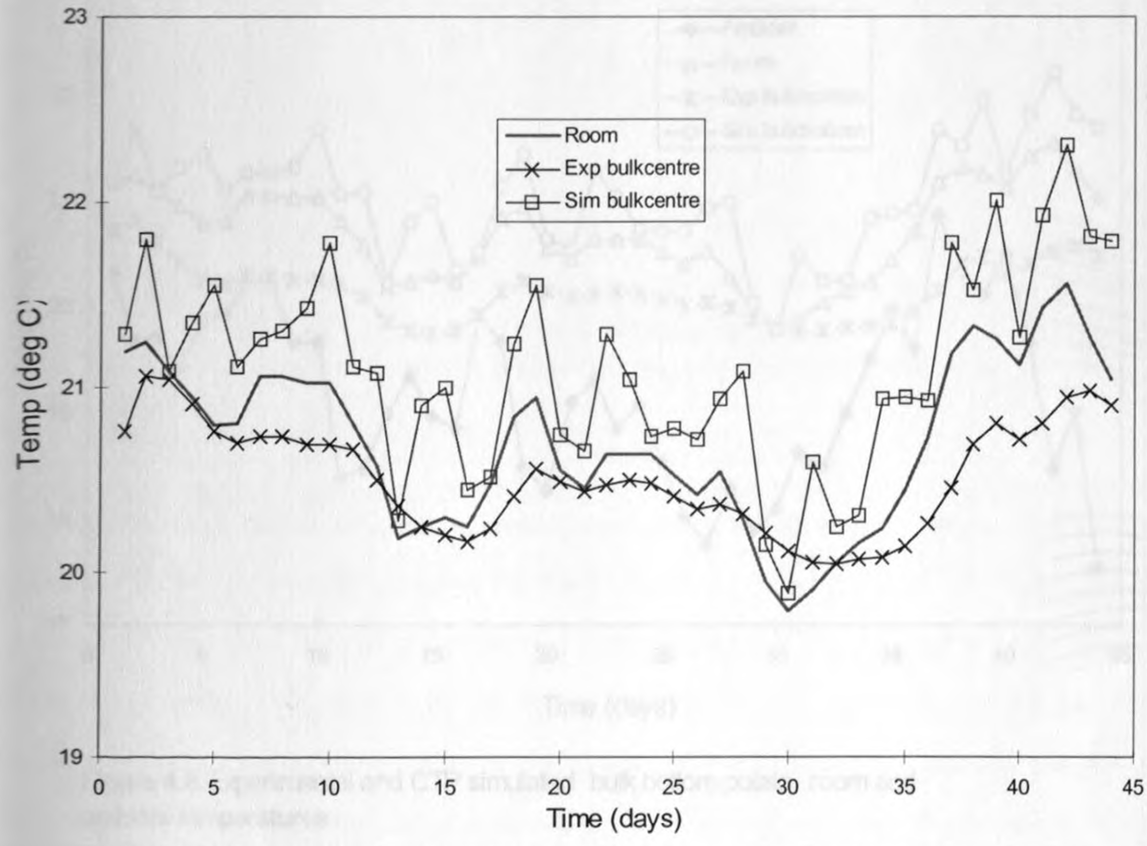


Figure 4.7 Experimental and CTP simulated bulk centre potato and room temperatures

the room and ambient temperatures. Unlike the top temperatures, the CTP simulated and observed centre temperatures do not have exactly the same trend and their magnitudes are slightly different. The simulated temperature (averaging 21.05 °C) is higher than the observed temperature (averaging 20.51 °C) with the former curve exhibiting a wider variation. The simulated temperature trend is similar to that of the room with the former displaced upwards by an average magnitude of about 0.3 °C. The similarity between the CTP simulated and room temperature can be attributed to the use of the room temperature in the CTP formulation.

Figure 4.8 compares the CTP simulated and measured bottom layer temperature in the box of potatoes. The comparisons of trends and magnitudes of the CTP and observed bottom temperatures are similar to those of the centre temperatures discussed in the preceding paragraph except with the specific values.

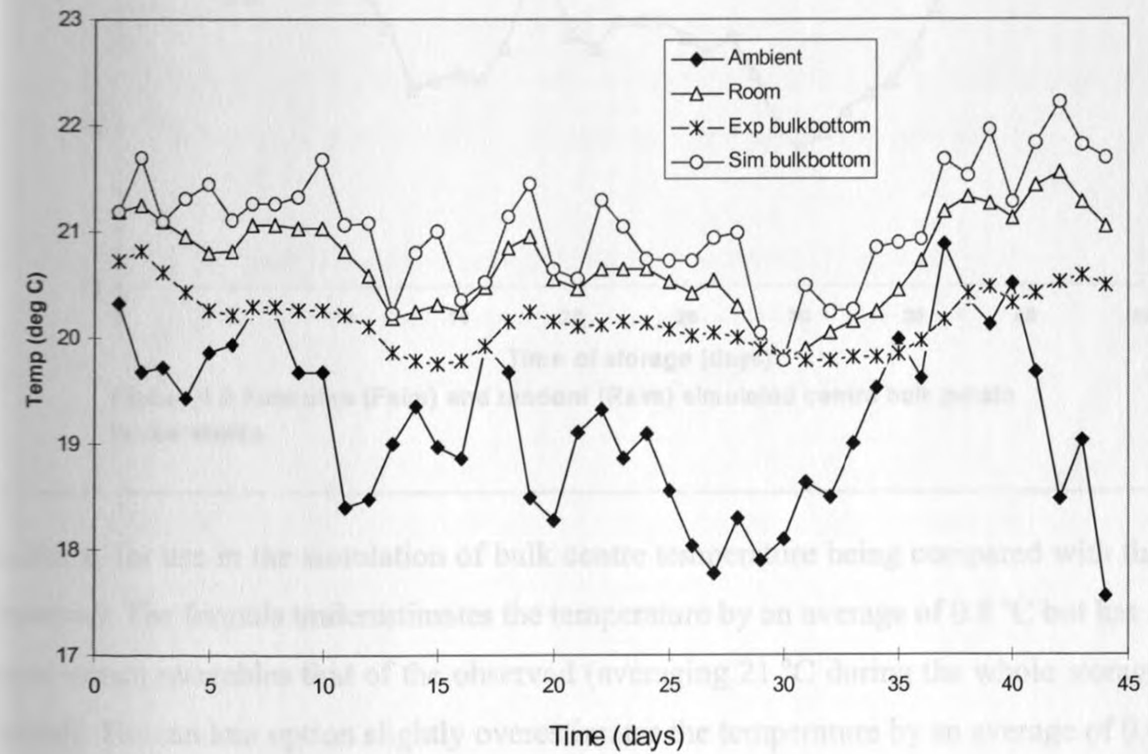
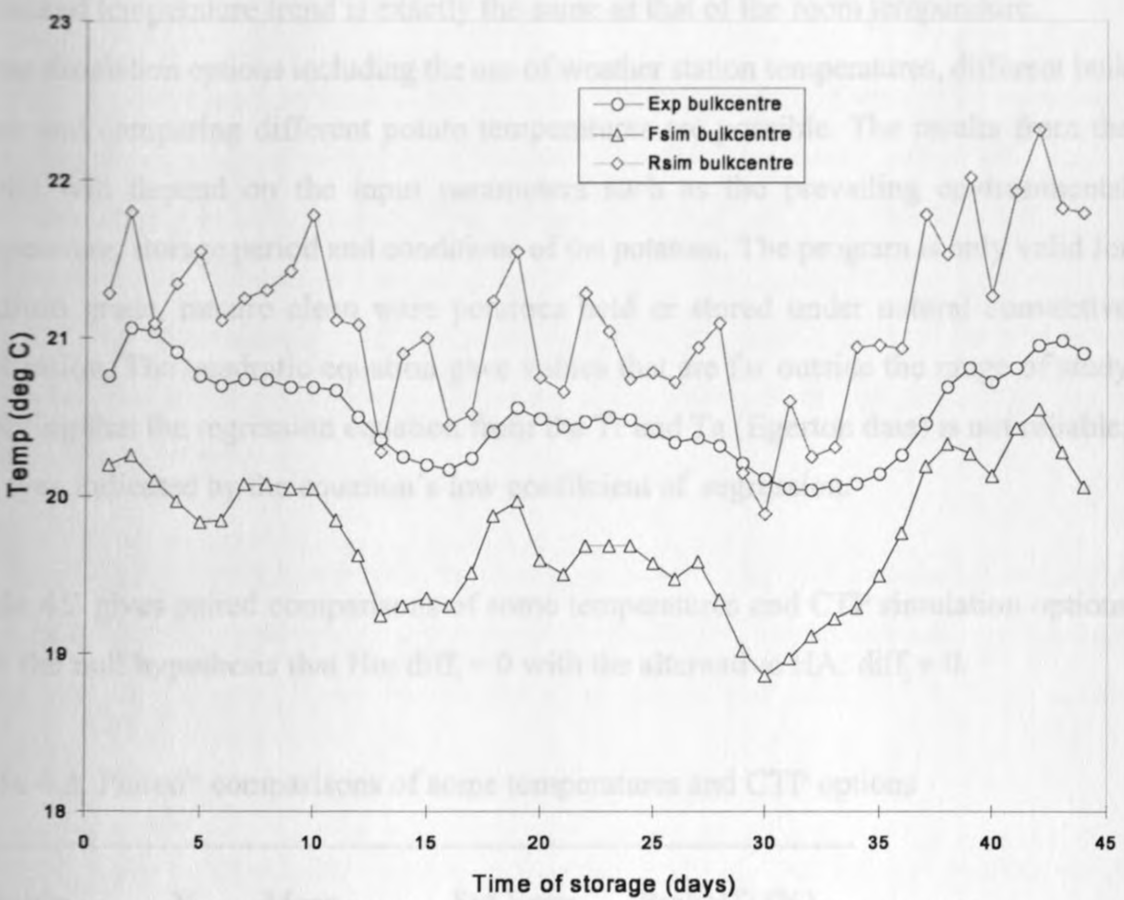


Figure 4.8 Experimental and CTP simulated bulk bottom potato, room and ambient temperatures

Figure 4.9 compares the use of the formula and the random options of generating the c_o and/or c_i for use in the simulation of bulk centre temperature being compared with the observed. The formula underestimates the temperature by an average of 0.8 °C but has a trend which resembles that of the observed (averaging 21 °C during the whole storage period). The random option slightly overestimates the temperature by an average of 0.4 °C with a trend that has greater deviations than the observed. There is a general similarity between the observed and simulated temperature trends, implying that the model is valid. The measured potato temperatures do not fluctuate as much as the simulated ones. This is true at all the vertical monitoring positions in the bulk, although it is more pronounced in the lower layers. The lower positions (near the inlet of the convective air flow) are more prone to the wider room or store temperature changes while the centre and upper



Figfure 4.9 Formulae (Fsim) and random (Rsim) simulated centre bulk potato temperatures

layers are cushioned against this by the poor conducting air-potato medium. The effect of the surrounding room temperature on the bulk temperature is evident in that the simulated temperature trend is exactly the same as that of the room temperature.

Other simulation options including the use of weather station temperatures, different bulk sizes and comparing different potato temperatures are possible. The results from the model will depend on the input parameters such as the prevailing environmental temperature, storage period and conditions of the potatoes. The program is only valid for medium grade, mature clean ware potatoes held or stored under natural convective ventilation. The quadratic equation gave values that are far outside the range of study implying that the regression equation from the Tr and Ta (Egerton data) is not reliable; this was indicated by the equation´s low coefficient of regression.

Table 4.3 gives paired comparisons of some temperatures and CTP simulation options with the null hypothesis that Ho: $diff_i = 0$ with the alternative HA: $diff_i \neq 0$.

Table 4.3 Paired* comparisons of some temperatures and CTP options

Variable	N	Mean	Std Error	Prob>|T| (%)
Ta-Tr	44	1.50	0.106	0.01
Ta-Tec	44	1.31	0.117	0.01
Ta-Tfsc	44	0.53	0.106	0.01
Ta-Trsc	44	1.90	0.119	0.01
Tr-Tec	44	0.19	0.035	0.01
Tr-Tfsc	44	0.97	0.003	0.01
Tr-Tec	44	0.19	0.035	0.01
Teb-Tec	44	-0.36	0.013	0.01
Teb-Tfsb	44	-0.10	0.034	0.45

*Variable in terms of difference between specified temperatures where N is the number of observations;

Ta is the ambient temperature; Tr is the room/ambient temperature; Te is the observed potato temperature; fs represents formula simulated; rs represents random simulated; c represents centre of bulk; b represents bottom of bulk.

Statistically, there are significant differences between all the experimental, CTP simulated (with the two options) at all points of determination (bottom, centre, top of bulk, room, and ambient) as is also evident from tables A2.3 and A2.5 (in the appendix). All differences are significant at a probability of 0.01%. The same pattern of relationships exits between the variedly CTP simulated temperatures among themselves and when compared to the observed values. This implies the assumptions and procedures in the model are accurate.

The individual temperature trends, by various options of the CTP simulation and at the different points of monitoring were same at probability of 1% as indicated by the SAS ANOVA and general linear model statistics (see tables A2.3; A2.5; A2.6 in the appendix).

Generally, the predicted values are higher than the observed. The differences could result from assumptions and constants used in the mathematical model in relation to the major modes of heat exchange and the quantification of the constants. The assumption that infiltration convection heat loss is equal to the respiration rate may not be absolutely correct due to the presence of other forms of heat exchange and restrictions to free natural air flow may have not been accurately quantified through the use of N. These two are therefore taken to be the major sources of error in the CTP simulation.

4.3 Extra Experimental Results

Table 4.4 gives a SAS output for comparing paired temperature differences with the null hypothesis Ho: $diff_i = 0$ and the alternative HA: $diff_i \neq 0$ at $P<5\%$.

Table 4. 4 ANOVA for paired temperature differences

Data	Variable	N	Mean	Std Error	T	Prob>|T|
SRIBurt	centre-top	102	-1.506	0.061	-24.823	0.01%
SRIexpt	lab-store	19	5.395	0.301	17.901	0.01%
SRIexpt	lab-bulkcent	19	7.085	0.136	52.261	0.01%
SRIexpt	lab-bulktop	19	6.376	0.174	36.584	0.01%
SRIexpt	store-bulkcent	19	1.690	0.329	5.128	0.01%
SRIexpt	store-bulktop	19	0.981	0.310	3.163	0.54%
SRIexpt	bulkcent-bulktop	19	-0.709	0.109	-6.514	0.01%

The results require that we reject the null hypothesis and accept the alternative hypothesis for all the paired differences. The differences show that they are significantly different ($p<1\%$).

Figure 4.10 shows the dewpoint and the dry bulb (thermocouple sensed) temperatures. The thermocouple temperature in the bulk of potatoes was about 3 °C lower than its surroundings (the store) at the start of free natural ventilation storage. This difference reduced to about 1.2 °C in less than of the 3 days with the store temperature remaining fairly constant at about 16.8 °C, indicating that there is heat generated by the potatoes. The store and bulk dewpoint temperatures were about 14 °C and 13.5 °C respectively at the start, both rising to 14.2 °C. The increase was greater in the bulk indicating some moisture input in the bulk from the potatoes' respiration process.

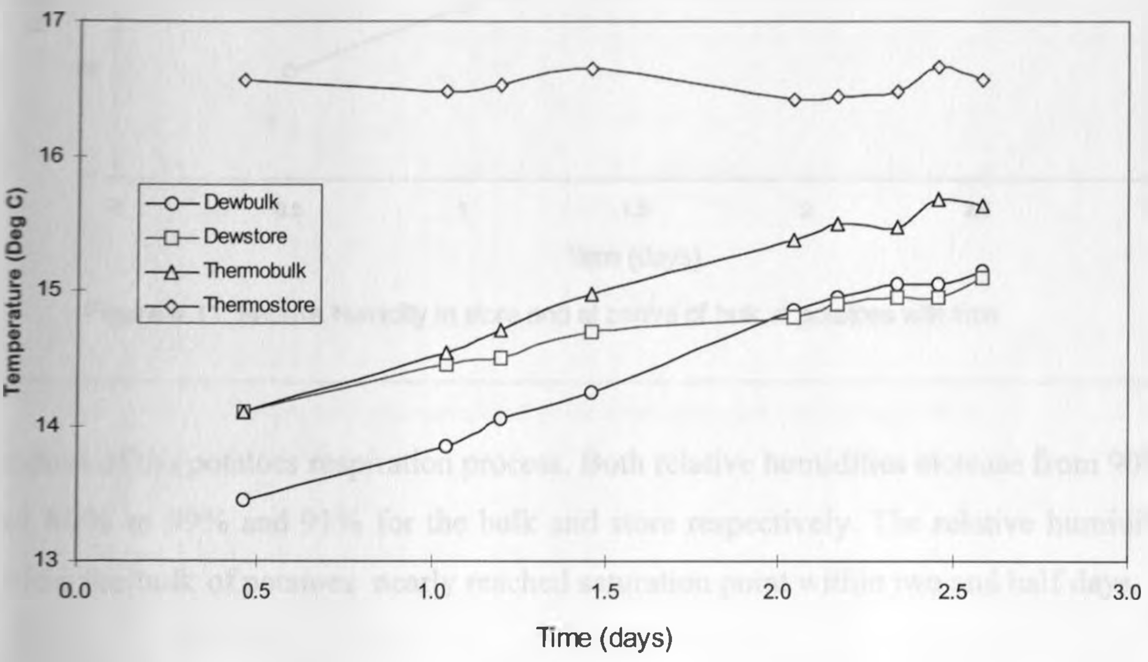


Figure 4.10 Dewpoint and thermocouple temperatures in store and at centre of bulk of potatoes with time

Figure 4.11 shows the relative humidity at the centre of the bulk of potatoes and in the room/store in which the potatoes are stored. It is evident that relative humidity in the bulk of potatoes is higher than that in the store due to the moisture being release as a by-

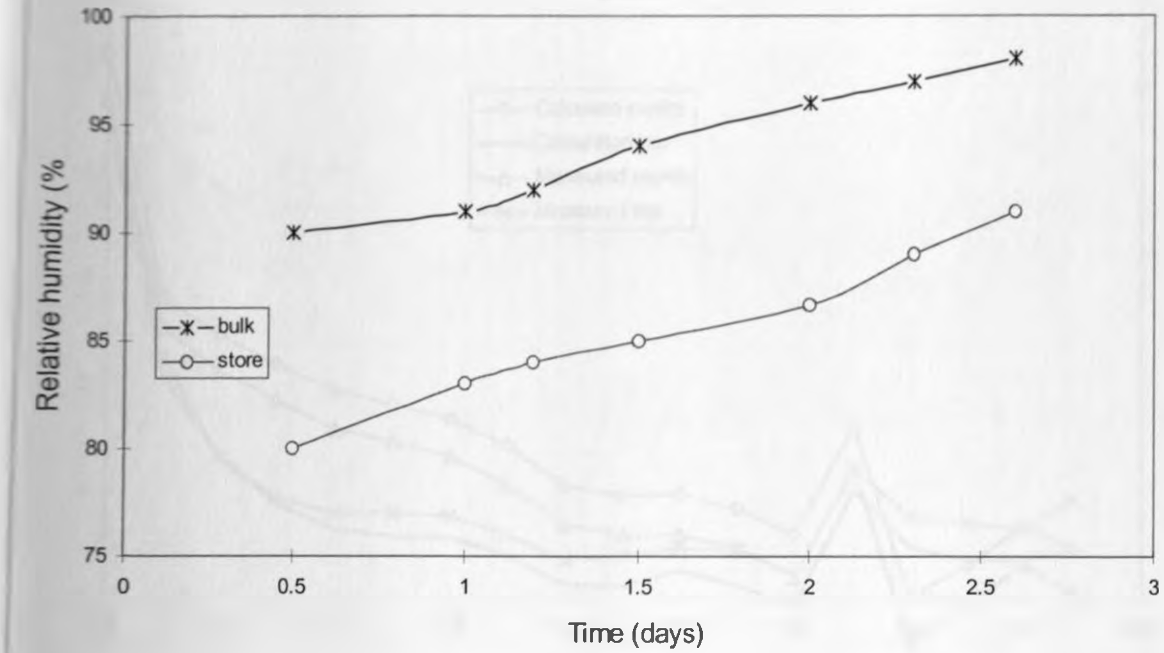


Figure 4.11 Relative humidity in store and at centre of bulk of potatoes with time

product of the potatoes respiration process. Both relative humidities increase from 90% and 80% to 99% and 91% for the bulk and store respectively. The relative humidity within the bulk of potatoes nearly reached saturation point within two and half days.

Figure 4.12 compares the measured and calculated differential temperatures between the centre of the bulk potatoes and the store (its immediate surroundings). The measured differential temperature (determined directly by differential sensor coupling) was always higher than the calculated temperature (obtained by subtracting the measured absolute store from the measured absolute bulk temperature) by an average of 0.36 °C. This difference could be attributed instrumental (coupling) errors. The former approach of coupling the thermal sensors such that the difference between two points can be measured is more accurate (Holman and Gadja, 1984)

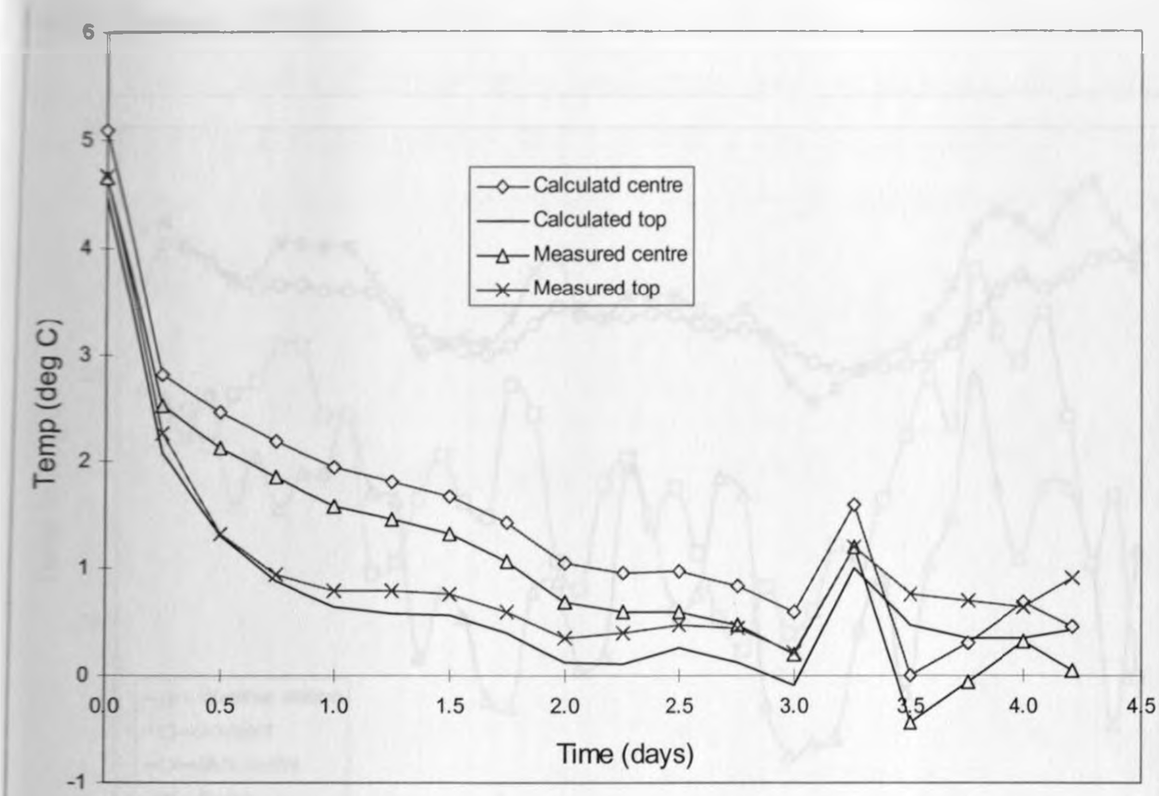


Figure 4.12 Measured and calculated differential temperatures between store and bulk of potatoes

Figures 4.13 shows the variation of the Egerton weather station, experimentally measured ambient, room and bulk potato temperatures (at the bottom, centre and top of the bulk). The weather station temperature was lower than the ambient temperature almost throughout the 44 days of experimentation and data collection. The trend of the bulk potato temperature was the same as that of the store/room temperature with small intermittent higher store temperatures on days when the ambient temperatures are high. difference could be attributed to the fact that the ambient temperatures were taken on the outside wall not fully shaded as in the weather station and the difference in the accuracy of the instruments. The weather station uses dry bulb mercury thermometer whose accuracy is ±0.5 °C while the ambient temperature was measured by thermocouple sensors and gged by a data logger whose whose accuracy was ±0.22 °C (Holman and Gadja, 1984; Delta-T Devices, 1992).

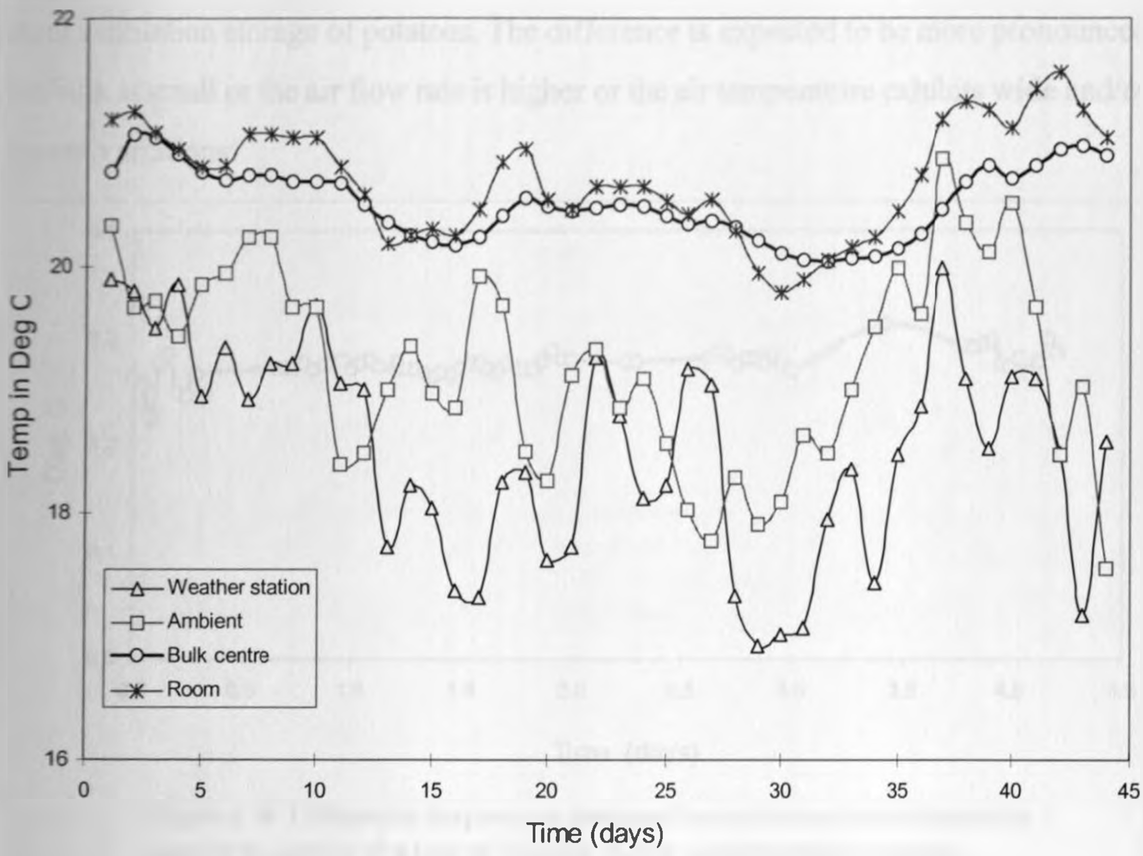


Figure 4.13 Weather station and experimentally measured outside, room and centre bulk potato temperatures (Egerton, April/May 1998)

Figure 4.14 gives the difference between the temperature measured inside a tuber (at its centre) and the air temperature around the surface of the tuber. The tuber was placed at the centre of a bulk of potatoes measuring 1.83 by 1.22 by 1.44 m and the temperatures were monitored for the next 4.5 days. The difference between the inside and surface air temperature during the free natural ventilation holding was fairly constant, being the same (averaging 0.27 °C) throughout the 4.5 days. Statistically , the two are not significantly different even at 95% confidence level. Thermocouple and data logger error of ± 0.22 °C could be a factor but this is unlikely since the tuber temperature was always higher, never zero at any time 0. Therefore, it can be said that tuber temperature is not exactly the same as the bulk potato temperature as alluded by Nyaanga (1991) and of which Burton *et al.* (1955) is silent about in his work on natural ventilation storage. It is thus necessary to specify which potato temperature (tuber or bulk/air) even in free natural ventilation storage of potatoes. The difference is expected to be more pronounced if the bulk is small or the air flow rate is higher or the air temperature exhibits wide and/or frequent variations.

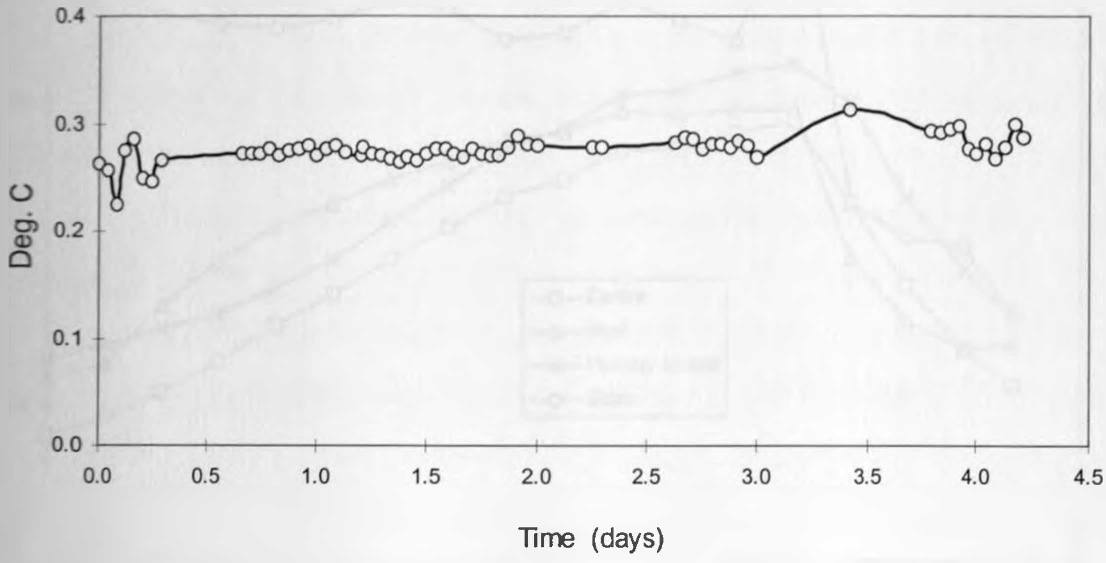


Figure 4.14 Differential temperature between the centre and the surface of a tuber at the centre of a bulk of potatoes during natural ventilation holding

The mean difference between the mean potato and mean observed ambient (Tpm-Tam) temperatures was 1.44 °C which is within the range (1-2 °C) reported by Burton *et al.* (1955), Burton (1989) and Nyaanga (1991) for a free natural storage system. The average of the various bulk temperatures was taken as mean potato temperature and was found to be nearly equal to the centre bulk temperature as has been suggested by Nyaanga (1991). The small overall (over the 44 days of storage) mean difference between the potato and room temperature (Tpm-Trm) of 0.16 °C supports Burton *et al* (1955) conclusion that the potato temperature during unventilated storage settles down to the average ambient/store temperature.

Figure 4.15 gives a comparison of the temperature history from the centre to the wall or edge of the bulk halfway from the bottom of the stack/box. Both temperatures are lower

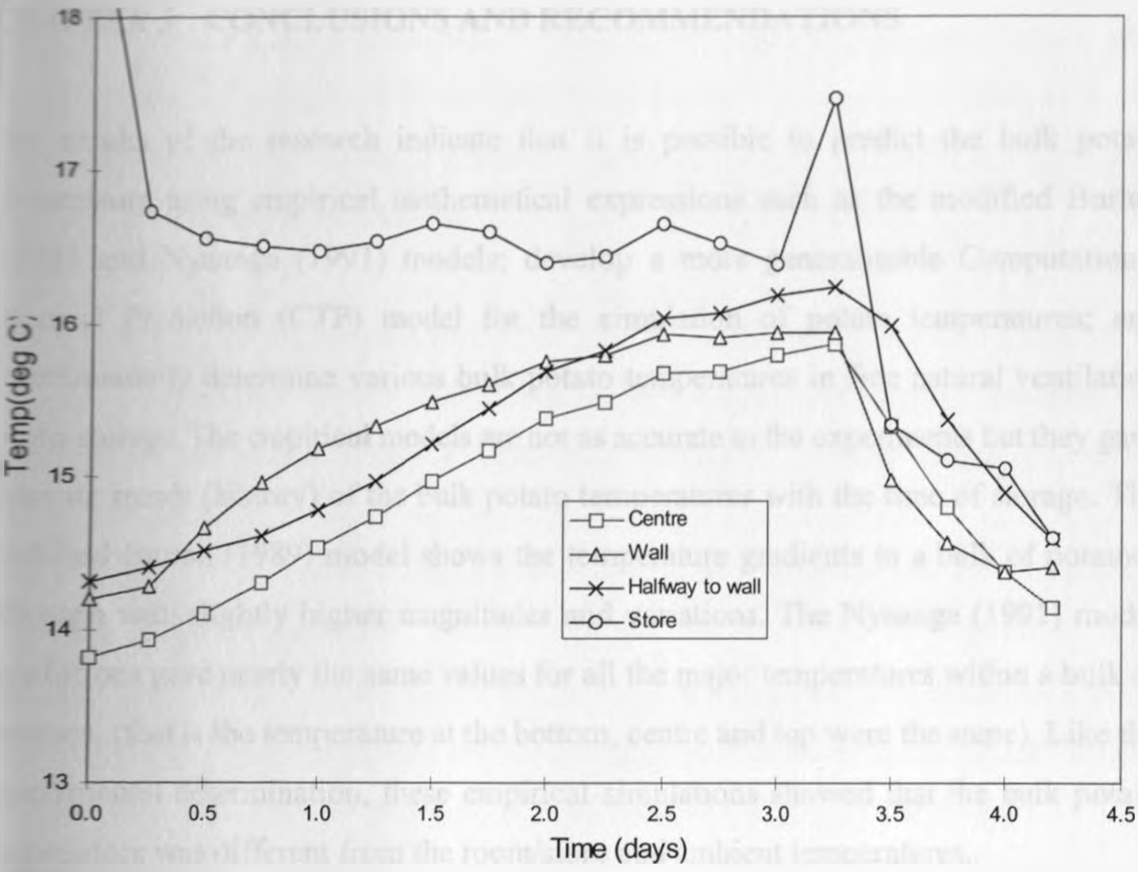


Figure 4.15 Lateral temperature variation at half the vertical distance in a bulk of potatoes with time during storage

than the store temperature during the 3 days of free ventilation holding after the potatoes and the store had been cooled to a given temperature. On the start the temperatures were the same and with time the wall temperature became higher being followed by the intermediate layer (halfway to wall) of potatoes. The centre temperature remained the lowest. This confirms the presence of lateral temperature gradients in free natural ventilation storage similar to those that have been reported to exist in forced ventilation and controlled storage by many researchers including Lerew (1978), Brugger (1979), Burfoot *et al.* 1996a and Burfoot and Xu (1997). It also implies that there is heat exchange not only at the top and bottom of the bulk of potatoes but also at the sides contrary to what has been assumed by Burton *et al.* (1955) and the CTP model.

"... conclusion of the matter: Fear God and keep His commandments for this is the whole duty of man" (Ecclessiates 12 13)

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

The results of the research indicate that it is possible to predict the bulk potato temperature using empirical mathematical expressions such as the modified Burton (1989) and Nyaanga (1991) models; develop a more generalisable Computational Thermal Prediction (CTP) model for the simulation of potato temperatures; and experimentally determine various bulk potato temperatures in free natural ventilation potato storage. The empirical models are not as accurate as the experiments but they gave accurate trends (history) of the bulk potato temperatures with the time of storage. The modified Burton (1989) model shows the temperature gradients in a bulk of potatoes although with slightly higher magnitudes and variations. The Nyaanga (1991) model simulations gave nearly the same values for all the major temperatures within a bulk of potatoes, (that is the temperature at the bottom, centre and top were the same). Like the experimental determination, these empirical simulations showed that the bulk potato temperature was different from the room/store and ambient temperatures.

The Computational Thermal Prediction (CTP) simulations were more accurate than the empirical models and the program gave a wide range of options. The individual temperature trends, by various CTP options and at the different points of monitoring were same at probability of 1% using SAS general linear model. Generally, the CTP predicted values are slightly higher than the observed. The small difference could have resulted from assumptions and constants used in the mathematical model such as the major modes of heat exchange and quantification. The CTP program using guidelines on free ventilation potato storage, gives the user information and recommendations about the specified storage system/environment with respect to bulk size, storage temperature and time.

Experimental determination of various bulk potato temperatures was possible by use of thermocouple sensors and data loggers which are programmed to detect and store the temperatures at any time intervals throughout the storage period. The data collected was used to verify and validate mathematical models. More data was generated which gave revelations about the system than the models used could such as the existence of lateral temperature gradients in a bulk of potatoes. Therefore, the extra experimental data could find use in other model validations.

This research has prompted need for further research and investigation into a number of areas if this variable natural system has to be predicted accurately. Therefore the following are recommendations for further study and research in free natural convective potato storage:

- establish exact effect of bulk dimensions on bulk potato temperature in terms of storage quality and storage period
- determine exact theoretical formulation for the determination of the constants used in the CTP model by adopting alterative assumptions such as the inclusion of heat storage, evaporative cooling and condensation in the bulk of potatoes during storage
- show effect of clearance, porosity, velocity on the prediction of bulk potato temperatures
- further CTP simulation with different time intervals and options, constants and conditions
- extend CTP model to 2D and 3D simulations for both uncontrolled and controlled potato storage studies
- adopt available fully dynamic models such as CFD in free natural ventilation storage of potatoes.

REFERENCES

Abrams, C.F. (1984). Depth limitation on bulk piling of potatoes. *Trans. ASAE* 25(5):1848-53.

AEA. (1996). Computational Fluid Dynamics (CFD) Model - *User's Guide. Harwell.* pp: 264-349.

Aurelius, A. (1926). Warme-austausch. *A. Angew. Math.* 6:291.

Arsdel, W.B. van. (1955). Simultaneous heat and mass transfer in a non-isothermal system: through-flow drying in the low moisture range. *Am. Inst. Chem. Eng, Symposium series No.* 16:47-58.

ASAE. (1989). Potato Storage technology and practice. *In ASAE Standards*, pp:74-282.

ASAE. (1995). Thermal properties of grains and grain products. *In ASAE Standards.*

ASHRAE. (1989). ASHRAE Fundamentals. *Handbook of the American Society of Heating, Refrigeration and Air Conditioning Engineering.* Atlanta. USA.

Awbi, H.B. (1991). Ventilation of Buildings. E & F N Spon. London, pp 33-59.

Bajpai, A.C.; Calus, I.M. and Fairley, J.A. (1983). Numerical Methods for Engineers and Scientists. *John Wiley.* Chichester.

Bakker-Arkema, F.W. and Lerew, L.E. (1974). Heating and cooling of potato piles. *ASAE Paper* 74-6513.

Bakker-Arkema, F.W. and Bickert, W.G. (1966). A deep bed computational cooling procedure for biological products. *Trans. ASAE* 9:834.

Bakker-Arkema, F.W.; Bickert, W.G. and Patterson, R.J. (1967). Simultaneous heat and mass transfer during the cooling of a deep bed of biological products under varying inlet conditions. *J. Agrc. Eng. Res.* 12:297-307.

Bakker-Arkema, F.W. (1970). Cooling of a bed of potatoes (or apples, tomatoes, sugar beets, onions): A simplified model. *Proceedings of the Institute for Simulation of cooling and drying beds of agricultural products.* Michigan State University. Michigan.

Bakker-Arkema, F.W.; Brook, R.C. and Lerew, L.E. (1977). Cereal grain drying. *In Advances in Cereal Science and Technology, Vol. II, edited by Y. Pomeranz,. Am. Assoc. Cereal Chem. Inc. Minnesota.*

Ballestrem, C.G. and Holler, H.J. (1977). Potato Production in Kenya. *The International Potato Centre (CIP).* Lima-Peru.

Bejan, A. (1993). Heat Transfer. *John Wiley & Sons, Inc.* New York.

Bergh, L. van den and Lentz, C. P. (1971). Moisture loss of vegetables under refrigerated storage conditions. *Can. Int. Food Technol. J.* 4:143-145.

Bergh, L. van den and Lentz, C. P. (1972). Respiratory heat production of vegetables during refrigerated storage. *J. Am. Soc. Hort. Sci.* 97:431-432.

Beukema, K.J. (1980). Heat and mass transfer during cooling and storage of agricultural products as influenced by natural convection. *Phd Thesis.* Wageningen University.

Bibby, I.P. (1997). A CFD Approach to Predicting airflow and heat transfer in bulk stored grains. *In Engineering and food at ICEF 7 edited by Jowitt, R. Part 2 pp N17-20. Sheffield Academic press,* London.

Bishop, C.F.H. and Maunder, W.F. (1980). Potato Mechanisation and Storage. *Farming Press Ltd.* Suffolk.

Bird, R.B.; Stewart, W.E. and Lightfoot, E.N. (1960). Transport Phenomena. *John Wiley and sons, Inc.* New York.

Boe, A.A.; Woodley, G.W. and Lee, T.S. (1974). Respiration studies on Russet Burbank potato tubers: Effects of storage temperature and chemical treatments. *Am. Pot. J.* 51:355-360.

Booth, R.J. and Rhodes, R.L. (1989). Potato Storage in Developing Countries. *The International Potato Centre (CIP).* Lima-Peru.

Businger, J.A. (1954). Lutchtbehndeling van producten in gestorte toestand verwarming en ventelatei. 2:31-35.

Burfoot, D.; Xu, Y. and Day, W. (1996a). Modelling the distribution of temperature and air velocities in potato storage. In *Silsoe Research Institute Annual Report.* Bedford.

Burfoot, D.; Smith, D.L.O.; Butler, E and Day, W. (1996b). Modelling the distribution of isopropyl N-(3-chlorophenyl) carbamate [CIPC] in box potato stores. *Potato Research* 39:241-54.

Burfoot, D. and Xu, Y. (1997). Control of heat and mass transfer processes in crop stores. *Interim Report Cr/733/96/1192.* Silsoe Research Institute. Bedford.

Burton, W.G. (1955). Biological and economic aspects of the refrigerated storage of potato. *Proc. Inst. Refrig.* 51:169-72.

Burton, W.G. (1963). Basic Principles of Potato Storage. *European Potato Journal* 6:77-92.

Burton W.G. (1972). The response of the potato plant and tuber to temperature. *In Crop Responses in Controlled Environments, pp. 217-33. Edited by Rees, A.R.; cockshull, K.E.; Hand, D.W. and Hurd, R.G. Academic Press,* London.

Burton W.G. (1973). Physiological and biochemical changes in the tuber as affected by storage conditions. *Proc. 5th trienn. Conf. Eur. Assn Potato Res.* Norwich. England 1972 pp.63-81.

Burton W.G. (1978). Post-harvest behaviour and storage of potatoes. *In Coaker (ed) Applied Biology, vol. II. Academic Press.* London, pp. 86-228.

Burton, W.G. (1982a). Potato storage principles. *In Potato Seed production for Tropical Africa. Edited by Nganga S. and Shideler F. pp 153-170. Westview Press.* London.

Burton, W.G. (1982b). Postharvest Physiology of Food Crops. *Longman.* London.

Burton, W.G. (1989). The Potato. *3rd Ed. Longman Scientific & Technical.* London. pp: 1, 547-598.

Burton, W.G.; Mann, G. and Wager, H.G. (1955). The storage of ware potatoes in permanent buildings II. The temperature of unventilated stacks of potatoes. *J. agr. Sci.* Camb. **46**:439-42.

Butcherbaker, A.F.; Nelson D.C. and Shaw R. (1967). Controlled storage of potatoes. *Trans. ASAE* **10**:534-7.

Butcherbaker, A.F.; Promersberger, W.J. and Nelson, D.C. (1973). Weight loss of potatoes as affected by age, temperature, relative humidity and air velocity. *Am. Pot. J.* **50**:124-132.

Brooker, D.B. (1961). Pressure patterns in grain drying systems established by numerical methods. *Trans. ASAE* **4**:72-77.

Brooker, D.B. (1967). Mathematical model of the psychrometric chart. *Trans. ASAE* **10**:558-563.

Brooker, D.B. (1969). Computing air pressure and velocity distribution when air flows through a porous medium and non-linear velocity-pressure relationships exist. *Trans. ASAE* **12**:118-120.

Brockett, B.L. and Albright, L.D. (1987). Natural ventilation in single airspace buildings. *J. of Agri. Engg. Res.* **37(*3*)**:141-154.

Bruce, J.M. (1978). Natural convection through openings and its applications to cattle building ventilation. *J. Agric. Eng. Res.* **23**:151-67.

Bruce, J.M. (1982). Ventilation of A Model Livestock Building by Thermal Buoyancy. *Trans. ASAE (***25)4**:1724-26.

Brugger, M. F. (1979). A Two-dimensional finite difference model of the transient environment within a potato pile. Unpublished *PhD Thesis.* University of Wisconsin-Madison.

Cargill, B.F. (ed) (1989). The Potato Storage: Design, Construction, Handling and Environmental Control. *Michigan State University.* Michigan. USA

Cargill, B.F.; Brook, R.C. and Forbush, T.D. *(eds)* **(1989).** Potato Storage Technology and Practice. *Proceedings of an International ASAE Symposium 1985.* Michigan. USA

Cebeci, T. and Bradshaw, P. (1988). Physical and Computational Aspects of Convective Heat

Transfer. *Springer-Verlag.* New York. Pp 263-280.

Charm, S.E. (1971). The Fundamentals of Food Engineering. *AVI Publishing Co. Inc.* Connecticut.

Clary, B.L. and Nelson, G.L. (1970). Determining convective heat transfer coefficients from ellipsoidal shapes. *Trans. ASAE* **13(3)**:309-314.

Cook, R.D. (1981). Concepts and Applications of Finite Element Analysis. 2ed. *John Wiley & Sons.* New York.

Delta-T Devices Ltd. (1992). Delta-T Logger; *User Manual.* Version 2.0. Cambridge.

Dorn, W.S and McCracken, D.D. (1972). Numerical methods with fortran IV case studies. *John Wiley & sons.* New York.

Durr, G. and Lorenzl, G. (1980). Potato Production and Utilization in Kenya. *International Potato centre (CIP)* Lima-Peru.

Ergun, S. (1952). Fluid flow through packed columns. *Chem. Eng. Prog.* **48**:89-94.

Fockenns, F.H. and Meffert, H. F. (1972). Biophysical properties of horticultural products related to loss of moisture during cooling down. *J. Sci. Fd. Agri.* **23**:285-298.

Glynne, M. D. and Jackson, V. G. (1919). The distribution of dry matter and nitrogen in the potato tuber. *J. Agri. Sci. Camb. 9*:237-58.

Grahs, L.; Hylmo, B.; Johanson, A. and Wikberg, C. (1978). The two point temperature measurement --A method to determine the rate of respiration in a pile. *Acta. Agr. Scand.*

Greenkorn, R. A. (1983). Flow Phenomena in Porous Media. *Maercel Dekker*, Inc. New York.

Gromo, M.A. and Krasovysaya, G.I. (1967). Physical heat constants of potatoes and vegetables. *Konsevnaya 'I Ovo-shchesushil' naya. Promyshlennost* 22:13-16

Gumbe, L.O.M. (1987). Mechanical Properties of Granular Materials as Related to Loads in Cylindrical Grain Silos. *Ph.D. Thesis.* The Ohio State University. Ohio. USA

Heldman, D.R. (1977). Food Process Engineering. *AVI Publishing Co. Inc.* Connecticut.

Henderson, S.M. and Perry, R.L. (1980). Agricultural Process Engineering. Third edition. The AVI Publishing Co. Westport, Connecticut.

Holman, J.P. and Gajda, J.W. (1984). Experimental Methods for Engineers. *McGraw-Hill Book Co.* Auckland

Hougen, O. A. and Marshall, W. B. Jr. (1947). Adsorption from a fluid stream flowing through a granular bed. *Chem. Eng. Progress.* **43**:197-208.

Horton, D. (1987). Potato Production, Marketing and Programs for Developing Countries. *IT Publ. Co.* London.

Hunt, G.L.T. (1982). A review of storage studies in tropical Africa. *In Potato Production for Tropical Africa, pp. 155-179, edited by Nganga S. and Shideler F. Westview Press,* London.

Hunt, G.L.T. (1987). Low cost potato tuber ventilated bulk storage in the tropics related to dormancy, ambient temperature and relative humidity. *A paper presented to EAPR Triennial Conference.* Aalborg, Denmark.

Hunter, J.H. (1976). Variation in respiration rates and moisture loss rates of the potato in storage as affected by time, temperature, and vapour pressure deficit. *ASAE Paper* No. 74-4504.

Hunter, J.H. (1977). Prediction of weight losses in stored potatoes by computer simulation. *ASAE Paper* No. 77-4060

Hunter, J.H. (1978). A simulation model for potato storage ventilation. *ASAE Paper* No. 78-4061

Hylmo, B.; Persson, T.; Wikberg, C. and Sparks, W.C. (1975a). Heat balance in a potato pile. Part I: The influence of the latent heat of removed water. *Acta Agrc. Scand.* **25(2)**81- 87

Hylmo, B.; Persson, T.; Wikberg, C. and Sparks, W.C. (1975b). Heat balance in a potato pile. Part ii: the temperature distribution at intermittent ventilation. *Acta Agrc. Scand.* **25(2)**88-91

Hylmo, B.; Johansson, A. and Wikberg, C. (1978). A simple method to determine the drying out of tubers in a potato pile. *Presented at European Potato Meeting. June, 1978.* Aalborg, Denmark.

Iritani, W.M.; Pettibone, C.A. and Wellar, L. (1977). Relationship of relative maturity and storage temperatures on weight loss of potatoes in storage. *Am. Pot. J.* **54**:305-314.

Jaluria, Y. (1980). Natural Convection Heat and Mass Transfer. *Pergamon,* Oxford.

Johnston, F.B.; Hoffman, I. and Petrasoviits, A. (1968). Distribution of mineral constituents and dry matter in the potato tuber. *Amer. Potato J.* **45**:287-92

Jones, W.E. (ed) (1965). Potatoes. Bulletin No. 94. *H.M. Stationary Office.* London.

Khankari, K.K.; Morey, R.V. and Patankar, S.V. (1995). Application of a numerical model for prediction of moisture migration in stored grain. *Trans. ASAE* **38 (6)** 1789-1804

Lee, K. (1986). Heat and mass transfer in highly porous media. *PhD Thesis.* The University of Texas at Austin. University Microfilms International. USA.

Lerew, L. E. (1978). Development of a temperature-weight loss model for bulk stored potatoes. *Phd Thesis.* Michigan State University. *University microfilms international. Ann Arbor,* Michigan. USA.

Lipson, C. and Seth N. J. (1973). Statistical Design and Analysis of Engineering Experiments. pp56-190. *John Wiley & Sons*, London.

Lutz, J.M. and R.E. Hardenburg. (1968). The commercial storage of fruits, vegetables, and florists and nursery stocks. USDA *Handbook No. 66.* Washington, D.C.

Marchant, J.A. (1976a). The Prediction of airflows in crop drying systems by the finite element method. *J. Agric. Eng. Res.* **21**:417-429

Marchant, J.A. (1976b). A computer program for the solution of the quasi-linear equation using finite elements. *Report # 20 Silsoe Research Institute.* Bedford. England.

Marvin, P.J.; Hyde, G.M. and Ralph, P.C. (1987). Modeling potato tuber mass with tuber dimensions. *Trans. ASAE* **30(4)**1154-9.

Mayhem, YR. and Rogers, G.F.C. (1970). Thermodynamic Properties of Fluids and other Data. British Thermal Units. *Basil Blacwell.* Oxford.

Meigh, D.F.; Filmer, A.A.E. and Self, R. (1973). Growth-inhibitory volatile aromatic compounds produced by *Solanum Tuberosum* tubers. *Phytochemistry.* 122:987-993.

Misener, G.C. (1973). Simulated cooling of potatoes. *Phd Thesis.*Ann Arbor University. *University Microfilms International.* Michigan. USA.

Misener, G.C. and Shove, G.C. (1976a). Simulated cooling of potatoes. *Trans ASAE* (**19**)**5**:954-57, 961

Misener, G.C. and G.C. Shove. (1976b). Moisture Loss from Kennebec potato tubers during the initial storage period. *Trans. ASAE* **19(5)**:967-9.

Mitchell, A. R. (1969). Computational Methods in Partial Differential Equations. *John Wiley & Sons.* New York.

Mohsenin, N. N. (1970). Physical Properties of Plant and Animal Materials. *Gordon & Breach Sci. Publ.* New York.

Mohsenin, N. N. (1980). Thermal Properties of Foods and Agricultural Materials. *Gordon & Breach Sci. Publ.* New York.

Montgomery, D.C.; Runger, G.C. and Hubele, N.F. (1998). Engineering Statistics, pp 175, 235-37. *John Wiley & Sons,* New York.

Murata, S. (1971). Extension of Schumann's theory to the case of low thermal diffusivity of solid particles. *J. of Chem. Engngr.* Japan. **4**:140-6.

Neale, S.F. and Messer, D.N. (1976). Air flowrates through a pile of potatoes. *Report*

Cr/3/76/19. Silsoe Research Institute. Bedford. England.

Nyaanga, D.M. (1991). Factors Affecting the Bulk Size of Stored Potatoes. *Unpublished Msc. Thesis.* University of Nairobi. Kenya.

Nyaanga, D.M.; Gumbe, L.O.M. and Mwaura, E.N. (1994a). Development of an equation/model predicting temperature stored potatoes. *Proceedings of the Kenya Society of Agricultural Engineers (KSAE), Annual International Conference held at University of Nairobi, Kabete Campus from 3rd to 5th August 1994.* pp 30-32. Nairobi. Kenya

Nyaanga, D.M.; Gumbe, L.O.M. and Mwaura, E.N. (1994b). Quantitative changes in some physical properties of potatoes during storage.*Proceedings of the Kenya Society of Agricultural Engineers (KSAE), Annual International Conference held at University of Nairobi, Kabete Campus from 3rd to 5th August 1994.* pp 33-34. Nairobi. Kenya

Nyangito, H.O. (1986). Socio-economic factors in potato storage. *Msc. Thesis.* Unpublished. University of Nairobi. Kenya.

Nassiuma, D. (1999). Statistical analysis approaches. Personal communication. Egerton University, Njoro. Kenya.

Ophius, B.G. (1957). The effect of ventilating capacity on weight losses in ventilated stores. *Neth. J. Agric. Sci.* **5**: 180-194

Osuji, G.O. (1983). Thermodynamics applied to the storage of yam tuber. Tropical root crops. Production and uses in Africa. pp 143-6. *Proceedings of 2nd Triennial Symposium of International Society for Root Crops.* Africa Branch. Dokala. Cameroon.

Patankar, S.V. (1980). Numerical Heat Transfer and Fluid Flow, pp3-101. *John Wiley.* London.

PMB (Potato Marketing Board) (1997). Potato Box. Bulletin of Potato Marketing Board *Sutton Bridge Experimental Station*, England.

Porges, F. (1995). HVAC Engineers Handbook, pp 90-93. 10th ed. *Butterworth-Heimann Ltd.* Oxford.

Pratt, P. and Buelow, F.H. (1978). Behaviour of potatoes under various storage conditions. *ASAE Paper No. 78-4059.*

Rao, M.A.; Bernard, J. and Kenny, J.F. (1975). Thermal conductivity and thermal diffusivity of process variety squash and white potatoes. *Trans. ASAE* **18**:1188-1192.

Reddy, J.N. (1984). An Introduction to the Finite Element Method. *McGraw-Hill Book Co.* New York.

Reece, G. (1986). Microcomputer Modelling by Finite Differences. *McMillan.* London.

Richtmyer, R.D. and Morton, K.W. (1967). Difference Methods for Initial-value Problems.

Intrescience Publishers. New York.

Rice, B. (1974). Computer simulation of temperature control in potato storage. *Acta. Horticulture.* 38:91-4.

Roenau, J.R.; Bakker-Arkema, F.W. and Lerew, L.E. (1970). Cooling of a bed of potatoes (or apples, tomatoes, sugarbeets, onions): A realistic model. *Proceedings of the Institute for Simulation of Cooling and Drying Beds of Agricultural Products.* Dept of Agri. Eng. Michigan State University, Michigan. USA

Rustowski, A. (1982). Potato storage and storage environment, in Survey Papers. *Eur. Ass. for Potato Research. Field Crop Abstr.* 35:5433.

Ryall, A.L. and Lipton, W.J. (1972). Handling, Transportation and Storage of Fruits and Vegetables. *Vol. 1 AVI Publishing*, Westport, Conn.

Salunkhe, D.C. and Desai, B.B. (1984). Post harvest Biotechnology of vegetables. *CBC Press.* Boca Raton. Florida. USA.

SAS Institute. (1994). SAS (Statistical Analysis Systems) user's guide: Statistics. SAS Inst. Cary, New York.

Sawyer, R.L.; Boyd, L.L.; Cetas, R.C. and Bennet, A.H. (1965). Potato Storage Research on Long Island with Forced-air Ventilation Systems. *Cornell Agri. Expt. Sta. Bull. 1002.* USA

Schaper, L.A.; Yaeger, E.C.; Flikke, A.M. and Junnila, W.A. (1967). Storage temperature maintenance and its effects on potatoes. *American Potato journal.* **44(5)**:159-164.

Schaper, L.A. and Hudson, D. (1971). Biological and Engineering factors affecting white potato losses in storage. *ASAE Paper No.* 71-377.

Schaper, L.A. (1975). The influence of storage conditions on chip colour of potatoes. *Pot. Res. J.* **18**:479-94

Schaper, L.A.; Cloud, H.A. and Lundstrom, D. (1976). An Engineering evaluation of potato storage ventilation system performance. *Trans. ASAE* **19**:584-590.

Scheele, C. Von; Svensso, G. and Ramsmusson, J. (1937). Die Bestimmung des Staerkegehalts und der Trockensubstanz der Kartofffel mit Hilfe des spezifischen Gewichts. Landw. Vers. Sta.

Schippers, P.A. (1971a). The Influence of storage conditions on various properties of potatoes. *Am. Pot. J.* **48**:278-286.

Schippers, P.A. (1971b). The relation between storage conditions and changes in weight and specific gravity of potatoes. *Am. Pot. J.* **48**:313-318.

Schumann, T.E.W. (1929). Heat transfer: A liquid flowing through a porous prism. *J. of Franklin Institute.* **208**:405-416.

Segerlind, L.J. (1976). Applied Finite Element Analysis. *John Wiley & sons, Inc.* New York.

Shaw, R.; Booth, R.H. and Rhoades R. (1982). On the development of appropriate technology: a case of Post harvest potatoes. *Food Techn.* **36(10)**114-7.

Shirokov, E.P. (1968). Practical course in storage and processing of vegetables and fruits. *Translated from Russian for USDA by Israel program for Scientific Translations.* Russia.

Simmonds, N.N. (1977). Relations between specific gravity, dry matter and starch content of potatoes. *Pot. Res.* **20**:137-140.

Singh, R.P.; Heldman, D.R. and Bedford, C.L. (1974). Weight loss during storage and reconditioning of potatoes. *ASAE Paper No.* 74-6512.

Singh, A.K.; Leonardi, E. and Thorpe, G.R. (1993). A solution procedure for the equations that govern three-dimensional free convection in bulk stored grains. *Trans. ASAE* **36 (4)** 1159-1173.

Singh, B.N. and Matthur, P.B. (1938). Studies in potato storage. II: Influence of the (1) stage of maturity and (2) storage temperature for a brief duration immediately after digging, on physiological losses in weight of potatoes during storage. *Ann. Appl. Biol.* **25**:1197-1200.

Smith, J.M. (1977a). Mathematical Modelling and Digital Simulation for Engineers and Scientists. *John Wiley & sons.* New York.

Smith, O. (1977b). Potatoes: Production, Storage and Processing. *Second ed. AVI Publ. Co. Inc.* Westport, Connecticut.

Smith, G.D. (1985). Numerical Solution of Partial Differential Equations: Finite Difference Methods. 3rd ed. *Clarendon Press.* Oxford.

Sparks, W.C. (1965). Effect of storage temperature on storage losses of Russet Burbank potatoes. *Am. Pot. J.* **42**:241-246

Sparks, W.C. (1973). Influence of ventilation and humidity during storage on weight and quality changes of Russet Burbank potatoes. *Am. Pot. J.* **16**:213-223

Sparks, W.C. (1975). Potato storage factors of economic importance. *Am. Pot. J.* **52**:89-97

Sparks, W.C. and Summers, L.V. (1974). Potato weight losses, quality changes and cost relationships during storage. Bulletin 535 *University of Idaho*, USA.

Versteeg, H.K. and Malalasekera, W. (1995). An Introduction to Computational Fluid Dynamics. The Finite Volume Method. *Longman Scientific and Technical.* Essex, England.

Villa, L.G. (1973). Single particle convection moisture losses from horizontal products in storage. *PhD. Dissertation.* Michigan State University. *University Microfilms International. Ann Arbor*, Michigan, USA.

Villa, L.G. and Bakker-Arkema, F.W. (1974). Moisture losses from potatoes during storage. *ASAE Paper No.* 74-6510

Watson, E.L and Staley, L.M. (1963). Heat transfer rates in potato bin. *Canadian Agr. Eng* 5:34-40

Williams, A. (1997). Breaking down barriers to maths and modelling. *A series of lectures offered to PhD students in June and July, 1997 at Silsoe Research Institute,* Bedford, England.

Workman, M.N. and Twomey, J. (1969). The influence of storage atmosphere and temperature on the physiology and performance of seed potatoes. *J. Am. Soc. Hort. Sci.* (**94**)260

Xu, Y. (1997). Personal communication on Fortran Subroutines in CFD to predict air and temperature distribution in potato stores. Researcher at Silsoe Research Institute, Bedford, England.

Xu, Y. and Burfoot, D. (1997). Predicting air flows in potato stores. *In Engineering and food at ICEF 7 edited by Jowitt, R. Part 2 pp N13-16. Sheffield Academic press.* London

Yamada, T. (1970). Thermal properties of Potato. *Nippon Nogei Kagaku Kaishi* **44(12)**587-90.

Yaeger, E.C.; Schaper, L.A. and Orr, P.H. (1987). Comparison of Potato Pile Pressures on Vertical and Inclined Walls. *Trans. of the ASAE* **30(6)**1811-3

Zak, J. and Schauer, P. (1976). Stanoveni termofyzikalnich viastnosti brambor metodou impulane pusobichiho primkovche zdroje tepia. *Zem technika.* **22**:23-28

Zienkiewicz, O.C. (1991). The Finite Element Method. Vol 2: Solid and Fluid Mechanics. *McGraw-Hill.* New York

APPENDIX 1: COMPUTATIONAL THERMAL PREDICTION

A1.2 The Computer Program

```
 program TemperaturePrediction ;
 { A program to simulate potato storage Temperature }
 uses
    crt,Graph;
    {Creating agraph of the temperatures with time}
 const
     Size=50;

 Procedure Axis;
 { Purpose draw axis }
 begin
     { set environment }
     SetColor(1);
     SetLinestyle(2,12,4);
     MoveTo(100,200);
     LineTo(100,400);
     LineTo(400,400);
     MoveTo(20,250);
     SetLinestyle(0,0,2);
     SetTextStyle(2,1,6);
     OutText('Temperature');
     SetTextStyle(2,0,6);
     MoveTo(250,435);
     OutText('Time');
end; { Axis }


Procedure Welcome;
{ Purpose : to display graphic scenes }
var
  color:word;
begin
    { set environment }
    GraphicsMode;

    Sound(520);
    Delay(500);
    Nosound;
    Sound(620);
    Delay(600);
    Nosound;
    OutTextXY(30,100,'  COMPUTATIONAL THERMAL ');
    OutTextXY(30,170,'  PREDICTION (CTP) PROGRAM ');
    OutTextXY(30,240,'  FOR POTATO TEMPERATURES ');
```

```
    OutTextXY(30,310,'        Nyaanga, D.M.');
    OutTextXY(60,380,'        May 1999');
    Delay(800);
    ClearDevice;
    { generate random polygons }
    SetLineStyle(0,0,3);
    SetColor(5);
    SetTextStyle(6,0,5);
    OutTextXY(10,250,' Press <enter> Key to continue ... ');
    Delay(1000);
    repeat
       Sound(100);
       Delay(200);
       Nosound;
       Sound(220);

       Line(random(640),random(470),random(630),random(470));
      Ellipse(random(600),random(400),random(600),random(400),random(200),random(300));
       Delay(500);
   until keyPressed;
   readln;
   CloseGraph;
end; { welcome }

Procedure LabelYAxis(Y:integer);
{ Purpose : label the Y axis grid lines }
 var
   Grid,Temp :integer;     { Grid line }
   y1 : integer;  { Temporary stores }
   i:integer;         { loop control }
   NumStr:string[4];   { numerical string store }
begin
    { set environment }

    for i:=1 to 5 do
    begin
        MoveTo(65,y1);
        str(Grid,NumStr);
        OutText(NumStr);
        Grid:=Grid+Temp;
        y1:=y1-40;
    end; { for }
end;  { LabelYAxis }

procedure LabelXAxis(XGreat :integer);
{ Purpose : Label the X axis  }
var
  Grid :integer;    { grid line }
```

```
   x1,Temp :integer; { temporary stores }
   i:integer;        { loop control }
   Gd:string[5];     { temporary string holder }

 begin
    { set the environment }
    SetColor(1);
    SetTextStyle(2,0,4);

    Temp:=XGreat div 10;
    Grid:=Temp;
    x1:=130;

    for i:=1 to 10 do
    begin
       MoveTo(x1,420);
       str(Grid,Gd);
       OutText(Gd);
       Grid:=Grid+Temp;
       x1:=x1+30;
    end;  { for }
end;  { LabelAxis }


procedure      ReadInput(var       Time:Time_Mat;var        Sim_Temp:Sim_Temp_Mat;var
Exp_Temp:Sim_Temp_Mat;
var Ta_Mat:Ta_array;var Source:integer;N:integer);
{ purpose : read input }
var
  a: array[1..4] of real;  { array for storing constants }
  t : real;          { Time }
  i,j: integer;        { array indices }
  Ta_Temp,Tpe,Tr: real;        { air/room temp }
  Ans,Reply: integer;
  Ta :array[1..size] of real;

begin
   Textcolor(2);
   case source of
     1 :
     begin
         { read input from file }
         TextColor(7);
         writeln;
         writeln( 'NB: Input file must be a text file with the format (columns) as below:  ');
         writeln;
        writeln(' File format -> Time(col 1), Ambient (2), Store (3), Observed temps(Tpei) (4...)
');
```

```
    writeln('            are from bottom to top   ');
    writeln;
    writeln('Enter null value to quit');
    writeln;
    Textcolor(2);
    write('Enter the pathname of the file');
    Textcolor(7);
    write(' ( e.g a:\file3.txt )');
    Textcolor(2);
    write(' => ');
    Textcolor(15);
    for i:=1 to 12 do
    begin
       if eoln then
         FileName[i]:=' '
       else
          read(FileName[i]);
    end;
    if FileName[1] = ' ' then
      halt;
    Assign(TextFile,FileName);
    Reset(TextFile);
    writeln;
    readln(TextFile);
    for i:=1 to N do
    begin
       read(TextFile,t);
       read(TextFile,Ta_Temp);
       read(TextFile,Tr);
       read(TextFile,Tpe);
       Exp_Temp[i,1]:=Tpe;
       read(TextFile,Tpe);
       Exp_Temp[i,2]:=Tpe;
       readln(TextFile,Tpe);
       Exp_Temp[i,3]:=Tpe;
       Time[i]:=t;
       Sim_Temp[i,1]:=Tr;
       Ta[i]:=Ta_Temp;
       Ta_Mat[i]:=Ta_Temp;
    end;
end;

2:
begin
   Textcolor(7);
   write('     1 . Linear equation');
   Textcolor(15);
   writeln(' [ Tr = 0.7613Ta+5.142 ] ');
```

```
Textcolor(7);
write('     2 . Quadratic equation');
Textcolor(15);
writeln(' [ Tr = a1*cub(t) + a2*sqr(t) + a3*t + a4 ]');
Textcolor(7);
writeln('     3 . Quit');
Textcolor(2);
writeln;
write( 'Enter your choice => ');
Textcolor(15);
readln(Reply);

    case Reply of
     1:
     begin
        Source:=1;
        Assign(TextFile,'a:\File3.txt');
        Reset(TextFile);
        readln(TextFile);
        for i:=1 to N do
        begin
           read(TextFile,t);
           read(TextFile,Ta_Temp);
           read(TextFile,Tr);
           read(TextFile,Tpe);
           Exp_Temp[i,1]:=Tpe;
           read(TextFile,Tpe);
           Exp_Temp[i,2]:=Tpe;
           readln(TextFile,Tpe);
           Exp_Temp[i,3]:=Tpe;
           Time[i]:=t;
           Ta_Mat[i]:=Ta_Temp;
           { calculate Tr }
           Sim_Temp[i,1]:=(Ta_Temp*0.7613)+5.142;
        end;
     end;
     2:
     begin
       { supply the constants a1 .. a4 }
       writeln;
       textcolor(7);
       writeln('Enter zero to quit');
       writeln;
       for j:=1 to 4 do
       begin
          Textcolor(2);
          write('Enter a',j, ' =>' );
          Textcolor(15);
```

```
                readln(a[j]);
                if a[j] = 0 then
                   halt;
             end;
             for i:=1 to N do
             begin
                Textcolor(2);
                { read time }
                write('Enter the time =>');
                Textcolor(15);
                readln(t);
                if t = 0 then
                   halt;

                { read constants }

                { computing the air/room/ambient temp }
                Ta_Temp:=(a[1]*sqr(t)*t)+(a[2]*sqr(t))+(a[3]*t)+a[4];

                Time[i]:=t;
                Sim_Temp[i,1]:=Ta_Temp;
             end;
           end;
           else
              halt;
         end;
   end;
   3:
   begin
      { supply time and temperature }
      Textcolor(2);
      write('Enter the time ');
      TextColor(15);
      write('(in days)');
      TextColor(2);
      write('and  store/room temp (Tr)');
      TextColor(15);
      write(' (in degrees centigrade)');
      TextColor(2);
      writeln('per row');
      writeln;
      Textcolor(7);
      writeln('Enter negative value for time to quit');
      writeln;
      Textcolor(15);
      for i:=1 to N do
      begin
         read(t);
```

```
        if t < 0  then
          halt;
          readln(Ta_Temp);
          if (t<=0) or (Ta_Temp<=0) then
            halt;
          Time[i]:=t;
          Sim_Temp[i,1]:=Ta_Temp;
      end;
    end;
    else
      halt;
  end;
end; { ReadInput }

procedure ProcessInput(var Sim_Temp:Sim_Temp_Mat; N, Max :integer);
{ Purpose : display output }
const
    A = 0.33;
var
  K,C,L,W,H :real;
  rho, Qr,Ni : real;
  Box_Vol, Layer_Vol : real;
  i,j :integer;   { array indices }
  Choice,Answer,Def_density:integer;    { users response }
begin
    { request user if to use default constants }
    writeln('Equations to simulate potato temperatures (Tps) ');
    writeln;
    TextColor(7);
    writeln('        Tps1 = Tr+K');
    writeln('        Tps2 = Tps1+c1 ... etc');
    writeln;
    writeln('NB: Only for mature, clean, medium size ware  potatoes ');
    writeln;
    { input dimensions of box }
    writeln;
    TextColor(2);
    write('Enter the length, width and height of the box in');
    Textcolor(7);
    write(' metres');
    Textcolor(2);
    write(' => ');
    Textcolor(15);
    readln(L,W,H);
    writeln;
    if (L<=0) or (W<=0) or (H<=0) then
      halt;
```

```
Box_Vol:=L*W*H;
Layer_Vol:=Box_Vol/(Max-1);


Textcolor(7);
writeln('         Options for generating K and C ');
writeln('         ------------------------------ ');
writeln;
writeln('        1 . Random constants => K (-1.5 to 1.5) and C ( 0 to 0.3 )');
writeln('        2 . Supply the constants => ',Max,' constants ');
writeln('        3 . Equation => C or K = (v*rho*Qr)/(0.33*Ni*V) ');
writeln('        4 . Quit');
Textcolor(2);
writeln;
write('Enter your choice => ');
Textcolor(15);
readln(Answer);
case Answer of
 1:
 begin
    { generate constants k and c }
    randomize;

    for i:=1 to N do
    begin
       if (sqr(H)/(L*W)) >=2 then
         K:=(-(random(15)*0.1))*Layer_Vol/Box_Vol
       else
          K:=(random(15)*0.1)*Layer_Vol/Box_Vol;
      Sim_Temp[i,2]:=Sim_Temp[i,1]+K;
    end;
    for i:=1 to N do
    begin
       for j:=3 to Max+1 do
       begin
          C:=(random(3)*0.1)*Layer_Vol/Box_Vol;
          Sim_Temp[i,j]:=Sim_Temp[i,j-1]+C;
       end;
    end;
end;
2:
begin
   { supply k or c constants }
   writeln;
   Textcolor(7);
   writeln('Enter zero to quit ');
   for i:=2 to Max+1 do
   begin
```

```
        Textcolor(2);
        write('Enter the constant for point ',i-1,'=>');
        Textcolor(15);
        readln(C);
        if c = 0 then
          halt;
        for j:=1 to N do
        begin
          Sim_Temp[j,i]:=Sim_Temp[j,i-1]+(C*Layer_Vol/Box_Vol);
        end;
      end;
  end;
  3:
  begin
     { input the density of the potatoes }
     Textcolor(7);
     writeln;
     writeln('         Option for bulk density');
     writeln('         -----------------------');
     writeln;
     writeln('         1 . Use Default density (rho = 626 kg/m^3 )');
     writeln('         2 . Supply density');
     writeln('         3 . Quit');
     writeln;
     Textcolor(2);
     write('Enter your choice => ');
     Textcolor(15);
     readln(Def_Density);

     case def_density of
     1: rho:= 626;
     2:
     begin
        TextColor(2);
        writeln;
        write('Enter the bulk density of the potatoes');
        Textcolor(7);
        write(' (kg/m^3)');
        Textcolor(2);
        write(' => ');
        Textcolor(15);
        readln(rho);
        if rho <= 0 then
        halt;
    end;
    3: halt;
    end;
```

```
writeln;
Textcolor(7);
writeln('        Options for Qr(Respiration rate) and Ni( No. of air changes per hr.)');
writeln('        ----------------------------------------------------------------');
writeln('         NB: Qr must be in W/kg');
 writeln;
writeln('        1 . By Computing Qr = (1.9986Tp -6.9)*10^-3 and Default Ni');
writeln('        2 . Default Qr and Ni');
writeln('        3 . Default Qr and Supply Ni');
writeln('        4 . Supply Qr and default Ni');
writeln('        5 . Supply Qr and Ni');
writeln('        6 . Quit');

Textcolor(2);
write('Enter your choice => ');
TextColor(15);
readln(Choice);
case choice of
 1:
 begin
    Ni:=90;
    for i:= 2 to Max+1 do
    begin
        for j:=1 to N do
        begin
            Qr := (1.9986*Sim_Temp[j,i-1])/1000;
            if (sqr(H)/(L*W)) >= 2 then
              C:=((rho*Qr)/(A*Ni))*Layer_Vol/Box_Vol
            else
              C:=-((rho*Qr)/(A*Ni))*Layer_Vol/Box_Vol;
            Sim_Temp[j,i]:=Sim_Temp[j,i-1]+C;
        end;
        Ni := Ni-(90/(2*Max));
    end;
 end;
 2:
 begin
    Ni:=90;
    for i:= 2 to Max+1 do
    begin
        if (sqr(H)/(L*W)) >=2 then
          C:=((rho*0.03282)/(A*Ni))*Layer_Vol/Box_Vol
        else
          C:=-((rho*0.03282)/(A*Ni))*Layer_Vol/Box_Vol;
        for j:=1 to N do
        begin
            Sim_Temp[j,i]:=Sim_Temp[j,i-1]+C;
        end;
```

```
        Ni := Ni-(90/(2*Max));
      end;
   end;
   3:
   begin
      writeln;
      for i:=2 to Max+1 do
      begin
         Textcolor(2);
         write('Enter Ni ( No of air changes per hour )');
         Textcolor(7);
         write(i-1);
         Textcolor(2);
         write(' => ');
         Textcolor(15);
         readln(Ni);
         if Ni <= 0 then
           halt;
         if (sqr(H)/(L*W)) >=2 then
           C:=((rho*0.03282)/(A*Ni))*Layer_Vol/Box_Vol
         else
           C:=-((rho*0.03282)/(A*Ni))*Layer_Vol/Box_Vol;
         for j:=1 to N do
         begin
            Sim_Temp[j,i]:=Sim_Temp[j,i-1]+C;
         end;
      end;
   end;
   4:
   begin
      Ni:=200;
      { input the respiratory heat removed }
      writeln;
      TextColor(2);
      write('Enter the potato respiration rate ');
      Textcolor(7);
      write(' (W/kg)');
      Textcolor(2);
      write('  => ');
      Textcolor(15);
      readln(Qr);
      if Qr <= 0 then
        halt;
      for i:=2 to Max+1 do
      begin
         if (sqr(H)/(L*W)) >=2 then
           C:=((rho*Qr)/(A*Ni))*Layer_Vol/Box_Vol
         else
```

```
              C:=-((rho*Qr)/(A*Ni))*Layer_Vol/Box_Vol;
           for j:=1 to N do
           begin
               Sim_Temp[j,i]:=Sim_Temp[j,i-1]+C;
           end;
           Ni := Ni-(90/(2*Max));
       end;
   end;
   5:
   begin
       writeln;
       TextColor(2);
       write('Enter the potato respiration rate ');
       Textcolor(7);
       write(' (W/kg)');
       Textcolor(2);
       write('  => ');
       Textcolor(15);
       readln(Qr);
       if Qr <= 0 then
         halt;
       writeln;
       for i:=2 to Max+1 do
       begin
           Textcolor(2);
           write('Enter Ni');
           Textcolor(7);
           write(i-1);
           Textcolor(2);
           write(' => ');
           Textcolor(15);
           readln(Ni);
           if Ni<= 0 then
             halt;
           if (sqr(H)/(L*W)) >=2 then
             C:=((rho*Qr)/(A*Ni))*Layer_Vol/Box_Vol
           else
              C:=-((rho*Qr)/(A*Ni))*Layer_Vol/Box_Vol;
           for j:=1 to N do
           begin
               Sim_Temp[j,i]:=Sim_Temp[j,i-1]+C;
           end;
      end;
  end;
else
   halt;
end;
```

```
      end;
      else
         halt;
     end;
  end; {processInput }

  procedure CheckUp;
  var
    i,j : integer;
    TpMax,TpMin,TrMin : real;
    MaxTps,MinTps: array[1..120] of real;

 procedure Message;
 begin
     TextColor(7);
     writeln('The storage is NOT SAFE - Therefore :');
     writeln;
     writeln('1 : Redesign the box ( dimensions, clearance and vents )  or ');
     writeln('2 : Stop the storage or');
     writeln('3 : Aerate/cool the potatoes if possible');
     writeln;
      TextColor(2);
     writeln('          Press <enter>  key to continue ...');
     readln;
 end; { message }

 begin
     TrMin:=Sim_Temp[1,1];
     for i:=1 to N do
     begin
         TpMax:=Sim_Temp[i,2];
         TpMin:=Sim_Temp[i,2];
         for j:=2 to Max+1 do
         begin
            if Sim_Temp[i,j] > TpMax then
              TpMax:=Sim_Temp[i,j];
            if Sim_Temp[i,j] < TpMin then
              TpMin:=Sim_Temp[i,j];
         end;
         MaxTps[i] := TpMax;
         MinTps[i] := TpMin;

         if Sim_Temp[i,1] < TrMin then
           TrMin:=Sim_Temp[i,1];
    end;
    TextColor(6);
    writeln;
```

```
 writeln('                    SUMMARY   INFORMATION ');
 writeln('                    =======   =========== ');
 writeln;
 TextColor(2);
 writeln;
 writeln('   Day  Tp Max  Tp Min ');
 TextColor(7);
 writeln;
 j:=0;
 for i:=1 to N do
 begin
     writeln(i:6,MaxTps[i]:8:2, MinTps[i]:8:2);
     j:=j+1;
     if j >= 10 then
     begin
          writeln;
          Textcolor(2);
          writeln('    Press <enter>  key to continue ...');
          readln;
          writeln;
          j:=0;
          ClrScr;
          TextColor(6);
          writeln;
          writeln('                    SUMMARY   INFORMATION ');
          writeln('                    =======   =========== ');
          writeln;
          TextColor(2);
          writeln;
          writeln('   Day  Tp Max  Tp Min ');
          TextColor(7);
          writeln;
    end;
end;
writeln;
Textcolor(2);
write('       Tr Min : ');
TextColor(7);
writeln(TrMin:6:2);
for i:=1 to N do
begin
       { check Ta }
     if Ta_Mat[i] > 30 then
     begin
         TextColor(6);
         writeln;
         writeln('Ta exceded !', ' at  time(day) : ',Time[i]);
         writeln;
```

```
          Message;
          exit;
      end;
       { check Tr }
      if Sim_Temp[i,1] > 30 then
      begin
          TextColor(6);
          writeln;
          writeln('Tr exceded !  at  time(day) : ',Time[i]);
          writeln;
          Message;
          exit
      end;
       { check Tps }
      for j:=2 to max+1 do
      begin
         if Sim_Temp[i,j] > 30 then
         begin
             TextColor(6);
             writeln;
             writeln('Tp exceded !  at  time(day) : ',Time[i]);
             writeln;
             Message;
             exit;
         end;
      end;
   end;
   if (TpMax-TrMin) > 2 then
   begin
      TextColor(6);
      writeln;
      writeln('TpMax - TrMin > 2 ! at  time(day) : ',Time[i]);
      writeln;
      Message;
      exit;
   end;
   if (TpMax-TpMin) > 1.5 then
   begin
      TextColor(6);
      writeln;
      writeln('TpMax - TpMin > 1.5 ! at  time(day) : ',Time[i]);
      writeln;
      Message;
      exit;
   end;

end; { Check up }
```

```
begin
    { write to output file }
    Assign(TextFile2,'c:\tp\bin\file2.pas');
    Rewrite(Textfile2);
    write(TextFile2,'Time Ta     ');
     write(TextFile2,'Tr      ');
    for j:=1 to 3 do
       write(TextFile2,'Tpe',j,'   ');
    for j:=1 to max do
       write(TextFile2,'Tps',j,' ');
    writeln(TextFile2);
    for i:=1 to N do
    begin
        write (Textfile2,Time[i]:4:2,'  ');
        write(TextFile2,Ta_Mat[i]:4:2,'  ');
        write(TextFile2,Sim_Temp[i,1]:4:2,'  ');
        for j:=1 to 3 do
           write(TextFile2,Exp_Temp[i,j]:4:2,'  ');
        for j:=2 to Max+1 do
           write(TextFile2,Sim_Temp[i,j]:4:2,'  ');
        writeln(TextFile2);
   end;
   writeln;
   writeln;
   y:=250;

   if source = 1 then
   begin
       OutText('SIMULATED [s] AND OBSERVED [e]');
       SetTextstyle(2,0,7);
       MoveTo(205,100);
       SetColor(1);
       OutText('POTATO TEMPERATURES (Tp) in deg C');
       Axis;
       SetLineStyle(0,0,1);
       SetTextStyle(2,0,4);

       YGreat:=30;
       XGreat:=0;
       for i:=1 to N do
       begin
          if Time[i] >= XGreat then
          XGreat:=Time[i];
       end;

       XGreat:=NextTen(Round(XGreat));
```

```
for i:=1 to 4 do
begin
   { display graph using simualted data }
   x1:=100+Round((Time[1]*300)/XGreat);
   y1:=round(400-(((Sim_Temp[1,i]*400)/YGreat)))+200;
   MoveTo(x1,y1);
   SetColor(i+1);
   SetFillStyle(1,i+1);
   for j:=2 to N do
   begin
      x1:=100+Round((Time[j]*300)/XGreat);
      y1:=round(400-(((Sim_Temp[j,i]*400)/YGreat)))+200;
      LineTo(x1,y1);
   end;
   if i = 1 then
   begin
      Bar(500,y,505,y+5);
      OutTextXY(520,y,'Tr');
      y:=y+20;
   end
   else
   begin
      str(i-1,Numstr);
      Bar(500,y,505,y+5);
      OutTextXY(520,y,'Tps');
      OutTextXY(540,y,NumStr);
      y:=y+20;
   end;
end;

{ display data using experimental data }
for i:=1 to 3 do
begin
   x1:=100+Round((Time[1]*300)/XGreat);
   y1:=round(400-(((Exp_Temp[1,i]*400)/YGreat)))+200;
   MoveTo(x1,y1);
   SetColor(i+6);
   SetFillStyle(1,i+6);
   for j:=2 to N do
   begin
      x1:=100+Round((Time[j]*300)/XGreat);
      y1:=round(400-(((Exp_Temp[j,(i)]*400)/YGreat)))+200;
      LineTo(x1,y1);
   end;
   str(i,Numstr);

end;
SetColor(4);
```

```
SetTextStyle(2,0,4);
OutTextXY(500,210,'KEY');
OutTextXY(550,450,'Fig 4.1');
OutTextXY(150,460,'Press space bar to view alternate values ');

LabelYAxis(Round(YGreat));
LabelXAxis(Round(XGreat));
Choice:=readkey;
if ord(choice) = 32 then
begin
   ClearDevice;
   y:=250;

   { prepare graphic system }
   setBkColor(11);
   SetTextStyle(6,0,3);
   MoveTo(150,60);
   SetColor(12);

   { Display heading }
   OutText('SIMULATED [s] AND OBSERVED [e]');
   SetTextstyle(2,0,7);
   MoveTo(205,100);
   SetColor(1);
   OutText('POTATO TEMPERATURES [Tp]');
   Axis;
   SetLineStyle(0,0,1);
   SetTextStyle(2,0,4);

   { display graph using simualted data }
   x1:=100+Round((Time[1]*300)/XGreat);
   y1:=round(400-(((Sim_Temp[1,(1)]*400)/YGreat)))+200;
   MoveTo(x1,y1);
   SetColor(i+1);
   SetFillStyle(1,i+1);
   for j:=2 to N do
   begin
      x1:=100+Round((Time[j]*300)/XGreat);
      y1:=round(400-(((Sim_Temp[j,(1)]*400)/YGreat)))+200;
      LineTo(x1,y1);
   end;
   Bar(500,y,505,y+5);
   OutTextXY(520,y,'Tr');
   y:=y+20;
   for i:=2 to 4    do
   begin
      { display graph using simualted data }
      x1:=100+Round((Time[1]*300)/XGreat);
```

```
        y1:=round(400-(((Sim_Temp[1,(i*2-2)]*400)/YGreat)))+200;
        MoveTo(x1,y1);
        SetColor(i+1);
        SetFillStyle(1,i+1);
        for j:=2 to N do
        begin
           x1:=100+Round((Time[j]*300)/XGreat);
           y1:=round(400-(((Sim_Temp[j,(i*2-2)]*400)/YGreat)))+200;
           LineTo(x1,y1);
        end;
        str(i*2-3,Numstr);
        Bar(500,y,505,y+5);
        OutTextXY(520,y,'Tps');
        OutTextXY(540,y,NumStr);
        y:=y+20;
     end;

     { display data using experimental data }
     for i:=1 to 3 do
     begin
        x1:=100+Round((Time[1]*300)/XGreat);
        y1:=round(400-(((Exp_Temp[1,i]*400)/YGreat)))+200;
        MoveTo(x1,y1);
        SetColor(i+6);
        SetFillStyle(1,i+6);
        for j:=2 to N do
        begin
           x1:=100+Round((Time[j]*300)/XGreat);
           y1:=round(400-(((Exp_Temp[j,(i)]*400)/YGreat)))+200;
           LineTo(x1,y1);
        end;
        str(i*2-1,Numstr);
        Bar(500,y,505,y+5);
        OutTextXY(520,y,'Tpe');
        OutTextXY(540,y,NumStr);
        y:=y+20;
     end;
  end
  else
  begin
     CloseGraph;
     exit;
  end;
end
else
begin
   OutTextXY(205,100,'SIMULATED TEMPERATURES');
   Axis;
```

```
SetLineStyle(0,0,1);
SetTextStyle(2,0,4);

YGreat:=30;
XGreat:=0;
for i:=1 to N do
begin
   if Time[i] >= XGreat then
   XGreat:=Time[i];
end;

XGreat:=NextTen(Round(XGreat));

x1:=100+Round((Time[1]*300)/XGreat);
y1:=round(400-(((Sim_Temp[1,(i)]*400)/YGreat)))+200;
MoveTo(x1,y1);
SetColor(i+1);
SetFillStyle(1,i+1);
for j:=2 to N do
begin
   x1:=100+Round((Time[j]*300)/XGreat);
   y1:=round(400-(((Sim_Temp[j,(i)]*400)/YGreat)))+200;
   LineTo(x1,y1);
end;

Bar(500,y,505,y+5);
OutTextXY(520,y,'Tr');
y:=y+20;

for i:=2 to  Max+1 do
begin
   { display graph using simualted data }
   x1:=100+Round((Time[1]*300)/XGreat);
   y1:=round(400-(((Sim_Temp[1,(i)]*400)/YGreat)))+200;
   MoveTo(x1,y1);
   SetColor(i+1);
   SetFillStyle(1,i+1);
   for j:=2 to N do
   begin
      x1:=100+Round((Time[j]*300)/XGreat);
      y1:=round(400-(((Sim_Temp[j,(i)]*400)/YGreat)))+200;
      LineTo(x1,y1);
   end;
   str(i-1,Numstr);
   Bar(500,y,505,y+5);
   OutTextXY(520,y,'Tps');
   OutTextXY(540,y,NumStr);
   y:=y+20;
```

```
        end;
    end;

    SetColor(4);
    SetTextStyle(2,0,4);
    OutTextXY(500,210,'KEY');
    OutTextXY(550,450,'Fig 4.2');
    OutTextXY(60,460,'     Press <enter> to quit                NB  output: "c:\tp\bin\file2.pas" ');

    LabelYAxis(Round(YGreat));
    LabelXAxis(Round(XGreat));
    readln;
    CloseGraph;
 end; { DislayOutput }

 begin
    { main program }

    { initialize variables }

    for i:=1 to size do
    begin
        Time[i] := 0;
        Ta_Mat[i]:=0;
        for j:=1 to size do
        begin
            Sim_Temp[i,j] :=0;
            Exp_Temp[i,j] :=0;
        end;
    end;

    { display welcome screen }
    Welcome;

    Textcolor(2);
    ans:='y';
    while UpCase(ans)='Y' do
    begin
        { Display Heading }

        Textcolor(12);
        writeln;
        writeln;
        writeln('A Turbo Pascal program that graphically compares observed (e) and simulated (s)
');
        writeln;
        writeln('  potato temperatures (Tp) in naturally ventilated boxes at various storage  ');
        writeln;
```

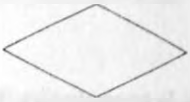
```
        writeln('temperatures (Tr) with storage time (days) writing data into c:\tp\bin\file2.pas ');
        writeln(' file and displaying Min and Max Temps and recommendations about system. ');
        Textcolor(7);
        writeln('    Sources of input data (Options)');
        writeln('    -------------------------------');
        writeln;
        writeln('     1 . Read input data from file ');
        writeln('     2 . Use equations to generate input data');
        writeln('     3 . Supply input data ');
        writeln('     4 . Quit');
        writeln;
        Textcolor(2);
        write('Enter your choice => ');
        Textcolor(15);
        readln(source);
        writeln;

        case source of
        1,2:
        begin
           Textcolor(7);
           writeln(' Enter zero to quit');
           writeln;
           { request for the number of time periods }
           Textcolor(2);
           write('Enter the number of time readings (days of storage)  => ');
           Textcolor(15);
           readln(N);
           if N<=0 then
             exit;
           writeln;
           Textcolor(2);
           { request for the number of potato temperatures }
           write('Enter the number of bulk potato temps (e.g. 3 for Tp1,2&3 for bottom, middle
and top temps)  => ');
           Textcolor(15);
           readln(Max);
           writeln;
           if Max = 0 then
             exit;
        end;
        readln(ans);
        writeln;
        ClrScr;
    end;
end. { TemperaturePrediction }
```

Appendix A1.2: Symbols used in the CTP computer program

Terminator

Process box

Input/Outp



Decision Box

Connector

Off Page Conn

Other Symbols

T - Time
Tr - Room temperature
Te - Experimental temperature
Tp - Layer/simulated temperatue
K & C - Constants
Ni - Number of air changes per hour
Qr - Respiration heat
Max - No of potato temperatures
N - Number of time readings

APPENDIX 2: DATA AND STATISTICAL ANALYSIS

A2.1 Egerton Data and Analysis

A2.1.1 SAS Command and Input File

```
Data ctpsim;
Input Days Ta Tr Te1 Te2 Te3 Tfs1 Tfs2 Tfs3 Trs1 Trs2 Trs3;
Title  'Egerton experimental (Tei) and CTP simulated (Tsi)';
Key ‘f represents values when qr and  k/c formulae were  used and r when random k/c were used';
diff1=Ta-Tr;diff2=Ta-Te2;diff3=Ta-Tfs2;diff4=Ta-Trs2;diff5=Tr-Tfs1;
diff6=Tr-Tfs2;diff7=Tr-Tfs3;diff8=Tr-Te1;diff9=Tr-Te2;diff10=Tr-Te3;
diff11=Te1-Te2;diff12=Te1-Te3;diff13=Te1-Tfs1;diff14=Te1-Trs1;
diff15=Te2-Tfs2;diff16=Te2-Trs2;diff17=Te3-Tfs3;diff18=Te3-Trs3;
diff19=Tsf1-Trs1;diff20=Tfs2-Trs2;diff21=Tfs3-Trs3;
cards;
;
```

‘Table A2.1.2 Experimental and CTP Simulation’

;

‘

Days	Ta	Tr	Te1	Te2	Te3	Tfs1	Tfs2	Tfs3	Trs1	Trs2	Trs3'
1	20.32	21.19	20.72	20.76	20.99	20.73	20.20	19.55	21.19	21.29	21.34
2	19.67	21.25	20.81	21.06	21.37	20.79	20.26	19.60	21.70	21.80	21.85
3	19.72	21.09	20.62	21.04	21.43	20.64	20.10	19.46	21.09	21.09	21.09
4	19.43	20.95	20.43	20.91	21.40	20.50	19.97	19.33	21.30	21.35	21.45
5	19.86	20.80	20.26	20.76	21.27	20.35	19.83	19.19	21.45	21.55	21.55
6	19.94	20.81	20.21	20.70	21.19	20.36	19.84	19.20	21.11	21.11	21.16
7	20.24	21.06	20.29	20.74	21.31	20.61	20.08	19.43	21.26	21.26	21.36
8	20.24	21.06	20.29	20.74	21.31	20.61	20.08	19.43	21.26	21.31	21.31
9	19.67	21.03	20.26	20.69	21.37	20.58	20.05	19.40	21.33	21.43	21.48
10	19.67	21.03	20.26	20.69	21.37	20.58	20.05	19.40	21.68	21.78	21.78
11	18.40	20.81	20.22	20.67	21.28	20.36	19.84	19.20	21.06	21.11	21.11
12	18.48	20.58	20.11	20.50	21.10	20.14	19.62	18.99	21.08	21.08	21.18
13	19.00	20.18	19.86	20.36	20.81	19.75	19.24	18.62	20.23	20.28	20.33
14	19.36	20.25	19.78	20.25	20.65	19.81	19.30	18.68	20.80	20.90	21.00
15	18.97	20.30	19.76	20.20	20.67	19.86	19.35	18.73	21.00	21.00	21.10
16	18.86	20.25	19.79	20.17	20.63	19.81	19.30	18.68	20.35	20.45	20.45
17	19.92	20.47	19.92	20.24	20.73	20.03	19.51	18.88	20.52	20.52	20.52
18	19.68	20.84	20.15	20.41	20.98	20.39	19.87	19.23	21.14	21.24	21.29
19	18.50	20.95	20.25	20.56	21.13	20.50	19.97	19.33	21.45	21.55	21.60
20	18.27	20.55	20.16	20.49	20.97	20.11	19.59	18.96	20.65	20.75	20.75
21	19.11	20.46	20.11	20.44	20.85	20.02	19.50	18.87	20.56	20.66	20.66
22	19.33	20.64	20.13	20.47	20.89	20.20	19.68	19.04	21.29	21.29	21.39
23	18.86	20.64	20.16	20.50	20.94	20.20	19.68	19.04	21.04	21.04	21.14
24	19.09	20.64	20.14	20.48	20.91	20.20	19.68	19.04	20.74	20.74	20.79
25	18.56	20.53	20.08	20.41	20.84	20.09	19.57	18.94	20.73	20.78	20.78

Table A2.1.2 Contd

Days	Ta	Tr	Te1	Te2	Te3	Tfs1	Tfs2	Tfs3	Trs1	Trs2	Trs3'
26	18.03	20.42	20.02	20.34	20.76	19.98	19.47	18.84	20.72	20.72	20.77
27	17.77	20.54	20.04	20.37	20.80	20.10	19.58	18.95	20.94	20.94	20.99
28	18.29	20.29	20.00	20.32	20.72	19.85	19.34	18.72	20.99	21.09	21.19
29	17.90	19.95	19.89	20.21	20.49	19.52	19.02	18.40	20.05	20.15	20.20
30	18.09	19.79	19.81	20.11	20.30	19.36	18.86	18.26	19.79	19.89	19.89
31	18.63	19.90	19.78	20.05	20.26	19.47	18.97	18.36	20.50	20.60	20.70
32	18.49	20.05	19.79	20.04	20.32	19.62	19.11	18.50	20.25	20.25	20.30
33	19.00	20.16	19.81	20.07	20.37	19.73	19.22	18.60	20.26	20.31	20.36
34	9.52	20.24	19.81	20.08	20.44	19.80	19.29	18.67	20.84	20.94	21.04
35	19.99	20.45	19.85	20.14	20.61	20.01	19.49	18.87	20.90	20.95	21.00
36	19.62	20.73	19.97	20.26	20.82	20.28	19.76	19.12	20.93	20.93	20.93
37	20.87	21.18	20.17	20.46	21.15	20.72	20.19	19.54	21.68	21.78	21.78
38	20.36	21.33	20.41	20.69	21.38	20.87	20.33	19.68	21.53	21.53	21.53
39	20.12	21.26	20.47	20.81	21.47	20.80	20.27	19.61	21.96	22.01	22.06
40	20.51	21.12	20.33	20.72	21.39	20.67	20.13	19.48	21.27	21.27	21.27
41	19.67	21.43	20.41	20.81	21.55	20.97	20.43	19.77	21.83	21.93	21.98
42	18.48	21.56	20.53	20.95	21.72	21.10	20.55	19.89	22.21	22.31	22.41
43	19.03	21.27	20.58	20.98	21.60	20.81	20.28	19.62	21.82	21.82	21.82
44	17.55	21.04	20.49	20.90	21.47	20.59	20.06	19.41	21.69	21.79	21.89

```
;
proc means n mean stderr prt;
var diff1 diff2 diff3 diff4 diff5 diff6 diff7 diff8 diff9 diff10 diff11 diff12
diff13 diff14 diff15 diff16 diff17 diff18 diff19 diff20 diff21;
run;
```

Table A2.1.3 SAS Ttest for Experimental and CTP Simulation

Variable	N	Mean	Std Error	Prob>|T|
DIFF1	44	-1.500	0.106	0.01%
DIFF2	44	-1.306	0.117	0.01%
DIFF3	44	-0.532	0.106	0.01%
DIFF4	44	-1.897	0.119	0.01%
DIFF5	44	0.445	0.002	0.01%
DIFF6	44	0.967	0.003	0.01%
DIFF7	44	1.603	0.005	0.01%
DIFF8	44	0.548	0.035	0.01%
DIFF9	44	0.193	0.035	0.01%
DIFF10	44	-0.294	0.024	0.01%
DIFF11	44	-0.354	0.013	0.01&
DIFF12	44	-0.845	0.031	0.01%
DIFF13	44	-0.103	0.034	0.45%

Table A2.1.3 Contd

Variable	N	Mean	Std Error	Prob>|T|
DIFF14	44	-0.892	0.056	0.01%
DIFF15	44	0.774	0.032	0.01%
DIFF16	44	-0.591	0.054	0.01%
DIFF17	44	1.898	0.022	0.01%
DIFF18	44	-0.149	0.046	0.23%
DIFF19	44	-0.789	0.035	0.01%
DIFF20	44	-1.365	0.037	0.01%
DIFF21	44	-2.047	0.041	0.01%

Ho: $diff_i = 0$
HA: $diff_i \neq 0$
Result: Reject null hypothesis and accept the alternative hypothesis. The paired comparisons between the differences the bulk bottom, centre and top potato temperatures (including the ambient and room) show that they are significantly different ($p<1\%$) (see appendix .

A2.2 The SRI Data and Analysis

Table A2.2 SRI Differential Temperatures

	Tc-Tr	Tt-Tr	Tqt-Tr	Tc-Tw	Tc-Thw	Tcp-Tca	Tb-Tr	Tqb-Tr	Tqb-Thw	Tqt-Tw	Tqt-Thw	Tt-Tw	Tt-Thw	Tl-Tw
0.00	-4.65	4.66	-4.74	0.38	0.50	0.26	-3.44	-5.19	-0.05	-1.62	0.06	-1.89	0.50	-0.36
0.04	-4.80	4.79	-4.92	0.37	0.50	0.26	-3.64	-5.38	-0.06	-1.65	0.06	-2.06	0.49	-0.42
0.08	-1.11	1.17	-1.15	0.32	0.47	0.22	0.12	-1.57	0.01	-1.49	0.10	-1.55	0.44	-0.39
0.12	-0.77	0.83	-0.81	0.34	0.46	0.27	0.44	-1.15	0.08	-1.40	0.16	-1.16	0.38	-0.37
0.17	-1.03	1.07	-1.09	0.34	0.46	0.28	0.08	-1.36	0.13	-1.34	0.21	-0.99	0.31	-0.36
0.21	-4.28	4.07	-4.38	0.33	0.47	0.25	-3.28	-4.54	0.09	-1.38	0.21	-0.21	1.04	-0.66
0.25	-2.52	2.26	-2.59	0.35	0.47	0.25	-1.65	-2.83	0.08	-1.42	0.22	-0.38	0.97	-0.81
0.29	-2.29	1.89	-2.35	0.40	0.49	0.27	-1.54	-2.60	0.10	-1.40	0.26	-0.41	1.03	-0.95
0.33	-2.36	1.54	-2.42	0.27	0.32	0.12	-1.73	-2.72	-0.08	-1.56	0.11	-0.56	0.90	-1.18
0.37	-2.22	1.51	-2.27	0.41	0.41	0.21	-1.67	-2.57	0.04	-1.42	0.24	-0.46	1.05	-1.17
0.42	-2.36	1.70	-2.40	0.50	0.45	0.27	-1.95	-2.72	0.10	-1.32	0.33	-0.35	1.17	-1.20
0.46	-2.20	1.45	-2.22	0.53	0.43	0.27	-1.85	-2.57	0.09	-1.29	0.35	-0.36	1.18	-1.28
0.50	-2.13	1.33	-2.14	0.56	0.41	0.27	-1.86	-2.51	0.10	-1.26	0.37	-0.35	1.18	-1.31
0.54	-2.08	1.23	-2.07	0.58	0.39	0.27	-1.89	-2.48	0.08	-1.25	0.37	-0.34	1.18	-1.35
0.58	-2.03	1.15	-2.01	0.60	0.37	0.26	-1.92	-2.45	0.08	-1.19	0.37	-0.33	1.16	-1.37
0.62	-1.99	1.09	-1.94	0.62	0.35	0.27	-1.94	-2.41	0.08	-1.13	0.39	-0.31	1.16	-1.38
0.67	-1.94	1.04	-1.88	0.63	0.34	0.27	-1.96	-2.39	0.07	-1.10	0.39	-0.30	1.15	-1.38
0.71	-1.90	0.99	-1.81	0.65	0.32	0.27	-1.98	-2.36	0.07	-1.05	0.39	-0.28	1.13	-1.38
0.75	-1.85	0.95	-1.76	0.65	0.31	0.27	-1.99	-2.34	0.06	-1.02	0.39	-0.27	1.11	-1.37
0.79	-1.81	0.92	-1.70	0.66	0.29	0.28	-2.00	-2.30	0.06	-0.97	0.40	-0.25	1.09	-1.36
0.83	-1.77	0.89	-1.65	0.66	0.28	0.27	-2.02	-2.28	0.04	-0.94	0.39	-0.25	1.07	-1.34
0.87	-1.72	0.86	-1.59	0.66	0.27	0.27	-2.02	-2.25	0.04	-0.91	0.39	-0.23	1.05	-1.32
0.92	-1.67	0.84	-1.54	0.67	0.27	0.28	-2.03	-2.22	0.03	-0.87	0.39	-0.21	1.03	-1.31
0.96	-1.63	0.82	-1.49	0.66	0.26	0.28	-2.04	-2.19	0.02	-0.84	0.39	-0.20	1.01	-1.27
1.00	-1.59	0.79	-1.45	0.65	0.24	0.27	-2.04	-2.17	0.00	-0.82	0.38	-0.20	0.98	-1.25
1.04	-1.54	0.77	-1.40	0.65	0.24	0.28	-2.04	-2.14	0.00	-0.79	0.38	-0.19	0.96	-1.22
1.08	-1.51	0.76	-1.36	0.64	0.24	0.28	-2.05	-2.12	-0.01	-0.76	0.38	-0.18	0.95	-1.19
1.12	-1.49	0.75	-1.34	0.63	0.23	0.27	-2.07	-2.11	-0.02	-0.74	0.37	-0.17	0.91	-1.17
1.20	-1.47	0.77	-1.33	0.62	0.23	0.27	-2.09	-2.11	-0.03	-0.72	0.36	-0.16	0.90	-1.14
1.21	-1.47	0.79	-1.33	0.61	0.23	0.28	-2.12	-2.11	-0.03	-0.69	0.37	-0.14	0.89	-1.11

key: T is temperature in degress Centigrade
e is experimental or observed
s is simulated
r = random k/c and qr formula used
f = formulae for k/c used
Diff = temperature difference as in the first row of the table above

Table A2.2.2 SAS Ttest for SRI Differential Temperatures

```
------------------------------------------------------------------------------------
  Variable   N       Mean      Std Error        T              Prob>|T|
------------------------------------------------------------------------------------
   DAYS     114     3.173       0.132         23.913           0.01%
   DIFF1    114     0.089       0.040          2.2003          0.03%
   DIFF2    114     0.305       0.032          9.3556          0.0%1
   DIFF3    114     0.114       0.023          4.8460          0.01%
   DIFF4    114    -0.119       0.004        -25.560           0.01%
   DIFF5    114     0.482       0.010         46.155           0.01%
   DIFF6    114    -0.022       0.020         -1.085           0.30%
   DIFF7    114     0.097       0.003         26.940           0.01%
   DIFF8    114     0.302       0.005         58.952           0.01%
   DIFF9    114    -0.070       0.022         -3.164           0.20%
   DIFF10   114    -0.037       0.005         -6.473           0.01%
   DIFF11   114     0.223       0.007         30.899           0.01%
   DIFF12   114     0.144       0.027          5.350           0.01%
   DIFF13   114     0.287       0.024         11.878           0.01%
   DIFF14   114     0.210       0.008         26.209           0.01%
------------------------------------------------------------------------------------
```

Key: N is number of observations
Diff is difference between given temperatures, as defined in the command file above
std is standard
T is the test statistic obtained for each variable
Prob is probability

Table A2.2.3 SAS Correlation Analysis on SRI Data

```
------------------------------------------------------------------
            Lab         Room        Bulkc       Bulkt
Lab       1.00000     0.53589     0.41224     0.39964
            0.0       0.0001      0.0001      0.0001
Room      0.53589     1.00000     0.61526     0.61684
          0.0001        0.0       0.0001      0.0001
Bulkc     0.41224     0.61526     1.00000     0.99518
          0.0001      0.0001        0.0       0.0001
Bulkt     0.39964     0.61684     0.99518     1.00000
          0.0001      0.0001      0.0001      0.0
------------------------------------------------------------------
```

where c represents the centre and t the top of the bulk of potatoes.

The table gives the Pearson Correlation Coefficients / Prob > |R| under Ho: Rho=0 / N = 86