Respiratory Response of Healthy and Diseased Potatoes (*Solanum tuberosum L.*) Under Real and Experimental Storage Conditions

A thesis submitted to
The Faculty of Graduate Studies and Research of
McGill University

By

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In Partial Fulfilment of the Requirements of the Degree of Doctor of Philosophy

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ABSTRACT

Mohamed A. Fennir Ph.D. (Agr & Biosystems Engineering)

Respiratory response of healthy and diseased potatoes (*Solanum tuberosum* L.) under real and experimental storage conditions

This study investigates respiration rate of potatoes (*Solanum tuberosum* L.) under real and experimental storage conditions. Real storage conditions were obtained by building a small-scale storage facility equipped with two independent storage bins including all controls. Each bin was filled with 2.5 metric tons of potatoes and these were stored for five months. Temperature, relative humidity, air flowrate and other operational parameters were collected. Also, mass loss and CO_2 analyses were performed.

A heat and moisture balance was applied to quantify heat and moisture rates produced by potatoes and were converted to respiration rates as CO_2 produced ($ml.kg^{-1}.h^{-1}$). Evaporation rates were also determined ($g.kg^{-1}.h^{-1}$). The balance was mainly applied on data collected from specific periods in which steady conditions were imposed; heaters and humidifiers were turned off and fans were operated to circulate air at a given flowrate for more than 8 h/day over a two month period. Respiration rates were determined as rates of heat produced (W) with stability and acceptable accuracy for a relatively large facility. Respiration rates were converted to CO_2 production ($ml.kg^{-1}.h^{-1}$), and these agreed fairly with ranges reported in the literature. Simultaneously, respiration rates were measured by in-store CO_2 analysis, and later they were measured under laboratory conditions using a closed gas analysis system. Comparing these with rates obtained by the heat and moisture balance, the later were slightly higher. Mass losses were also obtained by both weight losses and moisture balance; results from the two methods were quite similar and comparable with those reported in the literature.

Under experimental conditions, respiration rates were measured for healthy, diseased and sprouted tubers using a gas analysis method. Four treatments were used; healthy (H), sprouted (S), inoculated with soft rot (D), and a combination of disease and sprouting (SD). A Gas Chromatograph (GC) was used to analyze air samples. A significant (up to three fold) increase in respiration rate was attributable to disease and sprouting. This experiment demonstrated the need for a more

extensive investigation of disease development and its relation to respiration rates, and the need for a faster and more convenient gas analysis system.

This was addressed in a second experiment using an experimental storage system developed and tested for this purpose, consisting of 24-storage containers, an infrared gas analyzer (GA) and a sampling sequence for air analysis. The system performance was compared with an existing GC system being used for measuring respiration rates of potatoes. No significant difference in the accuracy of the two systems was detected. However, the GA system was 1 to 18 times faster than the GC system.

In a third experiment, the GA system was used for measuring respiration rates of potatoes infected with soft rot disease (*Erwinia caratovora*) and stored at 5, 10 and 15°C. Five treatments were tested at these three temperatures, healthy (H), healthy with holes (HW), inoculated and non incubated (I0), inoculated and then incubated for one day (I1), and inoculated and then incubated for two days (I2).

Disease did not develop in the I0 treatments at 5 and 10°C, and their respiration rates were not significantly different from those of the H and HW treatments. The I1 and I2 showed significantly (up to three-fold) higher respiration rates than the H and HW treatments. At these two temperatures, disease progression analysis showed that the I0 treatments did not exhibit disease development while the I1 and I2 showed progressive disease development. Respiration rates and disease progression showed similar trends.

At 15°C, the H and HW treatments showed similar respiration rates, and the three inoculated treatments (I0, I1, and I2) showed similarities in their respiration rates and were all significantly (up to three-fold) higher than the H and HW treatments. Disease progression was rapid and showed similar trend to the respiration rate. Respiratory quotient for the treatments showed that the RQ increased with both disease infection and storage temperature. The study addressed the feasibility of measuring respiration trends while produce was in storage.

The real and experimental respiration measurements demonstrated the accuracy of the heat and moisture balance and the significant effects of disease and sprouting on respiration rates; thus the study demonstrated the feasibility of using such experimental protocol for detecting respiration changes due to disease and sprouting under real storage conditions.

RÉSUMÉ

Mohamed A. Fennir Ph.D. (Génie agricole et biosystèmes)

Réponse respiratoire de pommes de terre saines et infectées (*Solanum tuberosum* L.) dans des conditions d'entreposage réelle et expérimentale

L'étude présentée porte sur l'évaluation du taux de respiration de pommes de terre (*Solanum tuberosum* L.) dans des conditions d'entreposage réelle et expérimentale. Les conditions d'entreposage réelles ont été obtenues en construisant des structures d'entreposage à petite échelle équipées de deux chambres indépendantes munies de contrôleurs, capteurs et actionneurs. Chaque chambre a été remplie de 2,5 tonnes métriques de pommes de terres qui ont été entreposées pendant cinq mois. La température, l'humidité relative, le débit d'air ainsi que tous les paramètres opérationnels ont été sauvegardés. De plus la perte de masse a été mesurée et des analyses de CO_2 ont été effectuées.

Un bilan massique et thermique a été utilisé pour déterminer la chaleur et l'humidité produites par les pommes de terre afin d'être converties en taux de respiration en termes de CO_2 produit ($ml.kg^{-1}.h^{-1}$). Le taux d'évaporation a également été déterminé ($g.kg^{-1}.h^{-1}$). Ce bilan massique et thermique a été principalement utilisé sur des données acquises lors de périodes stationnaires imposées; les éléments de chauffage et les humidificateurs ont été arrêtés et les ventilateurs ont été actionnés pour faire circuler l'air à un débit donné pendant plus de 8 h/jour sur une période de deux mois. Les taux de respiration ont été déterminés en tant que chaleur produite (W) avec une stabilité et une fiabilité acceptable pour ce type d'installation. Les taux de respiration ont été convertis en $ml.kg^{-1}.h^{-1}$ et ces derniers sont en accord raisonnable avec les valeurs retrouvées dans divers travaux cités. Simultanément, les taux de respiration ont été mesurés grâce à l'analyse en entrepôt du CO_2, et plus tard ils ont été mesurés en laboratoire en utilisant un

système d'analyse de gaz en système fermé. En comparant ces valeurs aux taux obtenus grâce au bilan massique et thermique, ces dernières valeurs sont légèrement supérieures. Les pertes de masse ont été également mesurées par le biais des pertes de poids et du bilan massique; les deux méthodes étaient tout à fait semblables et comparables à celles présentées dans la littérature citée.

Dans les conditions expérimentales, les taux respiratoires ont été mesurés pour des tubercules sains, infectés et germés en utilisant une méthode d'analyse de gaz. Quatre traitements ont été utilisés, sain (H), germé (S), inoculé avec la maladie *Erwinia caratovora* (D), et une combinaison de maladie et de germination (SD). Un chromatographe en phase gazeuse (GC) a été utilisé pour analyser des échantillons d'air obtenus. Une augmentation significative (jusqu'à trois fois) du taux de respiration était attribuable à la maladie ainsi qu'à la germination. Cette expérience a mené à un besoin de recherche plus approfondie sur le développement de la maladie et sa relation au taux de respiration, ainsi qu'à une nécessité d'accès à un système d'analyse de gaz plus rapide et plus pratique.

Dans la deuxième expérience, un système expérimental d'entreposage composé de 24 récipients interconnecté à un analyseur de gaz à infrarouge (GA) et d'un système de prélèvement pour l'analyse de l'air, ont été développés et testés. L'opération du système a été comparée avec un système existant utilisant un GC pour mesurer le taux de respiration des pommes de terre. Aucune différence significative dans l'exactitude des deux systèmes n'a été détectée. Le système de GA était cependant de 1 à 18 fois plus rapide que le système de GC.

Dans la troisième expérience, le système GA a été utilisé pour mesurer le taux de respiration des pommes de terre infectées par la maladie (*Erwinia caratovora*) et entreposé à 5, 10 et 15°C. Cinq traitements ont été testés à ces trois température, sains (H), sains avec des trous (HW), inoculés et non incubés (I0), inoculés et ensuite incubés pour un jour (I1), et inoculés et puis incubés pour deux jour (I2).

La maladie ne s'est pas développée lors des traitements I0 à 5 et à 10°C, et le taux de respiration des tubercules n'était pas très différent des traitements H et HW. Les traitements I1 et I2 ont montrés des taux de respiration plus élevés que les traitements de H et de HW et cela de manière significative (jusqu'au triple). À ces deux températures, l'analyse de progression de la maladie a prouvé que les traitements I0 n'ont pas stimulé le développement de la maladie cependant les traitements I1 et I2 ont stimulés un développement progressif de la maladie. Les taux de respirations et la progression de la maladie ont exprimés des tendances semblables.

À 15°C, les traitements H et HW ont exprimés des taux de respirations semblables, et les trois traitements d'inoculation (I0, I1, et I2) ont présentés des similitudes dans leurs taux de respiration qui étaient plus élevés que lors des traitements H et HW et cela de manière significative (jusqu'au triple). La progression de la maladie était rapide avec une tendance semblable au taux de respiration. Le quotient respiratoire métabolique (RQ) obtenu pour les traitements étudiés a démontrés que le RQ a augmenté avec l'infection et la température d'entreposage. L'étude a démontré la faisabilité des mesures des taux de respiration lorsque le produit était en entreposage.

Les mesures de la respiration dans les conditions réelles et expérimentales ont démontrés l'exactitude du bilan massique et thermique et les effets significatifs de la maladie et de la germination sur les taux de respiration; ainsi cette étude a démontré l'usage d'un tel protocole expérimental pour la détection des changements de respiration causés par la maladie et la germination dans des conditions réelles d'entreposage.

DEDICATION

This work is dedicated to my cousin (Uncle) Mohamed El-Hadi Fennir who passed away while I was in advanced stages of preparing this dissertation. This dedication is a token for my gratitude towards his profound role in my life.
I honour Uncle Mohamed for his endless help and support. Particularly, opening his house and heart to me during the extremely difficult times in my life and treating me as one of his children. With his care, encouragement, and support both morally and financially, I have taken the trail of learning until I graduated from the university and pursued my graduate studies.
Without the guidance of Allah and the initiatives of uncle Mohamed,
I would not have reached this stage.
Uncle Mohamed, you were my big brother, the wonderful gentleman, and the best friend from whom I sought advice on nearly every decision in my life. Your advice, inspiration and moral principles have been my guidance, and they will continue to be.
I profoundly miss you, and I will until we meet again in eternal life, Inshaa Allah,
I will keep praying Allah:
May Allah bless you and award you with his promised rewards for the faithful and martyrs; the highest place in paradise "Eden".
AMEEN.

ACKNOWLEDGEMENTS

I would like to express my utmost gratitude to my academic supervisors, Professor Vijaya Raghavan and Professor Jacques-André Landry, for their support and guidance throughout this study.

I sincerely thank Professor Raghavan, Chair, Department of Agricultural and Biosystems Engineering, McGill University for his devotion, encouragement, support and help, well beyond academics throughout the years of my enrolment in the department. I owe him a lifetime respect for assuming an important role in the most difficult stage of this study. I sincerely honour his vision towards graduate studies, his philosophy of supervision and his big heart. He has shown an understanding to my weaknesses, especially in occasions when language and cultural adversities impaired my expression of ideas. Even with his busy schedule, he always has time for me whenever I approach his office, or even when we meet outside. His diligence in meeting deadlines has provided me with the momentum to complete this work. Professor Raghavan has also inspired me in many other aspects of my life; his devotion to work, accomplishments, academic and research excellence, commitment and simplicity are emulative. Without his precious suggestions, commitment, and rapid feedback, this work would not have been accomplished.

I sincerely thank Professor Landry for his endless support, encouragement, and friendship. From the start of the study, he has provided me with full support both financially and morally. His devotion to students in and out of the academic arena has developed a long term friendship that indeed has been more than a student-supervisor type of relation. I appreciate all the advice he has given me and every moment we shared in discussion throughout the period that I have spent in the department of Agricultural and Biosystems Engineering. Although professor Landry has moved to the École de Technologie Superiéure (ÉTS) and become busy with the new position, his contributions to this work have been immense.

I also would like to express my gratitude to the members of my comprehensive examination committee, Professors, Ngadi, Barrington, and Ramaswamy for their advice that helped me in achieving my objectives. Special acknowledgment goes to Professor Ngadi for his inputs that have improved not only my academic knowledge but also given me the courage and energy to overcome many difficulties.

I sincerely thank Professor Kushalappa from the Plant Science department for his help and inputs in the pathological aspects of this study. Also his role in the project at early stages improved my approach in the pathology aspects of the study. He also provided me with great advice that helped me overcome many difficulties.

At the engineering shop where the storage facility and the gas analysis setup were built, the help of Dr Sam Sotocinal and Mr Ray Cassidy was highly appreciated. They provided me with the tools and a free access to the shop, as well as their technical advice and encouragement for which I am most appreciative.

I highly appreciate the help provided by professor Sheppard in giving me a free access to his laboratory facilities where most of the microbiological aspects of this study were done.

Also, the help of Dr Georges Dodds in proofreading this manuscript, and giving his invaluable comments that have improved the overall presentation of ideas has been highly appreciated.

From the departmental supporting staff, I appreciate the help of the former departmental administrative assistant (AA) Ms Susan Gregus and the AA, Ms Diane Chan for their roles in making my life easier.

I also acknowledge the "Conseil des Recherches en Pêche et en Agroalimentaire du Québec (CORPAQ)", the "National Science and Engineering Research Council of Canada (NSERC)" for funding the project, and the "Fonds la Formation de Chercheurs et dl'Aide à la Recherche (FCAR)" for giving me a scholarship.

Special thanks to my colleagues, with them I shared the best moments of my student life. Since they are indeed too many, I acknowledge the help of

anyone who has contributed in making my life easier and meaningful at the Macdonald campus of McGill University. Particularly, the Agr. & Biosystems Eng Students, and members of the Muslim Student Association (MSA).

To my family; I would like to express my gratitude to my wife Maryem and my children, Soad, Abdul-Migid, Hassan, Amal and Heba for their support, understanding, commitment, love and compassion that have been the source of my energy throughout the years. I am also indebted to my parents, sisters, brothers-in-law, sisters-in-law, nieces and nephews, and all members of the large family back home for their support and encouragement.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Table No. **Page**

LIST OF SYMBOLS

Symbol	Definition and/or value
a	Constant,-27,405.526
A/D	Analog-digital
A	Area of estimated openings at the bin shell, m^2
A_p	Surface area of each partition, m^2
ATP	Adenosine triphosphate (an energy rich biochemical compound)
b	Constant, 97.5413
Bin1	Storage bin #1
Bin2	Storage bin #2
Bottom	Temperature measurement location at the bottom of the potato pile
BTU	British Thermal Unit
c	Constant, -0.146244
cv.	Cultivar name
C. V.	Coefficient of variance
CA	Controlled atmosphere
C_D	Discharge coefficient for openings, dimensionless
CFH	Cubic feet per hour
CFU	Colony forming units
CIPC	isopropyl-N-(3-chlorophenyl)-carbamate (CIPC)
IPC	Isopropyl N-phenylcarbamate (Sprout inhibitor)
Cond	Conditioning room temperature, °C
CO_2	Carbon dioxide
C_p	Specific heat of air, $J.kg^{-1}.°C^{-1}$
d	Constant, 0.12558×10^{-3}
D	Diseased treatment

DAC	Digital-analog converter
DF	Degree of freedom
DMA	Direct memory access
DPI	Digital pressure indicator
e	Constant, -0.48502×10^{-7}
E. R.	Evaporation rate, $g.kg^{-1}.h^{-1}$
f	Constant, 4.34903
F	Degree Fahrenheit
ft	Feet
g	gram
g	gravitational constant, 9.81 $m.s^{-2}$
GA	Gas analyzer
GC	Gas Chromatograph
GC-MS	Chromatography-Mass Spectrometry (gas analysis method)
h	Hour
H	Healthy treatment
h_{fg}	Latent heat of evaporation of water (kj/kg)
HW	Healthy tubers with holes made (wounds) treatment
i	Constant, -0.39381×10^{-2}
I0	Inoculated and non incubated treatment
I1	Inoculated and incubated for one day
I2	Inoculated and incubated for two days
ID	Internal diameter
IPC	isopropyl-N-phenylcarbamate (Sprout inhibitor)
J	Joule
J	water flux from produce to the air ($g.s^{-1}.cm^{-2}$)
kg	Kilogram
K_m	Transpiration coefficient of the produce, $mg.kg^{-1}.s^{-1}.kPa^{-1}$

lb	Pounds
Left-Side	Left side of the of the facility (temperature measurement location)
m	Meter
m^3	Cubic meter
M_a	Mass of ventilation air, $kg.s^{-1}$
M_{air}	Ventilation rate air mass, $kg.s^{-1}$
$MgSO_4$	Magnesium sulphate
Middle	Temperature measurement location at the middle of the potato pile
min	Minute
ml	Millilitre
mm	Millimetre
mM	Millimole
m_p	Mass of the produce, kg
N_2	Nitrogen
NAD	nicotinamide adenine dinucleotide (a biochemical cell compound)
NaOCl	Sodium hypochlorite
NaOH	Sodium hydroxide
NPL	Neutral pressure level, m
O_2	Oxygen
OD	Outside diameter, m, cm, mm
Out-Side	Out side the storage bin temperature measurement location
P_a	Vapour pressure of the ambient atmosphere, kPa
Pa	Pascal
P_a	Actual water vapour pressure at temperature T, Pa
$P_{atm.}$	Atmospheric pressure , Pa

PC	Personal computer
PET	Photo-induced electron transfer quenching
psi	Pound per square inch
$P_{surf.}$	Vapour pressure at surface of the produce, kPa
PVC	Polyvinylchloride
Q	Airflow rate, $m^3.s^{-1}$
q_b	Rate of heat loss through bin structure walls, W
q_h	Rate of supplemental heat from heaters, W
q_r	Rate of heat produced inside the bin by potatoes, W
q_v	Rate of sensible heat gained by ventilation air, W
q_m	Rate of heat produced by mechanical devices, W
q_e	Rate of latent heat of evaporation of water, W
R	Gas constant ($m^3.Pa.g^{-1}.K^{-1}$)
R	Constant, 22,105,649.25
RH	Relative humidity of the air, %
RH-bin1	Relative humidity measured in bin #1, %
RH-bin2	Relative humidity measured in bin #2, %
RH-Mix1	Relative humidity measured in the mixing room #1, %
RH-Mix2	Relative humidity measured in the mixing room #2, %
RH-out	Relative humidity of the outside air before conditioning, %
Right Side	Right side of the of the facility (temperature measurement location)
R_m	Thermal resistance to heat for mineral wool, $°C.m^2.W^{-1}$
R_r	Thermal resistance to heat for the storage roof, $°C.m^2.W^{-1}$
R_p	Thermal resistance to heat flow of each partition, $°C.\ m^2.W^{-1}$
R_t	Thermal resistance to heat flow for storage outer walls, $°C.\ m^2.W^{-1}$
RQ	Respiration quotient, dimensionless
RR	Respiration rate as CO_2 produced or O_2 consumed, $ml.kg^{-1}.h^{-1}$
S	Sprouted treatment
SAS	Statistical analysis system package
SD	Sprouted and diseased

SS	Summed squares
SSR	Solid state relay
T	Dry bulb temperature of incoming or outgoing air, °C
T	Type T thermocouple
$T_{amb.}$	Temperature of the outside of each partition, °C
T_{bin}	Temperature inside the bin, °C
T_{bin}	Bin average temperature, °C
Temp	Temperature
T_{in}	Incoming air temperature, °C
Top	Temperature measurement location at the top of the potato pile
T_{out}	Outgoing air temperatures, °C
TR	Transpiration rate
T_{surr}	Average surrounding temperature, °C
V	Volt
V	Free volume inside the container, ml
VOC	Volatile organic compounds
VPD	Vapour pressure deficit
W	Watt
X	distance (cm)
ΔP	Pressure head created by the fan, Pa
ΔX	CO_2 or O_2 percentage change inside the container (%) during Δt, %
ΔH_{NPL}	Height from midpoint of lower opening to neutral pressure level (NPL)
Δt	Time between two consecutive GC analyses, hours
η	Fan efficiency, %
μ_{in}	Humidity ratio of the air entering the bin, $kg.kg^{-1}$
μ _Bin1	Humidity ratio of the air inside the bin #1,$kg.kg^{-1}$
μ _Bin2	Humidity ratio of the air inside the bin #2, $kg.kg^{-1}$
μ _Mix1	Humidity ratio of the air inside the mixing room #1, $kg.kg^{-1}$
μ _Mix2	Humidity ratio of the air inside the mixing room #2, $kg.kg^{-1}$
μ_{out}	Humidity ratio of the air leaving the bin, $kg.kg^{-1}$, $kg.kg^{-1}$

$\Delta\mu$	humidity ratio difference, $kg.kg^{-1}$

CHAPTER I

INTRODUCTION

Potato, *Solanum tuberosum* L. is the fourth most cultivated crop in the world after wheat, corn and rice. The world production of potatoes in 2001 exceeded 307 million metric tons. Canada and the United States produced over 24.5 million metric tons, representing 9% of the world production. In both countries combined, nearly half a million hectares are cultivated, producing the highest potato crop yield in the world at 37.4 t/ha (FAO,2002).

Among fresh harvested crops, potatoes are indeed considered as one of the best candidates for long term storage, since it can be stored for extended periods while maintaining good quality. In general, potatoes are stored for three market uses; table, processing and seed.

Studies on storing potatoes are not recent, it is in fact a two century old practice. The earliest documented attempt of storing potatoes was reported in a Scottish publication dated 1814. In what was then called a clamp, potatoes were kept dry and cool in an unventilated potato pile covered with straw for protection from freezing (van der Schild, 1987). Later, clamps were ventilated using a wooden ventilation duct installed under the pile, and the produce was cooled using the principle of the chimney effect. Currently, ventilated clamp storage systems are still being used in some parts of Europe and most developing countries for short term storage (FAO, 1998).

During the same era, the earliest establishment of potato storage started in North America, specifically in the state of New Hampshire, where a commercial potato production for starch manufacturing began in the early 1800s (Plissey, 1976). The practice gradually improved and in the late 1940s, more advanced storage warehouses were built, with larger storage capacities and equipped with better

control systems (van der Schild, 1987).

Giant food processing enterprises have become more involved in various potato processing operations namely; chips, frozen, french fries and other products. In fact, for the past 30 years, the North American market has exhibited an increase in consumption of processed potatoes (Anonymous, 2000a). Lately, the trend towards consuming processed potato products has reached Eastern Europe, Asia and other developing countries. The latest development in these regions, such as rising incomes, tourism, increased numbers of females in the workplace, and other factors will eventually lead to an increase in demand for potato products. For the processing enterprises, to keep pace with the rapidly increasing demands, potato processing operations will likely start in these regions (Anonymous, 2000a).

Canada and the United States process more than 50% of their annual production into french fries, potato chips and frozen potato products. According to the 1998 USDA statistical data, out of 21.6 million metric tons produced in the United States, 59% was processed into chips, french fries and frozen products (Anonymous, 2000b). Most of the potato supply to the industry comes from storage facilities operated by growers or the processing industry itself. To maintain a steady supply, more than 75% of the US production is stored (Kaschyk, 1976; Orr, 1987).

Given their important role, potato storage operations have been intensively investigated, leading to a tremendous improvement in produce quality, storage duration, reduced storage cost and improved economic return. More recently, research activities have focussed on early disease detection (de Lacy Costello *et al.,* 2000; Lyew *et al.*, 1999), biological control of disease in storage (Schisler *et al.*, 2000), ventilation and storage control (Jayas *et al.*, 2001; Landry, 1994; Forbush and Brook, 1993), handling and injuries (Mathew and Hyde, 1997), and the use of alternatives to chemical sprout inhibitors (Boylston *et al.*, 2001, Sonnewald, 2001). However, less attention is being given to the most important physiological activities,

respiration and transpiration.

The shortage in respiration and transpiration studies may be attributable to the complexity of the study, the time and amount of work required, and the broadness of the subject. Even for older studies, little if any attention has been given to initiating a comprehensive in store and laboratory-scale experimental investigation.

There is a legitimate need to undertake a potato respiration study under real and laboratory storage conditions. It could lead to further improvement of the storage operation and a better understanding of in-store respiration rate. Also, it could test the possibility of detecting changes in respiration rate and their use as indicators for biological activities such as disease and sprouting. However, it is well understood that such studies require a tremendous amount of time and effort. A storage facility that simulates real storage conditions has to be designed, built, and instrumented. Also, a better and faster respiration analysis setup with a multi-container system has to be built. Therefore, part of this study focuses on the development, testing and evaluation of the methodology used in the current study and of a framework for future studies.

The main aim of this study was to quantify respiration rate of potatoes stored under real and laboratory storage conditions in an attempt to investigate the feasibility of developing a method for early detection of disease development in commercial storage. In the first part, the heat and moisture balance was applied to determine heat produced by potatoes. In the second, an improved gas analysis system was developed, tested and applied for measuring respiration rate of potatoes as affected by soft rot disease (*Erwinia carotovora*). Secondary objectives were to determine weight loss, temperature distribution, heat loss and gain through the storage operation, and produce response to heating and cooling.

CHAPTER II

HYPOTHESES AND OBJECTIVES

2.1. Hypotheses

Stored agricultural products are alive and continue their physiological process of respiration. The process is generally simplified as a glucose oxidation reaction that produces carbon dioxide, water and heat as byproducts. The reaction has an efficiency of less than 40% (Salisbury and Ross, 1992), thus most of the respiration reaction energy is given off as heat. In a relatively airtight storage vicinity, the heat produced is accumulated, and if heat quantities are accurately quantified, they can be used to quantify produce respiration rates.

Hypothesis (I): stored potatoes generate an amount of heat that can be detected using the heat and moisture balance.

The respiration process is affected by several factors, in general these are classified into two groups; storage environment related factors and produce related factors. At stable storage conditions, the respiration process is certainly stable, unless produce related factors cause changes, thus.

Hypothesis (II): Postharvest biological and physiological stresses, namely sprouting and disease, lead to a significant increases in respiration rate.

Hypothesis (III): If no stresses are imposed, respiration rate remains stable.

2.2. Objectives

1. The application of a heat and moisture balance for in-store evaluation of respiration rate of potatoes.

2. The evaluation of the storage operation by visualizing the potato bulk pile temperature distribution and relative humidity levels.
3. The monitoring of CO_2 production inside the storage bins and the use of these measurements for evaluating respiration rates under real storage conditions.
4. The development of a more efficient gas analysis system that is comparable to an existing gas chromatography system, and its use for multi-chamber respiration rate study.
5. Studying the effects of soft rot disease (*Erwinia carotovora*) on respiration rate, and its development and progression under three storage temperatures (5, 10 and 15°C), covering temperature range normally encountered in a potato storage operation.

2.3. Scope

Although the study was performed by storing potatoes for an extended period of time under conditions similar to that obtained in a normal storage operation, and given that one may expect that a broader investigation scheme may be pursued, the scope of the study was narrowed down to investigate the possibility of measuring respiration rate of potatoes during storage. Under experimental storage conditions, the study was limited to investigate the effect disease on respiration rate and to correlate its rates with disease progression.

CHAPTER III

REVIEW OF LITERATURE

3.1. Storage Process Overview

Generally, the use of long term storage is driven by commodity abundance, its market value and suitability for storage. It is well understood that an investment in a storage operation is expensive and may require high levels of technical expertise (Thompson, 1996). From a pure marketing perspective, storing produce is very much related to the basic economic concept of supply and demand, and it is indeed a profit-driven operation.

Worldwide in general, and in developing nations in particular where storage practices are not well developed for most agricultural products, an abundant supply is encountered at harvest, with demand being distributed throughout the year. Such situations result in a market condition known as "market glut". The abundant supply and low demand lead to significantly lowered prices. From a postharvest perspective, losses are dramatically increased.

Storing of perishables is generally done at reduced temperatures and elevated relative humidities, and in some systems gas compositions are also modified (Kader, 1992, Raghavan *et al.*, 1996). The global aim of the storage process is to extend the availability of fresh fruits and vegetables by keeping them in their most usable conditions for consumers and processing industries (Gariépy *et al.,* 1988). However, the nature of the produce itself is very much related to its storage duration. For instance, some delicate commodities such as berries have a very short shelf life even under ideal storage conditions (Ryall and Lipton, 1979). In contrast, under less suitable storage conditions, root crops such as potatoes and cassava can nonetheless be stored for several months (FAO, 1998).

3.1.1 Storage facilities and design considerations

Unlike other agricultural, industrial and residential structures, a storage facility has to be designed to provide stable conditions of low temperature, high relative humidity, and indeed a superior degree of air tightness. Environmental conditions surrounding the storage facility are important factors in its design, as they influence its structure and internal conditions. Essential design considerations are as follows:

Storage structure durability: The storage structure must withstand prevailing weather conditions such as wind and snow loads, and extreme low and high temperatures. It must also withstand produce loads, particularly in bulk stored crops such as potatoes (Yaeger, 1986).

Possibility for expansion: When a storage facility is to be built, enough space around the storage must be kept for further expansion. Areas for delivery, loading and unloading operations must also be taken into consideration.

Insulation: Insulation is a material that reduces heat transfer from one point to another due to conduction, convection, and/or radiation. All construction materials have some insulation effect, yet insulation usually refers to a material that has high insulation value, better known as the R value. Several insulation materials are available in the market such as mineral wool, fibreglass and polyurethane. Important considerations in the selection of insulation material are; the ease of installation, fire resistance, ease of application, and cost (Raghavan and Gariépy, 1985). An efficient insulation material provides a stable storage environment that is less affected by outside conditions. It reduces heat exchange between the inside and the outside environments, and when combined with an adequate vapor barrier, prevents internal moisture migration through the structure, eliminates condensation on walls, roof and the outermost layer of the stored produce

(Rastovski, 1987a). From an economical point of view, large heat losses or gains lead to extra heating/cooling expenses.

3.2. Storage Systems For Potatoes

Potato crop may be left in the field until maturity is reached, or could even be left for a little longer. The later has the disadvantages of occupying the field and increasing the susceptibility of the produce to disease infestation and freezing, especially in cold regions (Thompson, 1996). Instead, produce is generally harvested at maturity and kept in the most suitable environment (Raghavan and Gariépy, 1985). Based on the cooling method, potato storage facilities can be classified into air-cooled (naturally ventilated) or mechanically refrigerated stores.

3.2.1. Air-cooled storage

Air-cooled storage systems, sometimes known as naturally ventilated systems, are used in regions where low temperature outside air can be used for cooling the produce. Air is drawn in, conditioned (humidified and/or heated) if necessary and brought in contact with the produce. The system has the advantages of low operational costs and can be efficiently used for storing potatoes targeted for chipping (Nash, 1979). Nevertheless, the method is entirely dependant on the outside air conditions. Warm conditions during late spring may result in higher storage temperatures, making such a system limited to certain regions and applications. Given the moderate temperatures in late fall and the cold winter, most potato storage facilities in the Northern United States and Canada use this type of storage system.

3.2.2. Mechanically refrigerated storage

In mechanically refrigerated storage, cooling is achieved by heat exchange between the air and a refrigerant fluid. The main components of the system are; a compressor, a condenser, an expansion valve and a cooling coil (Kader, 1992). During the operation mode, storage air is brought in contact with the system cooling element where a low temperature refrigerant fluid gains heat from the air (Raghavan and Gariépy, 1985; Wills *et al.,* 1981). When a mechanically refrigerated storage is designed, it is important to select a refrigeration unit with a cooling capacity capable of handling the maximum heat loads. Mechanically refrigerated storage systems have advantages over air-cooled storage system such as rapid cooling and the ability to maintain stable temperatures.

3.3. Potato Storage Operations

For a successful storage operation, the following procedures are the main contributors to preserving tuber quality.

3.3.1. Surface drying

Harvested tubers are covered with wet soil, and some tubers are immature and have a very thin skin layer. Such tubers are subjected to faster moisture losses and susceptible to physical injuries in the form of skinning (Halderson and Henning, 1993). Additionally, excessive free water around tubers prevents air exchange, leading to anaerobic respiration and enhanced pathogen growth (Schippers, 1976). After harvesting, surface drying is accomplished using ventilation air at high flow rates. Frequent produce inspection is important for preventing excessive ventilation that may cause produce dehydration.

3.3.2. Suberization

Due to harvesting, handling and transportation, tubers are subjected to physical damages such as wounds, bruises and skin removal. Injured tubers respire and give off moisture more than healthy ones. An increase in respiration of up to 50% can be associated with an open skin (van Es and Hartmans, 1987).

The suberization process is aimed at wound healing and developing skin maturity. Damaged skin due to cuts and bruises are cured by the formation of a periderm layer (corky tissue) on the damaged surfaces which appears as a rough skin layer (Meijers, 1987). Although this process results in a poor appearance, it maintains tissue vigour, prevents moisture migration, reduces respiration, and prevents pathogen invasion. Suberized tuber tissue produces the steroid glycoalkaloids α-chaconine and α-solanine, two compounds which inhibit the germination of *Fusarium sambucinum* , the main cause of dry rot disease (Ray and Hammerschmidt,1998).

Suberization is achieved by keeping the tubers for 10 to 15 days at temperatures between 15 and 20°C combined with a high relative humidity (>95%) and a minimum ventilation flow rate. High temperature is indeed an important factor in suberization but not absolutely necessary. Wound healing is primarily dependant on relative humidity, i.e. it can also be achieved at slower rate under conditions of low temperature and high relative humidity, but not under conditions of low relative humidity, regardless of the temperature being used (van Es and Hartmans, 1987).

3.3.3. Cooling

After suberization is achieved, the produce is slowly cooled to its storage temperature. Air at lower temperature and high relative humidity is brought in contact with the produce to remove suberization heat. Cooling is a process of heat and mass transfer whereby air gains heat and moisture from the produce. In a bulk potato

storage, air is forced to move through a large produce volume that generates large amounts of heat and moisture. Considering the fact that air has a low specific heat and at low temperatures also has limited moisture holding capacity, a good temperature and relative humidity control has to be applied to avoid undesirable conditions of temperature and relative humidity.

During the cooling process, the pile can be illustrated as several layers of produce, the first layer comes in contact with the air stream and picks up a substantial amount of heat and moisture. At the second layer, the same air stream picks up less heat and moisture compared with the previous one, and so on until it gets to the top layer. Consequently, a lag in cooling time between produce layers may occur and as air reaches higher layers, it becomes relatively warmer and more humid. The phenomenon results in cooling variations through the pile (Rastovski, 1987b; Lerew and Bakker-Arkema, 1976). Figures 3.1 and 3.2 illustrate cooling and humidifying lags in a potato pile.

Cooling time affects produce quality as it enhances starch conversion to sugar, high sugar contents are not desirable in fried potatoes as they result in dark colour products. Nevertheless, the application of slow cooling is believed to result in less starch conversion (Dennis, 1983). A maximum temperature decrease of 1.5 to 2°C every 6-12 days was recommended to prevent sugar formation (Forbush and Brook, 1993; Landry, 1994).

The selection of ventilation rates for potato storage is a very controversial issue, as wide variations in recommended flow rates has been observed in the literature. Variations are mostly due to differences in varieties, growing region, storage structure, and air handling systems (Brook *et al.*, 1995).

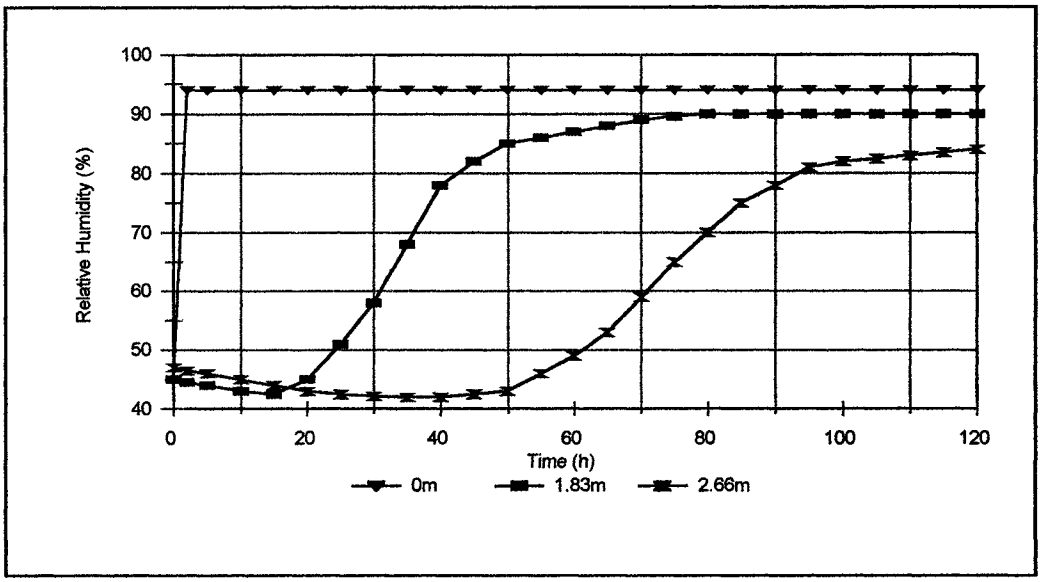


Figure 3.1. Relative humidity of interstitial air *vs* time at three vertical distances in a 2.66m pile during the cooling process. 94% inlet relative humidity. (Adapted from Lerew and Bakker-Arkema, 1976)

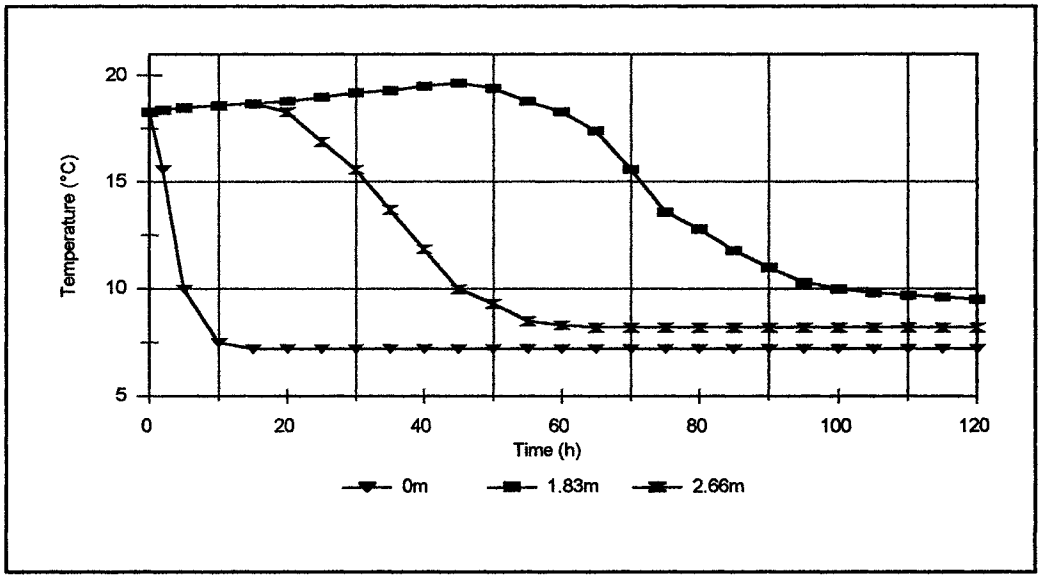


Figure 3.2. Tuber temperature *vs* time at three vertical distances in a 2.66m pile during the cooling process. 94% inlet relative humidity. (Adapted from Lerew and Bakker-Arkema, 1976)

3.3.4. Sprout inhibition

Sprouting can be inhibited by three methods: low temperatures, application of chemical agents, and irradiation (Buitelaar, 1987). Keeping tubers at temperatures below 4°C certainly prevents sprouting. However, the method is not suitable for potatoes targeted for processing, since at low temperature, starch is converted into sugar, causing undesirable properties at frying. Additionally, using low temperatures as an inhibitor is impaired by technical and weather related constraints that may risk losing the entire stored produce, when events such as failure in the cooling system or extended periods of warm weather occur.

Irradiation with beta, gamma or X-rays prevents cell division and proven to be effective for sprout inhibition. It also widely applied and has been approved by the World Health Organization (WHO) as a safe postharvest treatment (Buitelaar, 1987). However, most growers prefer the use of chemical agents, possibly because of the lower cost, convenience and consumer cautiousness towards irradiated foods. Chemical compounds such as isopropyl-N-phenylcarbamate (IPC) and isopropyl N-(3-chlorophenyl) carbamate (CIPC); commercially known as Propham and Chlorpropham are the most widely used chemical agents. However, alternatives of using natural compounds as sprout inhibitors have given promising results (Boylston *et al.*, 2001). In general, chemical sprout inhibitors prevent cell division and their application before suberization prevents or slows the process of wound healing, hence, they are commonly applied after suberization. Also, the effectiveness of sprout inhibitors can be impaired by temperature fluctuations, high relative humidity during application, and inefficient ventilation, and thus temporary conditions are imposed during the application of a sprout inhibitor (Lewis *et al.*, 2001).

3.3.5. Controlling storage conditions (holding)

Once the pile is cooled to the desired holding temperature, its temperature, relative humidity and gas composition are controlled. Monitoring air composition (CO_2 and O_2 levels) has been reported in the literature (Jayas *et al.*, 2001). Traditionally, monitoring gas composition measurement has no practical applications in commercial storage warehouses, since stores are not close systems, hence most CO_2 is lost by infiltration. However, pockets of CO_2 accumulation may affect the stored produce, therefore, a frequent air exchange is normally applied (van Es and Hartmans, 1987).

3.3.5.1. Temperature

Storage temperature is one of the principal factors affecting produce quality. Therefore, efficient temperature control throughout the storage period is one of the primary requirements for a successful storage operation. In a potato pile, temperature is subjected to variations due to the efficiency of the air handling system, cooling air temperature, and outside temperature. A storage facility must have an efficient ventilation system, effective control devices, and reliable temperature measurement. Measured temperatures should be displayed for manager information and sensors must be distributed uniformly through the pile and well protected from weight and loading damages (Rastovski, 1987c).

In an efficient storage operation, heat removal from the pile is achieved by introducing air at temperature slightly lower than that of the stored potatoes. To prevent condensation and excessive moisture loss, the control system must maintain maximum temperature variations of 0.5 to 1°C between the bottom and the top of the pile (Wilkes, 1976).

Temperature and relative humidity are very much related as they affect the ability of air to hold moisture in a gaseous form. Improper decrease in air

temperature could result in over saturated air, leading to condensation on the produce and store surfaces. In contrast, sudden increase in air temperature with no humidification reduces air relative humidity, and hence more water evaporation from the tubers occurs. To avoid these two extremes, it is important to apply slow heating or cooling and to maintain temperature difference between the produce and ventilation air of less than 1.6°C (Brook *et al.*, 1995). Holding temperature is normally determined based on the purpose of the storage. Table 3.1 summarizes temperature ranges for stored potatoes targeted for various market uses.

Table 3.1 Optimum storage temperature for potatoes stored for various market uses.

Use of the Tubers (Market)	Temperature (°C)
Table (long term)	4 - 5
Table (short term)	5 - 8
Processing (depending on product)	7 - 10
Seed (not sprouted)	2 - 4

Source Landry (1994).

3.3.5.2. Relative humidity

Relative humidity is a measurement that gives an indication of air moisture content. It is defined as the ratio of water vapor pressure of the air at a given condition (temperature and atmospheric pressure) to its water vapor pressure at saturation under the same conditions.

In the literature, there is a general agreement on considering high relative humidity as a key player in reducing weight losses and preserving produce quality. However, near saturation relative humidity causes free water around the produce, creating favourable condition for disease development. Nevertheless, relative humidity values between 10 and 100% can be encountered in a potato storage warehouse (Lerew and Bakker-Arkema, 1976).

Relative humidity has to be monitored throughout the storage season using reliable humidity transducers. Water is added to ventilation air as required to maintain high relative humidities close to the set-point. In practice, perfect air humidification of the ventilation air and precise measurement of relative humidity are quite difficult to obtain. Fluctuation of air temperature and humidity ratio may lead to imperfect humidification of the ventilation air, resulting in relative humidities that differ from the desired values. In addition, most of the commercially available humidity sensors can be less accurate at high relative humidities and can show measurement errors of up to ±5% above 93% RH (Landry, 1994).

3.3.5.3. Flow rate

Ventilation rate in a potato storage is a disputed issue. Wide variations in recommended ventilation rate have been reported. Differences have been linked to growing regions, harvesting conditions, variety, cooling method, and market use (Brook *et al.*, 1995; Dennis, 1983; Rastovski, 1987b). Geographical location plays an important role in the selection of flow rate; for two different regions, flow rate can vary by up to three-fold.

Studies have suggested the application of both continuous and intermittent ventilation, with the second being more favorable (Cargill, 1976a). In the intermittent air flow system, fans are only operated when heat accumulation reaches a level at which its removal becomes necessary (Brook *et al.*, 1995). Nevertheless, ventilating the stored produce is not only for cooling purposes but also for air exchange, mainly to reduce excessive moisture, CO_2 and other undesirable gases.

3.4. Important Potato Postharvest Diseases

Disease is the prime source of losses in a potato storage warehouse as it can cause extensive damages. Postharvest diseases are mainly caused by bacteria and

fungi. Most diseases are initiated in the field, transferred to the store and spread at favorable conditions of temperature and relative humidity (Meijers, 1987). However, a disease infestation may occur due to improper cleaning of the storage area from the remains of the previous season and improper disinfection.

Bacterial soft rot *(Erwinia* spp), pink rot (*Phytopthora erythoseptica*) and Fusarium dry rot (*Fusarium* spp.) are the most common potato postharvest diseases. The first is a bacteria while the second and the third are fungus, and they vary in their severity from one region to another. However, the most serious disease amongst these is soft rot, with its ability to develop rapidly in a potato storage facility at favourable conditions. By physical contact, the disease moves from one tuber to another, causing extensive damage within a few days at favorable storage conditions (de Lacy Castello *et al.*, 1999, Ouellette, 1988).

Among the above mentioned diseases, only two postharvest diseases will be discussed herein; viz., soft rot and dry rot as they commonly occur in potato stores and the fact that they present two different disease agents, bacteria in the case of soft rot and fungi in the case of dry rot. Additionally, the topic of postharvest disease is vast and the investigation of all diseases may require long term experimental investigation, and is beyond the scope of this investigation.

3.4.1. Soft rot

Soft rot is caused by several Erwinia species, *Erwinia carotovora* subsp. *atroseptica* and subsp. *carotovora,* and *Erwinia chrysanthemi.* The agents cause infections in the field known as blackleg, and in the storage as soft rot (Zimnoch-Guzowska *et al*, 1999). The three agents have temperature requirement ranging from cool to warm. While *Erwinia carotovora* subsp. *atroseptica* is common in moderate regions, *Erwinia chrysanthemi* is well adapted to warm regions, and *Erwinia carotovora* subsp. *carotovora* is well adapted to both climates (Weber,

1990). The disease agent infects the tuber through its lenticels. Once inside the tissue, it may stay inactive for extended periods of time, then under favorable conditions, it starts breaking down the tuber tissue making it soft, slimy and creamy. After a short period, the infected area becomes brown turning to black. At its early stages, the disease is odorless and tubers remain firm, and as time advances, in addition to tissue decomposition by the disease itself, a secondary invasion by other bacteria and fungi initiates, producing unpleasant odors and turning the infected area into a greasy mass of bacteria and decomposed tissues (Ouellette, 1988). The severity of infestation can be anywhere between an isolated empty hole to an entirety mushy and soft tuber.

In bulk storage systems, disease is transmitted from one tuber to another by physical contact forming isolated infected pockets. With time, disease advances more and the infected area becomes weak, causing spatial collapse of the pile that can be easily identified. Additionally, wet surfaces can be seen both in the bottom ventilation duct and on the top surface of the pile.

High temperature and relative humidity combined with poor ventilation are favorable conditions for the disease. However, once wet spots are noticed, lowering the temperature and applying high ventilation rates can be an effective measure for slowing disease advancement until the infected bin or area is emptied (Meijers, 1987).

3.4.2. Fusarium dry rot

Unlike soft rot, dry rot is caused by several species of *Fusarium* fungi. The pathogen infects the produce in the soil and may enter the harvested tubers through unavoidable injuries caused by harvesting and handling (Schisler *et al.*, 2000). Relatively little is known about the pathogenic properties of some species, but it is known that wounded and suberized tubers produce inhibitory compounds that

prevent disease infestation (Ray and Hammerschmidt, 1998). Infestation may occur during or before the suberization stage mainly because of high temperature and relative humidity.

Other characteristics of the disease are its slow development and its occurrence as a secondary infestation to soft rot. It is important to mention that because of the involvement of various species, the symptoms may vary. Generally, wrinkled and sunken tuber surfaces with light brown to black colour are the common signs of the disease (Ranganna, 1996).

Applying careful harvesting and handling procedure, efficient suberization, and good temperature and relative humidity control strategies are key factors in the prevention of these diseases.

3.4.3. Disease detection methods

In a storage warehouse, detection of disease is a very important consideration. Several techniques are used and are discussed in the following paragraphs.

3.4.3.1. Manager's inspection

Although literature on manager's inspection is very rare, some common signs of the disease are used as a practical detection tool. Conventional detection methods rely on the use of sensory and visual signs for disease inspections. Storage managers and inspectors employ their sense of smell and practical experience. While first entering the storage area, the sense of smell plays an important role as rotten tubers release unpleasant odors, which progressively increase as the disease advances.

The visual focuses on physical signs in the pile. Infected tubers decompose and infected tissues become creamy with watery portions that become free moisture.

Besides creating smellier conditions, free moisture is carried away by ventilation air, causing condensation on the top of the pile and store ceiling. At advanced stages, wet spots become obvious, giving strong indications of the existence of a diseased pocket deep in the pile. Infected pockets become weak, leading to spatial collapses of the pile.

Although frequent inspections confirm the existence of the disease, it is difficult to quantify its severity, leaving storage managers with very little time to decide on the proper measures to be taken.

3.4.3.2. Hot spots (temperature sensing)

Inside the pile, diseased potato pockets are biologically active spots that may have higher respiration rates, and hence generate more heat. Additionally, heat is generated by the disease agent activities and the breaking-down of tuber tissue, and therefore, heat is generated at higher rates than with healthy tubers. In theory, temperature sensing can be applied to locate hot spots in the pile using either temperature transducers or infrared detection instruments. However, both methods are impaired by several technical constraints, and their application in a real storage operation has not been reported in the literature.

Theoretically, locating several temperature transducers within the pile would indicate heat changes. Hot spots can then be identified, observed and further investigation can be made accordingly (Ouellette, 1988). Although early indication of suspected disease active spots can be determined, it requires a considerable number of precise temperature transducers, and a high level of instrumentation, and again, reports on such operations have not been found in the literature.

Hot spots can also be identified using infrared techniques whereby scanning the top of the pile with an instrument that detects thermal radiation, a heat map of the pile can be produced and hot spots can be located. Hot spots can be biologically

active pockets or may be due to poor ventilation.

The infrared method has been applied successfully for the determination of diseased portions of sugar beet piles in the US using a thermal imaging device mounted on an aircraft (Ouellette, 1988). In case of a storage facility, such a device can do the same job in a potato storage operations; it requires a special installation and extensive investigation prior to commercial installation attempts can be suggested.

3.4.3.3. Volatile monitoring and electronic sensing

Several studies have been conducted on the application of volatile monitoring as an early detection tool. Methods are based on the concept of identifying certain volatiles, or volatile organic compounds (VOC), that are associated with a specific disease. Some researchers used gas chromatography for analysing gas samples collected from the head space of a container filled with infected tubers (Lyew *et al.*, 2001; Lyew *et al.,* 1999, Ratti *et al.,* 1995), while others applied further analysis where the VOCs were identified using Chromatography-Mass Spectrometry (GC-MS) (de Lacy Costello *et al.*, 1999, Ouellette, *et al.,* 1990a, Ouellette, *et al.,* 1990b).

In principle, all analytical methods rely on analysing gas samples from an enclosure which contains infected tubers and identifying specific compounds that are associated with the studied disease. However, despite extensive research work on the application of volatiles as a detection tool, the method is still in the development stages and has not been adopted in potato storage warehouses.

3.5. Respiration Process

Respiration is a major metabolic process occurring in all living cells. It is defined as the oxidative breakdown of complex materials such as sugar, starch and organic acids into carbon dioxide (CO_2) water and energy (Kays, 1991). The

respiration reaction is shown in Equation 3.1. However, from a plant physiology point of view, the respiration process involves complex biochemical reactions and goes beyond a simple sugar oxidation reaction.

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + Energy \qquad (3.1)$$

In a living cell, the respiration reaction consists of three main steps: (i) *Glycolysis*, an enzymatic glycolysis of glucose to produce pyruvic acid, (ii) *the Krebs cycle* in which nicotinamide adenine dinucleotide (NAD) is reduced and limited amount of Adenosine triphosphate (ATP) is synthesized, and CO_2 released, (iii) *the electron-transport system and oxidative phosphorylation*, in which most of the ATP is produced, O_2 is consumed and water is produced (Salisbury and Ross, 1992).

Depending on whether respiration occurs in the presence of oxygen (O_2) or not, it is termed as aerobic or anaerobic, respectively (Wills *et al.*, 1981). Aerobic respiration is the normal and the preferred process in healthy fruits and vegetables. In practice, about 32% of the energy produced in a respiration reaction is fixed in the ATP synthesis and the rest is given off to the surrounding as heat (van Es and Hartmans, 1987)

3.5.1. Respiration rate

Respiration rate can be determined based on measuring CO_2 produced, O_2 consumed, or heat released. CO_2 and O_2 are determined using several methods, the most common method being gas analysis (GA). Heat produced by respiration is calculated based on the relation that each milligram of CO_2 produced or O_2 consumed, resulting in 10.767J of energy being released. Using the amount of measured gas, time between two consecutive measurements, and produce weight, the respiration rate is expressed as $mg.kg^{-1}.h^{-1}$. Respiration rate as heat produced

is expressed as $J.kg.h^{-1}$ and calculated based on the measurement of either gases (Hardenburg *et al.*,1990, Ryall and Lipton, 1979). Also, a method for measuring respiration rates as heat produced in a laboratory installation (Calorimetry) has been reported in the literature (Green *et al.*, 1941).

3.5.2. Respiration quotient

The respiration quotient (RQ) is defined as the molar fraction of CO_2 produced over O_2 consumed (Eq. 3.2). In a natural situation of glucose combustion, the respiration quotient is at unity. However, this is not valid in the shortage of O_2 or with the use of a substrate other than glucose. Other compounds such as fats and organic acids may serve as substrates for respiration in some situations. The RQ for fats is less than unity while for an organic acid is above unity. When the respiration rate is measured in term of CO_2 and O_2, the calculated RQ gives an indication of the oxidized substance used in the respiration, and also indicates wether the respiration is aerobic or anaerobic (Bidwell, 1979). Although it is generally assumed that RQ for stored potatoes is at unity, long term respiration rate measurements show high RQ at the beginning of storage followed by a stage of unity, with an RQ in the range of 0.9 and 1 being normal (Schippers, 1977a).

$$RQ = \frac{CO_2 \ produced}{O_2 \ consumed} \qquad (3.2)$$

3.5.3. Factors affecting respiration rate

The following subsections discuss the main factors affecting the respiratory process and its rate.

3.5.3.1. Temperature

Temperature is the most important postharvest factor to be considered in a storage operation. It directly affects the respiration process of stored fruits and vegetables. Up to a certain limit, the higher the temperature the higher the respiration rate. Keeping a produce at low temperatures just above the freezing point leads to lower respiration rates (Shewfelt and Prussia, 1993). For potatoes in particular, respiration rates measured in the range of 0 to 27°C have been reported in the literature (Schippers, 1977a). Stable temperatures are a key element in maintaining stable respiration rate, and under fluctuating temperatures respiration takes time to stabilize (Salunkhe *et al.,* 1991, Schippers, 1977a).

3.5.3.2. Atmospheric composition

The gas composition of the storage vicinity has a significant effect on maintaining produce quality factors such as color and in delaying maturity. Moreover, reduced O_2 and increased CO_2 levels have anti-pathogenic effects (Herner, 1987). However, in the case of potatoes and most other root crops, the use of controlled atmosphere storage has no significant effect neither on quality nor on storage duration (van Es and Hartmans, 1987).

Conditions of low O_2 and high CO_2 levels may exist in a potato storage, and lead to anaerobic conditions. High CO_2 level leads to physiological disorders in potatoes known as black heart. Affected tuber shows no apparent symptoms, but when cut through, black coloring of the internal tissue can be observed (Meijers, 1987).

3.5.3.3. Physical injuries

During harvesting, transportation and handling, harvested produces are subjected to cuts, bruises, and skin removal. While cuts are noticeable injuries,

bruises are not, yet both have profound impacts on respiration and transpiration. Bruising occurs by breakage of the cell membrane and further reaction takes place, resulting in tissue degradation and browning (Shewfelt and Prussia, 1993). Injured tubers respire and transpire more rapidly than healthy ones and their respiration rate is proportional to the severity of the damage (Kader, 1987).

3.5.3.4. Preharvest factors

Preharvest factors affect respiration indirectly, and are different from harvesting and storage environment factors. Preharvest factors refer to conditions encountered prior to storage, such as water and heat stresses, shortage or excess in nutrients, field-borne diseases and other field practices. These factors can affect the produce in the form of physiological or pathological disorders. Mineral and nutrient contents during produce development are major factors influencing produce composition and postharvest behaviour (Shaul and Goren, 1987). In a comprehensive review of literature on respiration rate of potatoes in storage, Schippers (1977a) reported an increased respiration rate of potatoes with potassium deficit. Moreover, temperature and relative humidity during growth are strongly linked to some postharvest diseases. Irrigation rates can affect water content, texture, skin, shape and responsible for size deformations.

3.6. Methods of Measuring Respiration Rates

3.6.1. Gas analysis methods

Several techniques for measuring respiration rate are available, the most commonly used being the gas analysis method. In this method, the produce sample is kept in an airtight chamber and periodic air samples are drawn and analysed for CO_2 and O_2 contents. Respiration rate is calculated and expressed as CO_2 produced or O_2 consumed. Other methods for the measurement of respiration rate, such as

loss of dry weight and loss of energy content can also be used. However, since the later methods are destructive and difficult to perform, they are not commonly used (Kader, 1987). Gas analysis methods are sub-classified into closed and open systems, and discussed in the following subsections.

3.6.1.1. Closed system

Respiration rate measurement is carried out by keeping a known produce mass inside an airtight chamber, and air samples are then taken at known time intervals, analyzed in a gas analysis apparatus such as a gas Chromatograph, and the CO_2 and O_2 contents are determined. The respiration rate is calculated using the change in gas composition between two consecutive air analyses, produce mass and time elapsed between the two measurements. Respiration rate is expressed as $ml.kg^{-1}.h^{-1}$ or $mg.kg^{-1}.h^{-1}$ of CO_2 produced or O_2 consumed.

The method has been criticized of being performed in a non equilibrium state in which the depletion of O_2 and the accumulation of CO_2 may influence the respiration process itself (Schippers, 1977a, Kader, 1987). However, a CO_2 percentage of less than 3% is considered to have no significant effects on respiration rate, and thus being used as threshold at which experimental storage containers are aerated.

3.6.1.2. Flowing air system

These techniques are again based on gas analysis, with few modifications. The produce is kept in an airtight chamber that is periodically ventilated with CO_2-free air at a known flow rate. At the outlet, a column containing a CO_2 absorber such as Sodium hydroxide (NaOH) is installed. After a pre-determined period of time, the column is taken and analyzed for its CO_2 content. Alternatively, air samples can be taken from the outlet and analyzed for their CO_2 and O_2 contents (Kader, 1987).

Since they provide a relatively fast determination of the respiration rate, and no risk of CO_2 accumulation, flowing air measurement systems are sometimes named "online gas analysis".

Although the air flow system has the advantage over the closed system of performing the measurement in a condition of lesser gas accumulation, the two systems efficiency are still dependant on the gas analysis apparatus.

3.6.1.3. Apparatuses used for gas analysis

Several gas analysis techniques are used for determining CO_2 and O_2 percentages in the sample, the most common are gas chromatography, mass spectroscopy, and infrared gas analyzer.

3.6.1.3.1. Gas chromatography

The use of gas chromatography is generally considered as reliable and precise for determining the gas composition of an air sample. For a respiration study, the system relies on storing produce in an airtight chamber, preferably with a large storage volume, and a scheme for air sampling is deployed. However, the use of GC can be blamed for making the method time consuming. In studies reported by Gariépy and Raghavan, (1988); Ramachandra, (1995); and Chimphango, (1996), two to three gas samples were withdrawn in a 0.5 ml syringe and analyzed. Practically, it required 6 minutes to analyze each sample, thus, 12 to 18 minutes were required to analyze samples taken from one chamber. Considering the fact that respiration measurements can be extended for months and gas analysis has to be performed frequently, it is clear that the method can be quite time consuming.

3.6.1.3.2. Mass spectroscopy

Gas analysis procedures employed in this type of systems are based on the

ionization of sample molecules. Various chemical analyses are carried out using mass spectrometry systems. However, its application in gas analysis for measuring respiration rate is very limited. Recently, Wareham and Persaud (1999) reported a setup and an experimental procedure using mass spectrometry for measuring respiration rate of agricultural products stored under modified atmosphere conditions. The system uses a small storage chamber (<350 ml) and small produce samples (<40 g), and there was no indication of multi-chamber use. Furthermore, for the small size of the test chamber, samples were cut which may affect the respiration process itself. Although the system may be used for modified atmospheres for processed commodities, its applications in respiration studies are very limited. Also, the method has technical limitations, such as a complicated calibration procedures and special installation, in addition to sensitivity and high costs.

3.6.1.4. Other gas analysis systems

Other systems are those which do not adopt common laboratory apparatus such as gas chromatography or mass spectrometry. Those systems are intended to be less expensive, more practical, and suit special applications, yet measurement accuracy is not much compromised. Calegario *et al.* (2001) reported a closed loop air flow analysis system that uses a conductometeric detector to measure CO_2 produced by tomato fruit. The flow system used consists of a CO_2 -rich stream and deionized water acting as a receptor. The two streams pass through opposite sides of a membrane which acts as a diffusion cell. The receptor stream is connected to a conductivity-meter which displays the results on a chart. The system analysis time was estimated as 10 minutes. However, one limitation of the system is that it does not measure O_2, which is an important parameter for calculating the respiration quotient (RQ). Additionally, system measurements have not been compared with other existing gas analysis systems. Also, the system uses a single small storage

chamber with a capacity of a single fruit.

Harman *et al.* (1999) reported the preliminary stage of the development of a CO_2 sensor using the principle of photo-induced electron transfer (PET) quenching. The system is still very much at the development stage, and may be oriented towards medical uses. No indication of O_2 measurement by the system was reported. Additionally, no application of the system for measuring respiration rates of agricultural products has been reported in the literature.

3.6.1.5. Pressure variation methods

This class of apparatus is based on the principle of pressure variation. Pressure increases in an airtight chamber containing plant parts is mainly caused by changes in gas composition (increased CO_2 and reduced O_2 levels) due to the respiration process. The Warburg apparatus is one of the commonly used devices for such measurements. In fact, it is one of the earliest developed instrument and has been used for several biochemical reaction studies. Measurements are based on the principle of pressure change when an alkali is introduced to absorb CO_2 (Kader, 1987).

Forcier *et al.* (1987) reported the development of a respiration measurement device based on the pressure variation concept. Samples were kept in an airtight chamber, after some time air was passed through an absorbing column to collect CO_2 and pressure changes were monitored using a pressure transducer. Pressure change, time, volume of the chamber, temperature, and produce mass were used for the calculation of respiration rates as CO_2 produced and O_2 consumed. The method is a combination of a closed system and an air flow method with the advantages of low operational cost and accuracy. However, no further respiration studies using the system have been reported in the literature.

3.6.1.6. Calorimetry

The first setup for the calorimetric measurement of respiration rate of produce was developed by Green *et al.* (1941). The CO_2 produced, O_2 consumed, and heat produced were measured in one experimental setup. It consisted of an insulated structure in which several jars were installed and submerged in a constant temperature water bath. Produce samples were kept inside the jars, and temperature differences between the water bath and the produce in the jar were recorded. Additionally, filtered air was introduced into the jars and exhausted. At the outlet, CO_2 and evaporated water were collected. Temperature data was used for the calculation of heat generated by the produce, evaporated water was used for calculating latent heat of evaporation, and CO_2 was used for the calculation of respiration rate by using CO_2 production rate.

This method gave comparable results for heat of respiration measured directly and that calculated based on CO_2 production. The method has since been considered as a reference for other respiration measurement methods. (Hardenburg *et al.,* 1990; Ryall and Lipton, 1979). Although it is accurate for measuring CO_2 and heat produced, it is labour intensive and requires special installations.

3.7. Transpiration

Together with respiration, excessive transpiration rates lead to fast quality degradation of the stored produce. Water losses accelerate quality degradation and indeed have severe effects on the quality aspects of the stored produce. Losses can be in the form of wilting, shrivelling and loss of turgor. Such undesirable appearances have negative effects on the marketability of the produce, resulting in a decrease in consumer appeal and produce unsuitability for processing.

3.7.1. Transpiration mechanism

In fresh fruits and vegetables, transpiration is defined as a mass transfer process by which water moves from the produce surface to the surrounding air (Ben-Yehoshua, 1987). As a diffusion phenomena, the process is governed by Fick's Law and expressed as:

$$J = -D \frac{dC}{dx} \tag{3.3}$$

Where:

J = the water flux ($g.s^{-1}.cm^{-2}$),

D = mass diffusivity of water ($cm^2.s^{-1}$),

C = concentration of water ($g.cm^{-3}$)

X = distance (cm)

The above equation can be expressed in term of pressure difference between the produce surface and the surrounding air as:

$$J = \frac{-D}{R\,T} \left(\frac{dp}{dx}\right) \tag{3.4}$$

Where:

J = water flux from the produce to the surrounding air ($g.s^{-1}.cm^{-2}$),

D = mass diffusivity ($cm^2.s^{-1}$),

R = gas constant per gram ($kPa.cm^3.g^{-1}.°K^{-1}$),

T = temperature (°K),

P = pressure difference between the produce and the surrounding air (kPa),

x = distance (cm).

The application of the above equation in the evaluation of transpiration is fraught with difficulties, mainly the existence of steady state situations under which water vapour pressure of plant tissues is measured. These difficulties are due to variations in temperature, effect of solutes, osmotic and turgor pressures, and other physiological effects. Instead, a relative humidity of 99-99.5% is used as an estimate for the produce tissue, and hence vapour pressure can be calculated accordingly (Ben-Yehoshua, 1987).

3.7.2. Factors affecting transpiration

3.7.2.1. Temperature and relative humidity

Temperature and relative humidity together are the primary causes of vapour pressure differences between the produce and its surrounding air. A slight change in either temperature or relative humidity affects the psychrometric properties of the air. Therefore, they are discussed together.

Potatoes and other vegetables contain 80 to 95 percent virtually free water in the intercellular space of the tissue, making it a saturated condition (Dennis, 1983). At lower relative humidity, the air has a vapour pressure lower than that of the produce, causing a situation of VPD, and water tends to move from the produce to the surrounding air. Ideally, ambient air must be at or near saturation with a temperature similar to the produce surface temperature (Dennis, 1983; Salunkhe and Desai, 1984). However, in a real situation such conditions may not exist, and near saturation conditions may lead to the accumulation of free water around the produce, resulting in potential growth and multiplication of pathogenic bacteria and fungi (Bertz and Eckert, 1987).

3.7.2.2. Flow rate

During water evaporation from the produce, a film of saturated air is formed

around the commodity and reduces moisture evaporation. Air movement takes away that film, resulting in more water evaporation. Some research suggest a slight effect of air movement on transpiration (Sastry and Buffington, 1982). However, very little information is available on the state of equilibrium between the produce and its surrounding air.

3.7.2.3. Physical injuries

Injuries such as cuts and bruises act as open surfaces and increase water loss (Wills *et al.*, 1981). However, injuries due to mechanical forces can be reduced by using proper harvesting techniques, careful handling and transportation operations. In the case of potatoes, physical injures are normally healed by suberization.

3.8. Measurement of Transpiration Rate

Transpiration rate can be calculated based on the measurement of temperature and relative humidity at the surface of the produce and the surrounding atmosphere. Vapour pressure of the produce and its surrounding air can be determined and at steady state conditions, the transpiration rate is calculated using Equation 3.3.

Although the equation gives the theoretical rate, it is fraught with difficulty in determining the transpiration coefficient. Several factors affect the measurement of the coefficient such as variety, degree of maturity, picking time, air velocity, and produce size and shape (Dennis, 1983).

Romero *et al.* (1985) conducted an experiment to measure transpiration coefficients of some fruits and vegetables. In their experiment, the estimation of transpiration coefficients was based on the direct measurement of mass losses. A temperature range of 15.4 to 24°C and relative humidities between 45 and 65% were

maintained inside a chamber and various air flow rates were introduced. Dry bulb and dewpoint temperatures were also measured and used for the determination of air relative humidity. Vapour pressure of the produce was calculated numerically and transpiration coefficient was calculated from weight losses. The effect of respiration was considered insignificant. However, this assumption is questionable when one considers the temperature range being 15 to 24°C.

Koca *et al.* (1993) conducted an experiment for measuring mass losses due to respiration and transpiration of pears stored under CA conditions. Pears were placed in a CA plexiglass box and hanged on a weight scale in a cold room. Dry bulb and dewpoint temperatures of the air surrounding the fruits and their surface were used for the evaluation of vapour pressure of the air, vapour pressure of the fruit, and relative humidity of the air, respectively. The experiment sought to study the effect of temperature fluctuations due to the refrigeration system defrost cycles. Mass variations before and after defrost cycles were used to evaluate overall losses. The authors concluded that their estimation was close to what was predicted and reported in the literature.

One must consider the complexity of the factors affecting transpiration and the difficulties in measuring some of these parameters. Technical difficulties are associated with a precise measurement of produce surface temperature and hence its saturated water vapour pressure. Additional difficulties are related to maintaining steady state conditions between the produce and the surrounding atmosphere. Thus, a precise measurement of transpiration rate can be quite difficult (Chau *et al.*, 1985).

3.9. Heat and Moisture Balance for Agricultural Applications

The only study other than that conducted by the author, aimed at the application of direct measurement of respiration and transpiration in a setup similar

to a vegetable storage facility was reported by McDermott and Feddes (1991) and Feddes and McDermott (1992). In both studies, heat and moisture balance equations were applied on an animal housing facility and the results were compared with indirect measurements of respiration. Results showed that mean heat rates measured by the direct method was 2 to 6% higher than that measured by an indirect method.

In the field of fruit and vegetable storage, Fennir and Landry (1997) have studied the application of the heat and moisture balance for the evaluation of heat rates and moisture generated inside a small scale experimental setup. Experiments were designed to measure simulated respiration and transpiration activities. In their studies (Fennir, 1997; Fennir and Landry, 1997; Landry and Fennir, 1995), a 0.21m^3 chamber was used (Figure 3.3), heat was generated using precision heat sources that gave heat rates ranging between 15 and 105W at 15W intervals, and moisture was generated using an evaporative pad. Air was delivered using a centrifugal fan and its rate was controlled at the outlet using an adjustable louver. Flow rate was measured using a pressure sensor, incoming and outgoing air temperatures were measured using type T thermocouples, and air relative humidities were measured using wet and dry bulb temperatures.

Heat and moisture balances of the chamber were made at combinations of low and high temperatures and flow rates. High relative humidity was not achieved due to limitations in the experimental setup and its surrounding environment.

When no consideration was given to moisture, heat rates generated were measured with a precision of ±5%. However, when moisture was introduced, some difficulties were encountered due to the small size of the chamber and difficulties in achieving a steady state of high relative humidity. It was recommended that the method be applied on a larger scale setup to overcome the limitations experienced.

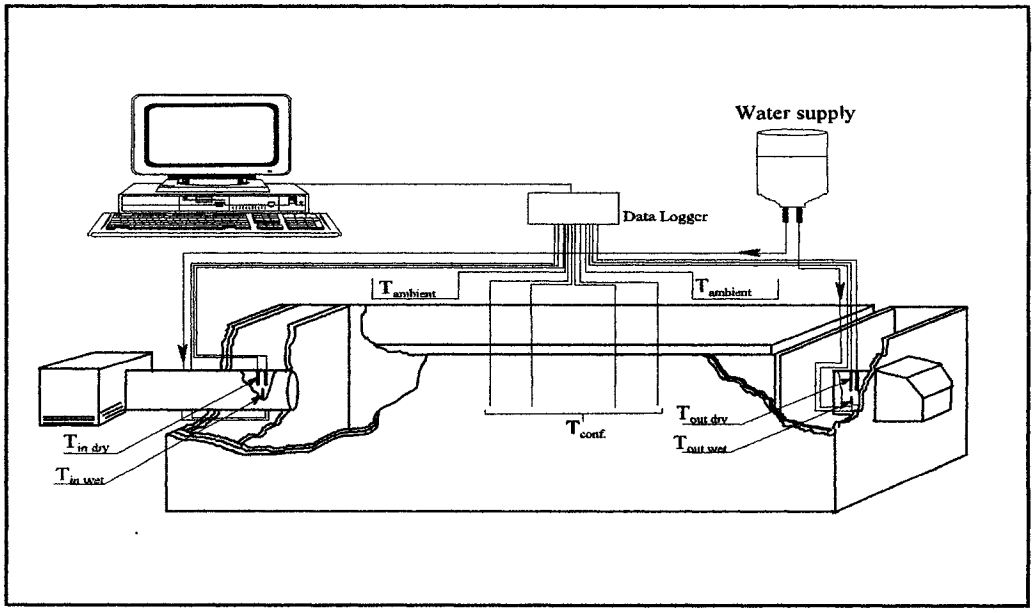


Figure 3.3. A schematic of the experimental setup used by Fennir and Landy (1997) for quantifying heat rates produced inside a 0.21m^3 chamber.

3.10. Summary of the Potato Storage Operation

From the previous sections, it is evident that a potato storage operation is a complex system that involves multi-variables. Its main purpose is to preserve quality and reduce losses. A schematic overview of the storage process that addresses potatoes targeted for chipping is presented in Figure 3.3. Nonetheless, the scheme shows interrelated parameters that generally occur in most potato storage operations. Variety and growing conditions are the most influential factors on storage duration and quality parameters. Once the tubers are stored, temperature, relative humidity, vapour pressure deficit (VPD), and flow rate play their roles in quality changes by affecting respiration, transpiration, and sugar formation. Since sugar contents are more critical for chipping potatoes, those parameters affect quality losses by influencing flavour, chip colour and texture, and oil uptake, at the end they affect cooking and frying qualities of processed tubers. Storage conditions besides their influence on respiration and transpiration may trigger sprouting and disease.

For potatoes targeted for any market use, the four parameters (temperature, relative humidity, VPD and flowrate) are the main contributors to water and dry matter loss, leading to weight losses which results in less physical appearance.

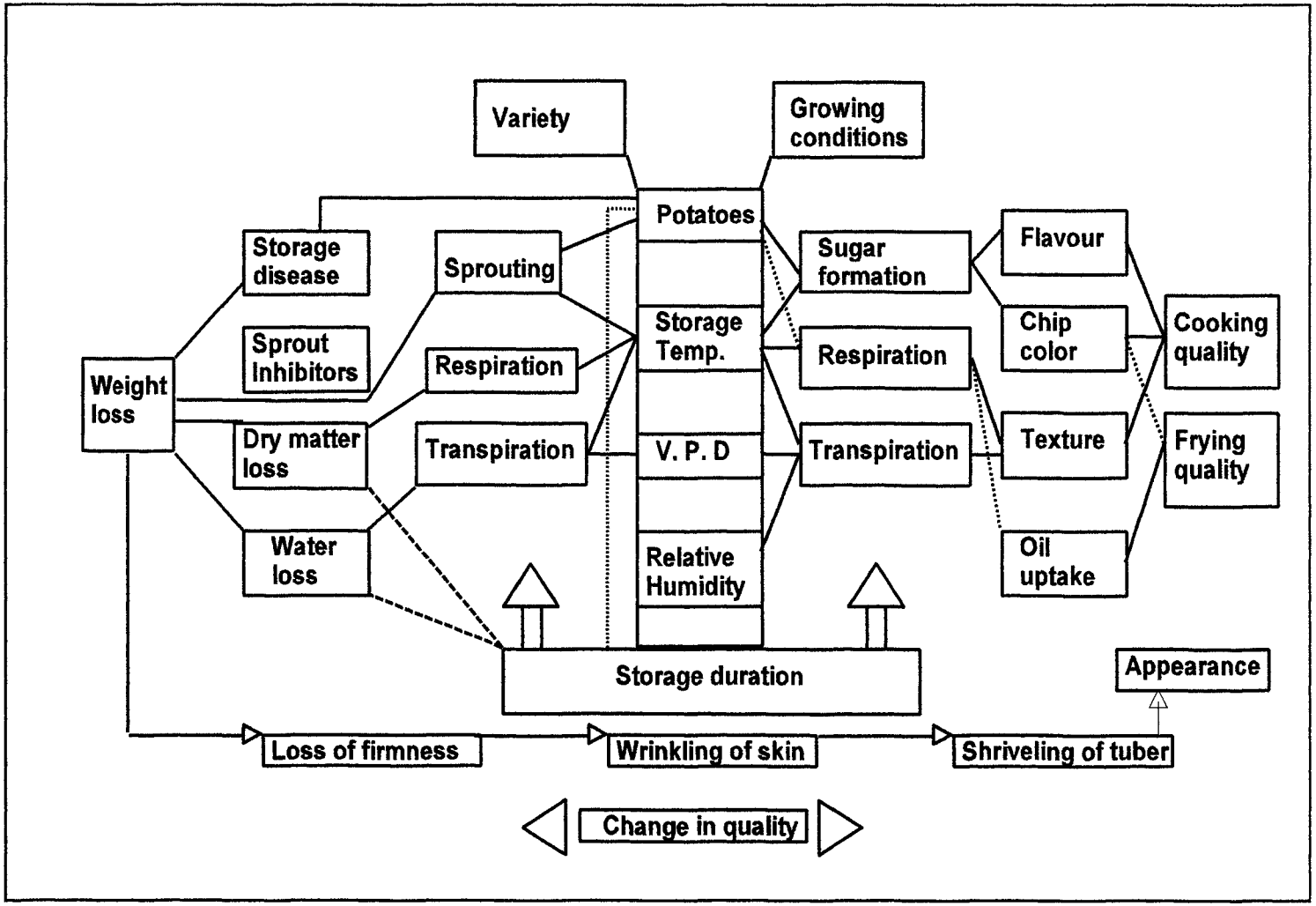


Figure 3.4. Summary of potato storage operation and process interactions. (Adapted from Schippers, 1976).

CHAPTER IV

HEAT AND MOISTURE BALANCE APPROACH

The heat and moisture balance equations were applied in an attempt to measure the respiration rate of stored commodities. In the heat balance, respiration is considered as one of the heat sources in a confined storage. It is necessary to include the moisture component, since part of the heat produced inside the storage is used as latent heat for evaporation of water, and thus has as effect on the heat balance. Figure 4.1 shows a schematic representation of both the heat and moisture balance applied to a storage room.

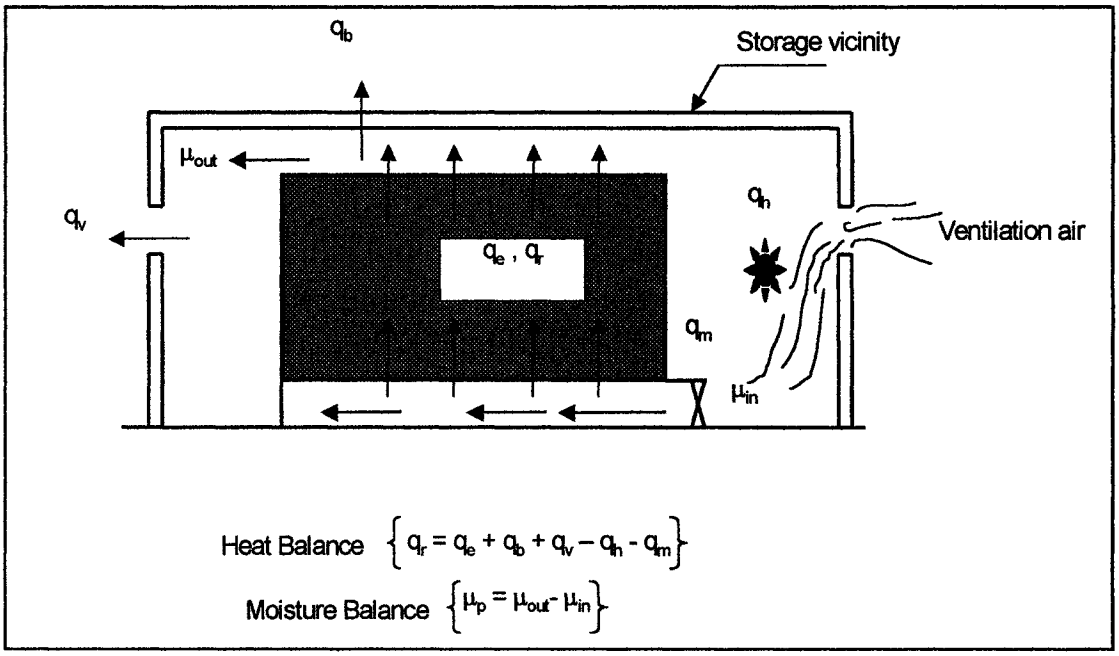


Figure 4.1. Layout of the heat and moisture balance of a potato storage. Parameters are listed in Eq. 4.1 to 4.12.

4.1. Heat Balance

The application of the heat balance is performed based on the measurements of temperature, relative humidity and ventilation flow rate. Measured variables are applied in the heat and moisture balance equations, which can be programmed in a programming language or in a spreadsheet to calculate each heat component of the equation.

The heat balance can be simplified as heat sources being equal to heat losses, as expressed in the following equation:

$$q_r + q_m + q_h = q_b + q_v + q_e \qquad (4.1)$$

Where:

q_r = rate of heat produced inside the bin by potatoes (W),

q_m = rate of heat produced by fans, lights and other mechanical devices (W),

q_h = supplemental heat rate from heaters (W),

q_b = rate of heat loss through bin structure walls (W),

q_v = rate of sensible heat gained by ventilation air (W),

q_e = rate of water evaporative heat measured as a difference between inlet and outlet air water contents (W).

Since the rate of heat produced by the commodity (q_r) is to be calculated, Equation 4.1 can be rearranged as:

$$q_r = q_v + q_b + q_e - q_m - q_h \qquad (4.2)$$

The following equations are used to calculate the components of the heat balance equation:

1- Rate of sensible heat gained by ventilation and infiltration (q_v):

1.a. Ventilation:

Rate of heat gained from or lost to ventilation air is primarily the amount of heat added to or removed from the system with the introduction of an air mass at a temperature lower or higher than the system temperature.

$$q_v = M_a C_p (T_{out} - T_{in}) \quad (4.3)$$

Where:

M_a = mass rate of ventilation air ($kg.s^{-1}$),

C_p = specific heat of air ($J.kg^{-1}.°C^{-1}$),

T_{in} = incoming air temperature (°C),

T_{out} = outgoing air temperatures (°C),

1.b. Infiltration:

Air infiltration in this study was due to the temperature difference between the bins and their surrounding. The air flow was calculated based on the following equation (ASHRAE, 1997).

$$Q = C_D A \sqrt{2g\Delta H_{NPL}(T_{bin} - T_{surr})/T_{bin})} \quad (4.4)$$

Where:

Q = airflow rate ($m^3.s^{-1}$),

C_D = discharge coefficient for openings (dimensionless),

A = area of estimated openings at the bin shell (m^2),

g = gravitational constant (9.81 $m.s^{-2}$),

ΔH_{NPL} = height from midpoint of lower opening to neutral pressure level (NPL),

T_{bin} = bin average temperature (°C),

T_{surr} = average surrounding temperature (°C).

The discharge coefficient of openings was determined as:

$$C_D = 0.40 + 0.0045|T_{bin} - T_{surr}| \quad (4.5)$$

Conditions and recommendation made regarding the use of equation 4.4 were carefully considered for meeting the conditions of the experimentations.

2- Rate of heat loss through the store structure (q_b) :

Heat losses or gains through the structure is the summation of the rates of all heat losses from the six sides of the building (partitions), sidewalls, end walls, doors, roof, and floor.

$$q_b = \sum_{p=1}^{n} \frac{A_p}{R_p} (T_{bin.} - T_{amb.}) \quad (4.6)$$

Where:

A_p = surface area of each partition (m^2),

R_p = total resistance to heat flow of each partition ($m^2.°C.W^{-1}$),

$T_{bin.}$ = bin temperature (°C),

$T_{amb.}$ = temperature of the outside of each partition (°C).

3- Rate of water evaporative heat (q_e) :

The amount of sensible heat rate being used as latent heat for evaporating water from the stored produce. It is assumed that the amount of water evaporated was due to heat being used from the system.

$$q_e = \Delta\mu \; M_a \; h_{fg} \tag{4.7}$$

Where:

q_e = rate of evaporative heat of water (W),

$\Delta\mu$ = humidity ratio difference between incoming and outgoing air (kg water/ kg dry air),

M_a = mass rate of ventilation air ($kg.s^{-1}$),

T_{bin} = temperature inside the bin (°C),

h_{fg} = latent heat of vaporization of water ($J.kg^{-1}$), Eq. 4.8.

$$h_{fg} = (2{,}502{,}535.259 - 2{,}385.76 T_{bin}) \tag{4.8}$$

4- Rate of heat produced by fans (q_m):

Fans, heaters and other mechanical components of the storage facility produce heat. Most of these heat sources have known values, and the rate of heat generated by a fan is calculated a:

$$q_m = \frac{Q \; \Delta P}{\eta} \tag{4.9}$$

Where:

Q = ventilation flow rate ($m^3.s^{-1}$),

ΔP = pressure head created by the fan (Pa),

η = fan efficiency (%).

5- supplemental heat rate produced by heaters (q_h) has a known value from the heater specifications.

4.2. Moisture Balance

Calculation of changes in air psychrometric properties is performed using psychometric equations based on the measured dry bulb temperatures and relative humidity of the air entering and leaving the potato pile. The following equations were adapted from ASAE Standards (1999) and used for the calculation of psychrometric properties of ventilation air. The equations were programmed in a spreadsheet and used for the calculations of air properties and the amount of water evaporated from the pile.

$$\ln (P_s/R) = \left[\frac{a + b(T+ 273.16) + c(T+ 273.16)^2 + d(T+ 273.16)^3 + e(T+ 273.16)^4}{f(T+ 273.16) + i(T+ 273.16)^2}\right] \quad (4.10)$$

$$P_a = P_s \times RH \quad (4.11)$$

$$\mu = \frac{0.6219\ P_a}{(P_{atm.} - P_a)} \quad (4.12)$$

Where :

P_s = saturated water vapour pressure at temperature (T) within a range of 0 to 40°C, (Pa),

T = dry bulb temperature of incoming or outgoing air (°C),

R = 22,105,649.25 a = -27,405.526

b = 97.5413 c = -0.146244

d = 0.12558×10^{-3} e = -0.48502×10^{-7}

f = 4.34903 i = -0.39381×10^{-2}

μ = humidity ratio of the air entering and leaving the bin ($kg.kg^{-1}$),

P_a = actual water vapour pressure at temperature T (Pa),

$P_{Atm.}$ = atmospheric pressure (Pa),

RH = Relative humidity of the air (%).

Evaporation rate is evaluated based on the psychrometric calculation of the amount of water evaporated. Equations 4.9, 4.10, and 4.11, are used for determining the amount of water evaporated as humidity ratio which is applied in Equation 4.12 to calculate the evaporation rate (ER).

$$ER = \Delta\mu \; M_{air} \qquad (4.13)$$

Where:

ER = evaporation rate ($kg.s^{-1}$),

$\Delta\mu$ = change in humidity ratio between air entering and leaving the pile ($kg.\ kg^{-1}$),

M_{air} = mass of air ventilation rate ($kg.s^{-1}$).

Calculation procedure can be developed for applying the heat and moisture balance, and thus net heat rate produced inside the storage facility can be quantified. Similarly, water evaporation rates can be quantified as mass losses using the moisture balance. The determined net heat rate produced by the stored produce can be converted to respiration rate.

In this study, the above equations were programmed in a spreadsheet to calculate the heat and moisture balance that was applied on a research scale storage facility. The components of heat and moisture balance were calculated based on a real time measurements of temperature, relative humidity and air flowrate. The heat and moisture balance was used to quantify respiration rate and water loss for stored potatoes.

CHAPTER V

THE APPLICATION OF HEAT AND MOISTURE BALANCE ON A RESEARCH SCALE STORAGE FACILITY

5.1. Introduction

Respiration is the major physiological process which continues after a produce has been detached from the parent plant. Under good storage conditions, respiration proceeds at relatively low and stable rates throughout the storage period. However, respiration can increase or decrease based upon the effect of several factors, usually classified into two groups; the storage conditions-related factors, and the produce-related factors. Both were extensively discussed in previous chapters. Respiration rate is certainly considered as an indicator of the physiological activity of the stored produce. Therefore, it can be used as an indicator of the condition of the stored produce.

For potato storage systems, from a practical stand point there are few, if any existing methods for knowing the physiological and health status of the produce in storage. While attempts to measure respiration rate under real storage conditions have been made, they are not aimed at knowing the condition of the stored produce as per the reports in the literature. Apart from respiration, several studies on early disease detection methods have been reported. Although some have led to promising results at the experimental stage, their practical application under real storage conditions has not been reported.

Since respiration rate indicates the physiological activity of the produce, its measurement while a produce is in storage could serve as a monitoring tool, and its increase can serve as a flag for sudden changes in the status of the stored produce. Therefore, this study aims at quantifying respiration rate of potatoes stored under

real storage conditions by applying the heat and moisture balance on data collected from a research-scale storage facility. The facility was designed, built, instrumented, and tested as part of this study. It was also intended to provide an infrastructure for future potato storage studies.

5.2. Materials and Methods

A research storage facility based on the model of an air-cooled system was constructed, simulating the most common storage system in the province of Québec. For successful storage facility, design and operational considerations were such as to facilitate stable storage conditions.

5.2.1 The Storage facility

5.2.1.1. Construction of the facility

The storage facility with external dimensions of 6.71 × 1.83 × 2.44 m (22' × 6' × 8') was divided into a control room, two storage bins, two air mixing rooms, and a conditioning room. Figures 5.1 and 5.2 show plan and section views of the facility, respectively. For the collected data to include replicates, to allow comparative treatments and to facilitate future use for long term storage studies, the two bins were built to be identical in size and large enough to simulate real storage conditions. Both bins were equipped with identical air handling systems and equipped with similar instrumentation.

External walls and partitions were built from 50.8 × 101.6 mm (2" × 4") wood studs spaced at 406 mm (16"). Between the studs, mineral wool sheets with a thermal resistance (R_m) of 1.76 °C.m^2.W^{-1} (10 F.hr.ft^2.BTU^{-1}) were installed and covered with a vapour barrier on the warm side of the walls. The internal and external sides were covered with 12.7 mm (0.5") thick treated plywood sheets. Overall thermal resistance (R_t) value of walls was determined to be 2.048 °C.m^2.W^{-1}

(11.64 F.hr.ft^2.BTU^{-1}) and of the roof the (R_r) value was 2.1 °C.m^2.W^{-1} (11.93 F.hr.ft^2.BTU^{-1}). It is to be noted that this facility was built inside an existing unheated building, therefore lower R values were required.

5.2.1.1.1. Storage bins

The heart of the facility was two identical and independent storage bins, each with internal dimensions of 3.28 × 0.84 × 2.44 m (10' 9" × 2' 9" × 8') and a storage capacity of about three metric tons. Figure 5.3 shows an internal view of a single storage bin. To support the horizontal pressure of the produce, sidewalls were joined using four pairs of 12.6 mm (5/8") diameter threaded steel rods distributed at equal distances above and below the potato pile. To reduce infiltration, corners and joints were filled with silicon and airtight doors were installed. The produce was cooled using a slotted floor type ventilation system. A rectangular ventilation duct with dimensions 0.305 × 0.305 × 3.28 m (1' × 1' × 10' 9") was built beneath the pile. Corners of the duct were also sealed to prevent air leakage. The duct was covered with sections of 50.8 × 203.2 mm (2" × 8") treated wood spaced at an adequate slot spacing to facilitate uniform air distribution. Figure 5.4 shows an internal view of the ventilation duct and the slotted floor. At the entrance of the duct and on the bottom of the wall separating the bin from the mixing room, a variable speed centrifugal fan (Model AXC 150A, AEROFLO, Mississauga, ON) was installed. The fan delivered a flow rate of 0.076 m^3.s^{-1} (160 ft^3.min^{-1}) against 125 Pa (0.5" water) pressure head. Air flow delivered by the fan was controlled via a custom built variable-speed drive interface connected to the control system. Prior to storage, ducts were tested for air distribution uniformity and fans were also calibrated.

Above the pile, each bin was equipped with two 279.4 mm (11") diameter circular galvanized steel ducts for air exchange and circulation. The air exchange duct was extended to the outside, while the air mixing duct delivered air to the mixing

room. Both ducts were opened and closed using a mechanical louver operated by an electrical motor and activated by the control system.

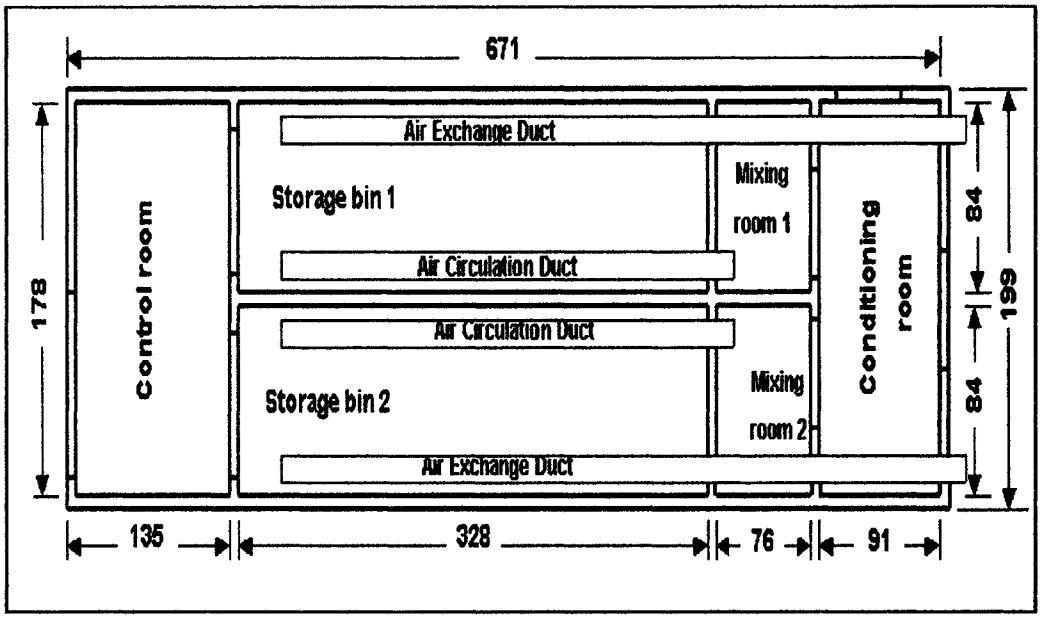


Figure 5.1. Plan view of the storage facility. All dimensions are in cm. Wall thickness is 10.2 cm.

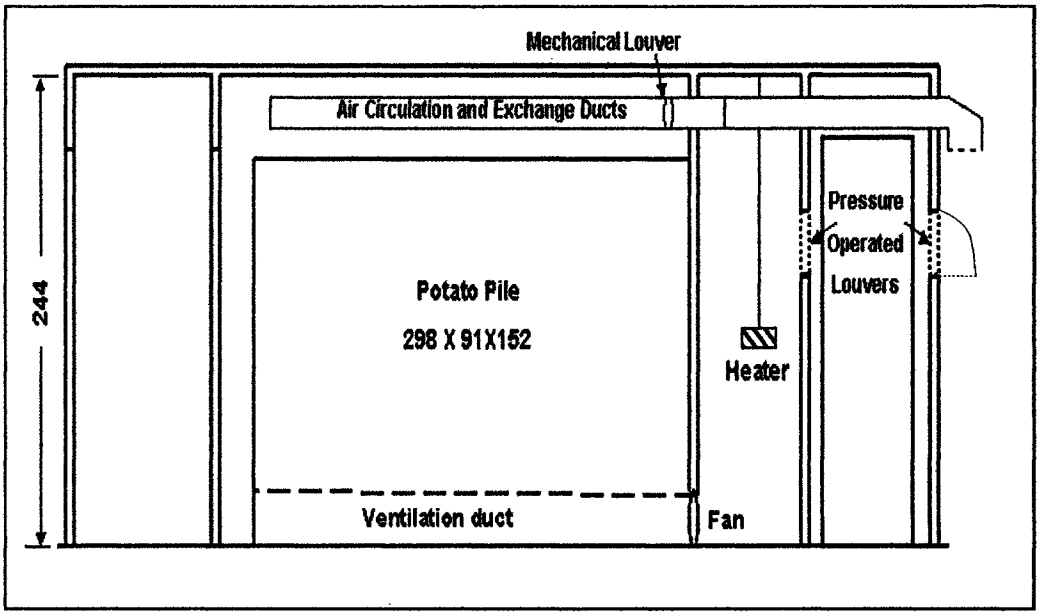


Figure 5.2. Section of the storage facility showing internal details of the storage bins.

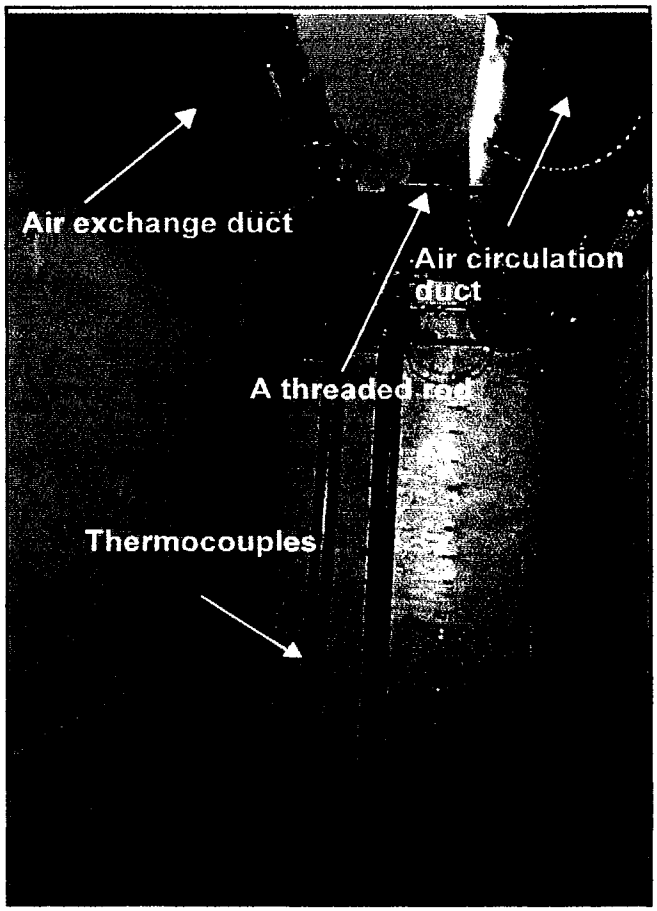


Figure 5.3. Internal view of the storage bin.

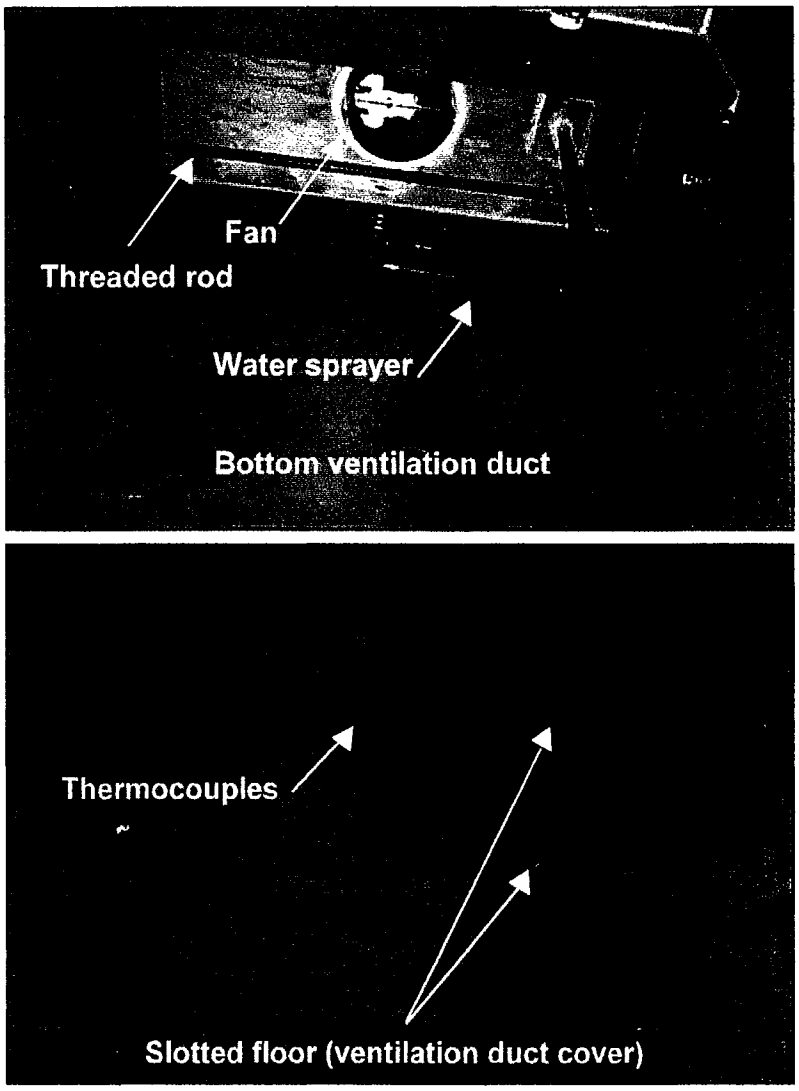


Figure 5.4. Bin floor: Fan and water sprayer (top) and slotted floor of the bottom ventilation duct (bottom).

5.2.1.1.2. Mixing room

Each storage bin was attached to an air mixing room with internal dimensions of 0.762 × 0.84 × 2.44 m (2' 6" × 2' 9" × 8'). Mixing rooms were separated from each other to ensure independency of their ventilation systems and to facilitate the application of different conditions to each bin. On the door of each mixing room, a 0.305 × 0.305 m (1' × 1') pressure operated louver was installed. In each room, a portable bench heater with a 500 W heating capacity and a water supply system were installed. The water supply system consisted of an automatic in-line balanced diaphragm control valve (WaterMaster, Model 57103, ORBIT Irrigation products, Inc. Bountiful, Utah) and a mist nozzle. The valve is activated by a 24 volt source and its operational pressure could be adjusted to the desired nozzle pressure. The nozzle was installed in the ventilation duct facing the fan, and operated at a pressure range of 6.42-18.86 kPa (30-60 psi).

Air exchange is made based on pressure variation between the bin and the outside, and air circulation was based on pressure variation between the bin and the mixing room. During air exchange, the louver in the air exchange duct was opened and the one in the circulation duct was closed, the fan was operated, pushing air through the pile to the outside through the open exchange duct. Thus, pressure inside the bin became lower than that of outside, and cold air entered the mixing room through the pressure-operated louver. When air circulation between the mixing room and the bin was required, the louver in the air circulation duct was opened and the one in the air exchange duct was closed. The fan then pushed air through the potato pile to the mixing room, and no outside air entered the mixing room since the pressure difference was only between the bin and the mixing room. Also, partial mixing could be performed by partially opening both louvers allowing both air circulation and exchange.

Since outside air can be cooler and drier than that of the storage

environment, adding moisture and/or heat to the system was based on measured air temperature, relative humidity and their comparison to their respective set-point.

5.2.1.1.3. Conditioning room

The conditioning room was the outermost component of the storage facility, and had internal dimensions of 0.914 × 1.78 × 2.44 m (3' × 6' × 8'). A side door was installed to provide convenient access to the conditioning room and the two mixing rooms, and on the exterior wall, a 0.61 × 0.305 m (2' × 1') pressure operated louver was installed to allow fresh air to enter the system.

5.2.1.1.4. Control room

The control room was 1.35 ×1.78 × 2.44 m (4' 5" × 6' × 8'), and housed the control system and electrical controllers, and allowed inspection and sampling.

5.2.1.2. Instrumentation

5.2.1.2.1. Temperature

Temperature was measured using a total of 59 type (T) thermocouples (FF-T-24-TWSH-SEL 500, OMEGA Eng. Inc. Laval, QC). The temperatures collected were used for both the control process and the application of heat and moisture balance equations. Thermocouples were distributed as follows: 12 through each pile, 2 in each ventilation duct, 2 in each of the air exchange and air circulation ducts, 2 in each pile's head space, 8 distributed around the storage facility, 3 in each mixing room, 3 in the conditioning room, and 2 for the outside air. All thermocouples were calibrated using a mercury thermometer as a reference. Several readings were taken starting with an ice bath, and warm water was added gradually until water temperature exceeded 50°C. A linear regression analysis was made for each thermocouple, and temperature measurements were corrected. Figure 5.5 shows

an example of a calibration curve.

5.2.1.2.2. Relative humidity

Relative humidities were measured for outside air, at the mixing room and above the pile using RH transducers (model HU-224-2VAC, Mamac Systems, Minneapolis, MN, USA). Sensors were calibrated by the manufacturer and have a maximum error of 2% within a measurement range of 0 to 100%.

5.2.1.2.3. Flow rate

Air flow rate provided by fans was calibrated at several fan speeds. At every measurement, the air exchange louver was opened, and air flow rate was measured at several points along the cross section of the duct using a hot wire anemometer (model 37000.60, Tri-Sense air velocity transducer, Cole-Parmer Instrument Co. Vernon Hills, Illinois). A mathematical relation for flow rate versus fan operation percentage was developed and used for the determination of the flow rate at corresponding fan speed. Figure 5.6 shows a fan calibration curve.

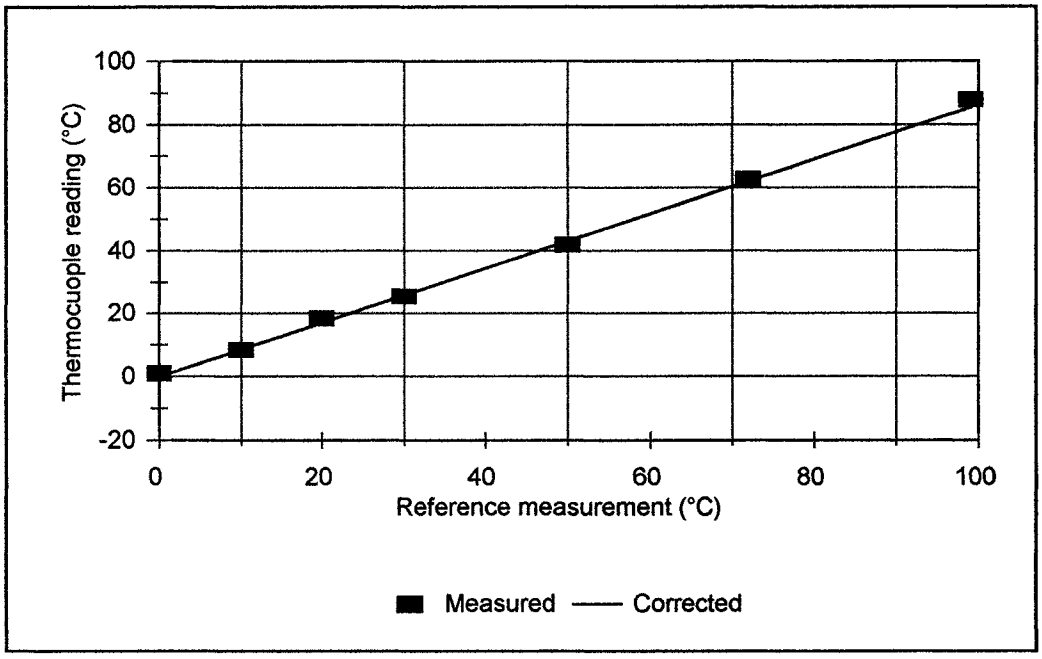


Figure 5.5. Calibration curve of a thermocouple.

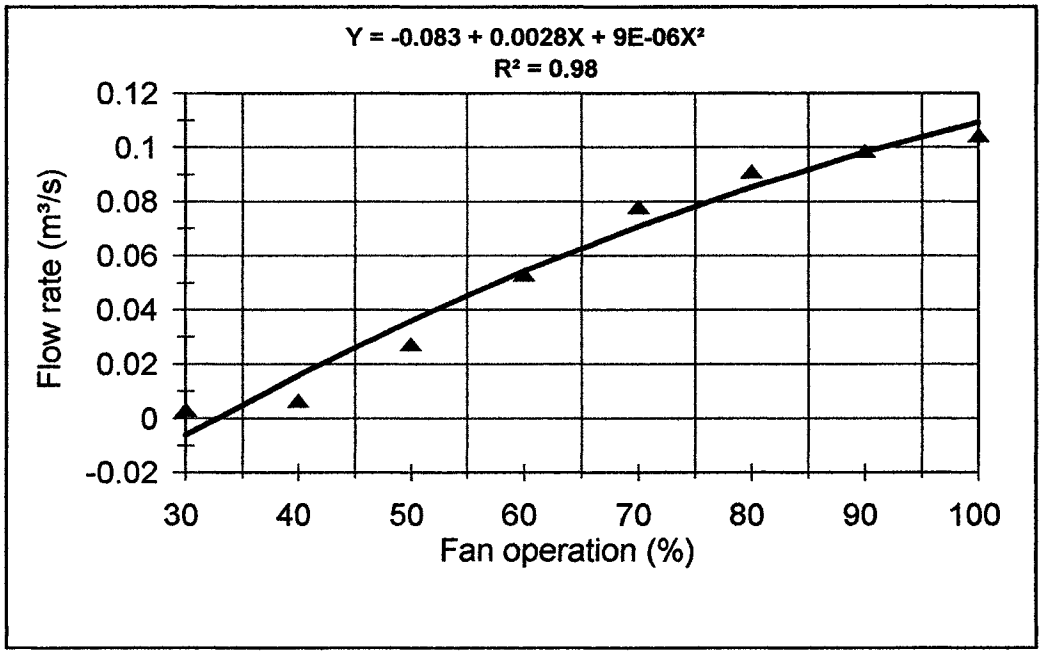


Figure 5.6. Fan calibration curve.

5.2.1.3. Computer hardware and software

Measurement and control processes were performed using an IBM Compatible PC equipped with several OMEGA interface products as described in the following paragraphs.

5.2.1.3.1 Data acquisition

Data acquisition and control was performed using various OMEGA interface products. Figure 5.7 shows a view of the low voltage portion of the control system (data cards) and of the high voltage portion (electrical connections to fans, louvers, heaters and water sprayers). The centre of the data acquisition system consisted of two plug-in cards installed in the PC. These were: the CIO-DAS08 and CIO-DDA06. The remaining cards served for the amplification, filtering and conditioning of sensors.

The CIO-DAS08 card was an 8 single-ended channel 12 bit high speed A/D converter and timer/counter board with a resolution of 1/4095 parts of full scale. It was controlled and monitored by writing to and reading from 12 consecutive 8 bit I/O addresses. It supported dip switch-selectable analog ranges of ±5V, ±10V, and 0-10V.

To allow multiple analog input capacity, the CIO-DAS08 is connected to three CIO-EXP32 boards via a 37-conductor ribbon. The CIO-EXP32 was a 32 channel analog signal multiplexer capable of multiplexing 32 inputs into two A/D channels of the CIO-DAS08. The CIO-EXP32 board provides on-board amplifiers for use with low-level signals as well as cold junction compensation circuitry, enabling them to directly read thermocouple signals.

The CIO-DDA06 is an analog/digital I/O expansion board that provides 6 independent channels of 12 bit analog output and 24 lines of 1 bit digital I/O. The digital block consists of a single 82C55, 24 line digital I/O chip. The analog block

consists of 3 identical circuits, each made up of one dual DAC, two OP07 output buffers and range control. Each of the 6 analog output channels are capable of individual switching and jumper selectability to any of the following ranges:0 to 10V, 0 to 5V, ±2.5V, ±5V, and ±10V.

The CIO-Terminal and SSR-RACK24 were connected to the CIO-DDA06 via a 37- conductor ribbon cable. The CIO-Terminal allowed analog output connections and the SSR-RACK24 digital I/O connections. Thus, the SSR-RACK24 accepted up to 24 of OMEGA's single channel SSS series solid state I/O modules.

All control and data on the CIO-DDA06 were read and written with simple I/O read and write signals. Thus, no interrupt or DMA software was required. Altogether, the configuration provided 96 differential analog input channels, 6 analog output channels and 24 digital in/out channels. Among the analog input channels, 59 were used for thermocouples and 5 for the humidity sensors. Two analog output channels were used for controlling the two mechanically operated louvers, and 2 others to control the two fans. Four of the digital in/out channels were configured as output and were used to turn heaters and sprayers on and off by solid state relays (SSR).

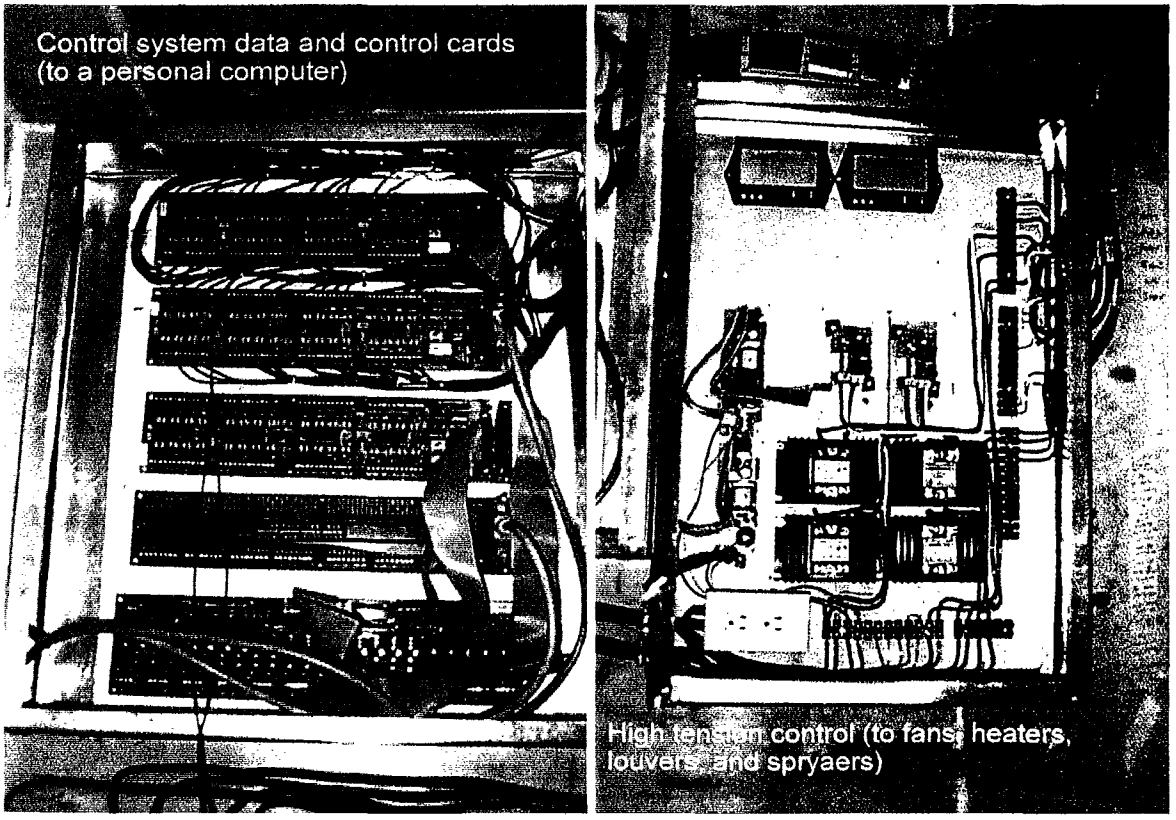


Figure 5.7. View of the control system, low voltage portion (left) and high voltage portion (right).

5.2.1.3.2. Control software

A computer program described by Markarian and Landry (1999) was used for the measurement and control processes throughout the storage season. The software facilitated full automation of the essential operations and data collection. Measured temperature, relative humidity and flow rate were used for the control purposes. Temperature and relative humidity measurements and the status of the heaters, water sprayers, louvers, and fan speed operational percentage were saved every 10 seconds. The software saved data in three main files, Bin1, Bin2, and a third file in which temperature measured by the 59 thermocouples were saved. Data collected on a daily basis was transferred from the control computer and used for the application of heat and moisture balance.

5.2.2. Potatoes

Potato tubers cv. Chieftain, harvested in the Quebec city region were purchased from a grower, unwashed and packaged in 22.21 kg (50lb bags). The produce was transferred to the research facility in a refrigerated truck, on December, 6th, 2000. Tubers were surface dried, suberized, treated with an unknown sprout inhibitor and kept at 5°C at the producer's storage facility. Growing conditions were also unknown, but the physical appearance of the tubers was excellent.

Upon receiving the produce, the two storage bins were filled up to about 2 m in height by emptying the bags, a total mass of 2.5 tons (110 bags) were bulk stored in each bin. Tubers maintained a stable temperature throughout the filling and handling operations, and when the filling of the two bins was completed, the mean temperature of both bins was 5°C.

5.2.3. Experimental procedure

The control system was set to provide the desired storage temperature of 4°C and a relative humidity of 95%. The use of a low temperature set point was chosen to keep the produce for a longer period and minimize losses. However, in the last month of storage the produce temperature was gradually raised to 10°C, first due to higher outside temperatures, and second, tubers were conditioned to avoid injuries during emptying the bins.

The control system provided automated operations of heaters, louvers, water sprayers and fans. However, for the purpose of gathering data for the application of the heat and moisture balance, the system was periodically adjusted to a minimal fan speed, and heaters and water sprayers were turned off. Data collected from these periods were used for selective short-period applications of heat and moisture balance. Data collected from a 24 hour operation were used for evaluating the storage operation and the long term monthly application of heat and moisture balance.

5.2.4. Mass loss determination

At the beginning of the storage period, four samples of tubers were weighed, placed in mesh bags and distributed in the pile. At the end of the storage operation, bags were weighted again, and mass loss determined. Two bags from each bin were weighed on a daily basis for an extended period and their mass loss determined on a daily basis.

5.2.5. Measurement of CO_2 level in the bins

A portable infrared gas analyzer (Model 309BT; NOVA Analytical Systems Inc, Hamilton, ON) was used for one analysis of CO_2 level per day. Air circulation and exchange were halted for a period of 8 hours. The air exchange louvers were

closed and the air circulation duct ends at the mixing rooms were wrapped with plastic sheets and taped. After the designated time, the air exchange louver was opened, the fan was operated at 40% capacity and air was sampled in four replicates of one minute each. The sampling was carried out without opening the bins, and was performed for bin1 followed by bin 2.

5.3. Results and Discussion

5.3.1. Performance of the storage system

Figures 5.8 and 5.9 show samples of the temperature distribution inside the storage bins and their surroundings for the month of February. Similar graphical representations for the entire storage period are presented in Figures A.1 to A.4 in Appendix A.

Temperature inside the storage bins was relatively stable as compared to the fluctuation of the surrounding areas. Although the temperature of the ventilation air (outside) was much lower than the desired storage temperature, the air conditioning process performed very well in raising its temperature and relative humidity to values closer to that existing in the bins.

Temperatures measured at the exterior surfaces of the bins were near bin temperatures, showing a steady heat flow from the bins to the surrounding environment. Temperatures measured at three horizontal and three vertical levels in the pile at a 4°C set point are presented in Figure 5.9. Although the temperatures at the three vertical levels fluctuated slightly due to the correction effect of the control system and the effects of the changing surrounding conditions, the variation remained within a range of ±0.5°C, with the exception of a few rises or falls where sudden disturbances occurred. Nonetheless, temperature variations within the pile were in a good agreement with those reported in the literature. Landry (1994) reported similar temperature variations as being acceptable in a commercial storage

facility. A temperature gradient from the bottom to the top of the pile was also recorded, exhibiting vertical heat flow due to effects of temperature difference between inside and outside and the effects of ventilation and infiltration.

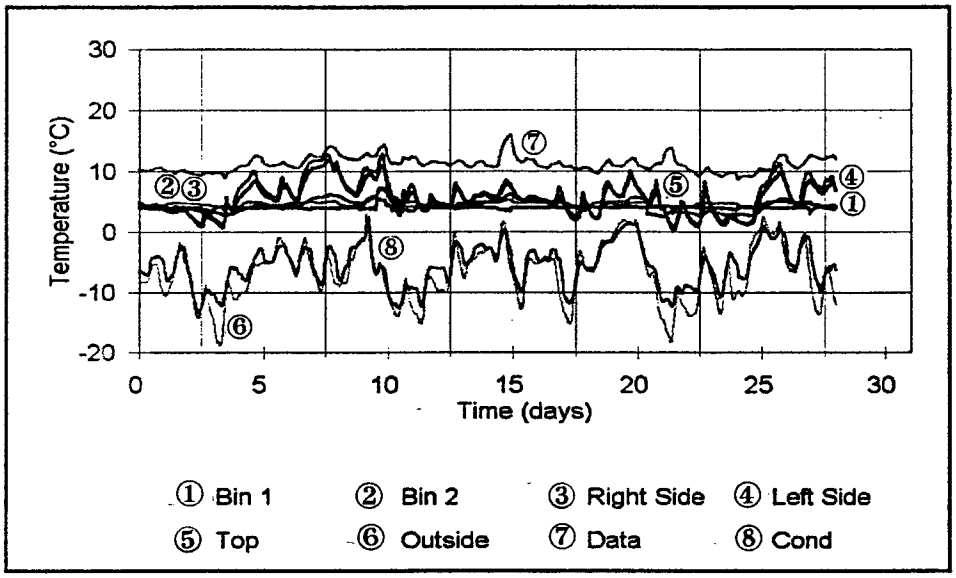


Figure 5.8. Pile average temperatures for the two bins and their surroundings during February, 2001.

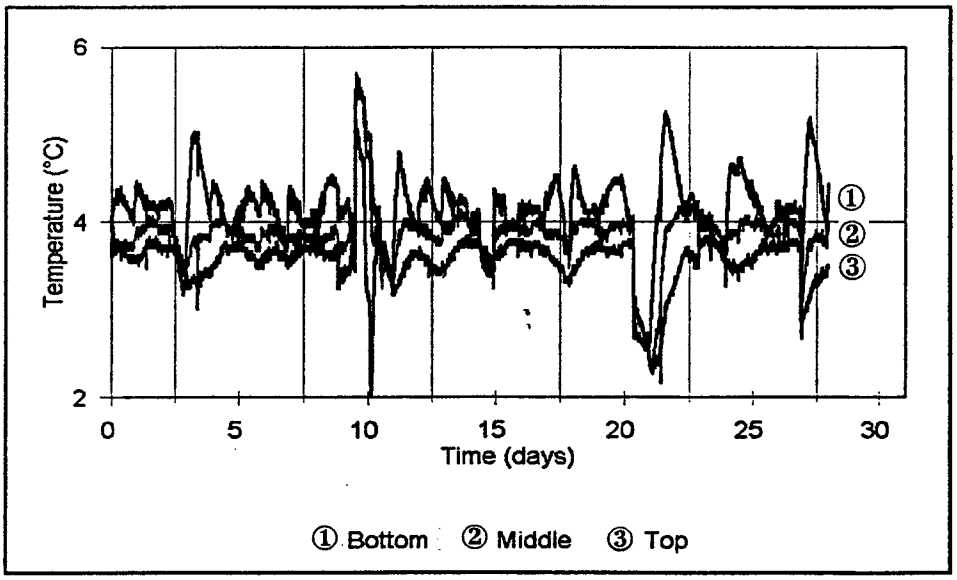


Figure 5.9. Temperature profile within the pile during February, 2001.

Temperature differences between the ventilation air and the pile remained at 1.6°C throughout the study, showing a good agreement with the recommended storage conditions reported by Brook *et al.* (1995). Graphical representations of such data can be seen in Figures A.5 to A.12 in Appendix B.

Figure 5.10 shows measured relative humidity and calculated humidity ratio of air entering and leaving the pile at ten second intervals in a 24 hour period. Relative humidity of the cold outside air was elevated to levels close to that in the storage bin before being used for ventilation. Ventilation air was humidified to above 85%, and since mixing room temperature was higher than the bin average temperature, it exhibited lower relative humidity. But the humidity ratio of the mixing room air was maintained higher than that of the bin, and once the ventilation air entered the pile it would loose heat and its relative humidity would increase.

Figures 5.11 shows samples of the fan and heater operation schemes for a 24 hour period. The ventilation system was operated on the basis of continuous air flow as described by Cargill (1976b). The fans were operated in a range between 40% to 75% of their maximum operational speeds, resulting in a flow rate between 0.0067 and 0.085 $m^3.s^{-1}$. The lower flow rate was applied for air circulation, while the higher flow rate was applied during air exchange and heating. Accordingly, fan and heater operations exhibited similar operational schemes. Additionally, one can observe that heating and air exchange were performed for very short periods as compared with air circulation, indicating that the stable bin temperature was maintained by heat of respiration and the heat produced by the fans. Hunter (1985) in his simulation study of heat and moisture balance of a potato storage concluded that a temperature difference between the storage and the outside greater than 8°C required extra heating to maintain acceptable temperature and humidity levels.

Mean bin and outside temperature data showed that bin temperature was maintained at 6.9°C and the outside average temperature was -6°C, showing an

agreement with the literature (Hunter, 1985). Also, the heating operation scheme showed that heat produced by potatoes was in fact a major contributor to keeping stable storage conditions.

Detailed investigation of interactions between the stored produce and the storage environment are beyond the scope of this study, and discussions on such matters are intended exclusively to show that the stored potatoes were subjected to the recommended storage conditions, and stable storage conditions were generally maintained.

The system maintained pile temperature within ±0.5°C of the temperature set points. Since temperature fluctuation is a normal occurrence in air-cooled storage systems where internal conditions are quite dependant on outside air; on cold days, one can expect that heating the incoming air may not be very efficient, particularly when heat losses from the bins would be higher than the values on warm days. Additionally, sudden temperature changes and disturbances may cost the system more time to return to the normal pattern.

Other sources of instability in storage operation include heating and humidification, through their influence on water evaporation from the produce and surface condensation. Stable relative humidity and perfect air humidification are very difficult to achieve as they are dependant on both air temperature and water content. In general, the system performed very well, and high bin relative humidities were maintained without surface condensation. When humidity ratios of the bin and the mixing room were compared, those of the mixing rooms were relatively higher than those for the storage bins, indicating that the ventilation air was kept more humid than that of the bin. Although relative humidities of the outside air and that of the mixing room were fluctuating, bin relative humidity was generally maintained above near 90%.

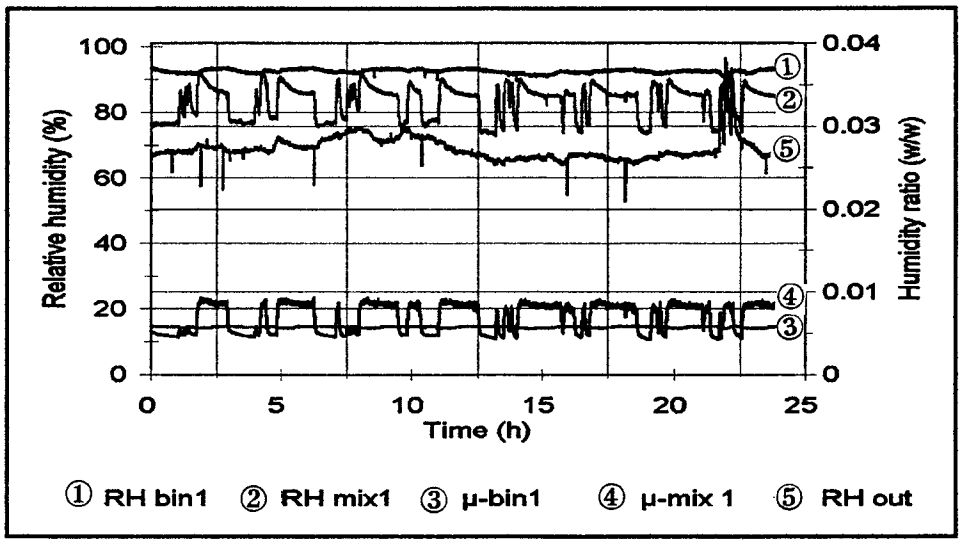


Figure 5.10. Humidity properties of air entering and leaving the pile of bin1, December, 20, 2000.

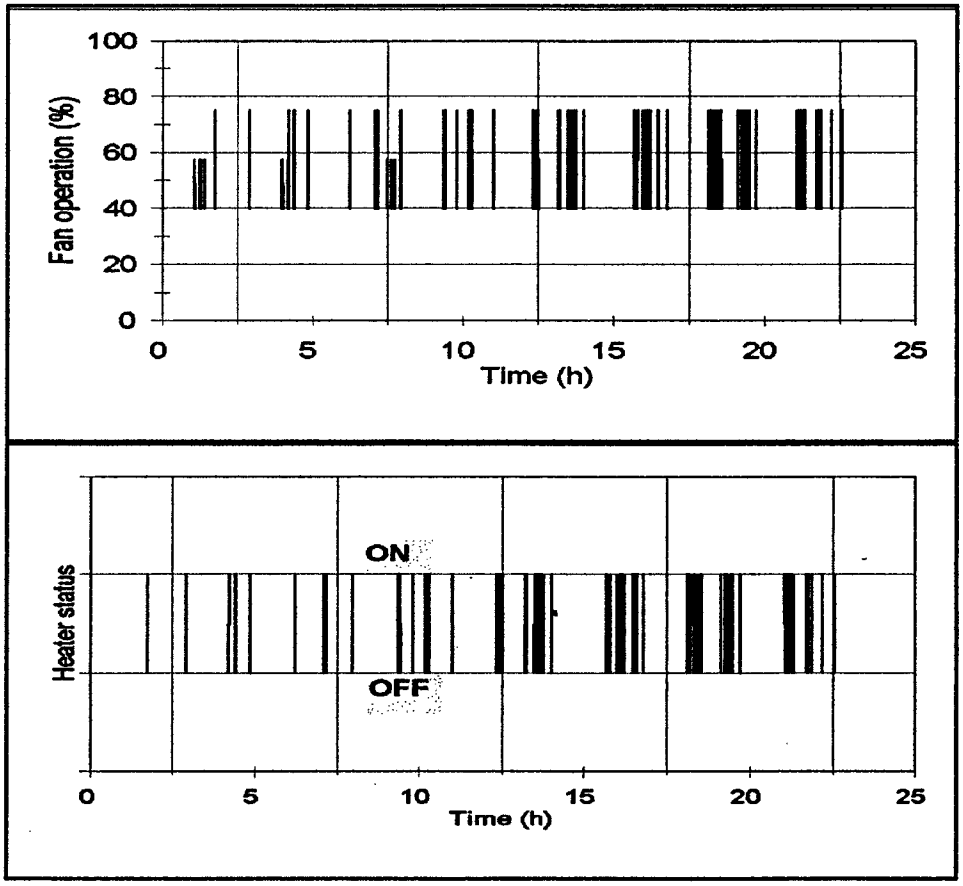


Figure 5.11. Fan operation (top) heater operation (bottom) in 24 hour period for bin1, on December, 20, 2000.

Attempts were made to achieve near-saturated conditions (above 95%) at the beginning of the study. Unfortunately, achieving such conditions was impaired by the small size of the storage facility and the fluctuating temperatures of the ventilation air before its conditioning. Free water accumulated in the ventilation ducts and condensed on the humidity sensors, rendering them inaccurate. Accordingly, their recalibration was required, and thus no relative humidity data were collected for January, February and March. Instead the air humidification system was operated manually. Two humidifiers were placed in the mixing rooms and adjusted to operate continuously at low rates, and relative humidities of the mixing room was evaluated frequently using a relative humidity probe (Model 37000.60, Tri-Sense air velocity-temperature-relative humidity transducer, Cole-Parmer Instrument Co. Vernon Hills, Illinois). Generally, relative humidities near saturation without condensation and free water are difficult to achieve and maintain, particularly in air cooled systems. Instead, maintaining relative humidities in a range of 90 to 95% range is generally acceptable.

5.3.2. Heat balance

Although the heat and moisture balance in this study were interrelated, only the heat balance is presented in this section for the purpose of simplifying discussions. In the calculation of the heat and moisture balance, rate of latent heat of evaporation was determined based on the amount of water evaporated estimated using the moisture balance. The water evaporation rate itself is presented in the moisture balance portion in a later section.

The heat and moisture balance was mainly applied to data collected from certain periods of short durations (specially imposed conditions for a minimum of 8 hours per day), named as: selected periods heat balance. Also, the heat and moisture balance was applied to data arranged for long duration on a monthly or longer period basis: long duration and monthly heat balances. The second was

intended to further evaluate the moisture balance part and to address the application of heat and moisture balance under normal system operation.

i) Data handling and representation

Data were collected from 59 thermocouples, fan operational speed percentages, status of heaters (On-Off), status of water sprayers (On-Off), status of air exchange and circulation louvers (opening %), and relative humidity measured inside the two bins, the mixing rooms and outside (%). Air ventilation rates were evaluated using the fan operational speed and flow rate calibration curve presented in Figure 5.6. Heat and moisture balance equations were programmed in a spreadsheet, using calculation procedures and mathematical models presented in Chapter IV.

Several assumptions were made including: (i) heat losses from the bin structure were due to conduction. (ii) heat gained by the ventilation air was due to convection in one-dimensional flow. (iii) heat gain and loss due to irradiation were neglected. (iv) condensation inside the bins had minimal effect and thus was neglected. (v) air infiltration was assumed to be entirely due to thermal forces (air temperature difference between the storage bins and their surroundings).

Rate of heat gained by ventilation air from the potatoes bulk (q_v) was calculated using temperatures measured before the air reaching the produce (in the bottom ventilation duct) and temperature measured above the pile (at the bin head space). Rate of heat introduced by the heaters and fans were eliminated from the heat balance calculations by applying the balance between the ventilation duct and the air space, and considering the mixing rooms as a separate entities that undergo heat exchange with the storage bins.

Data obtained from the storage facility were recorded at ten second intervals, these were used for the application of heat and moisture balance on the selected

periods. However, because of the size of the files, for the monthly balance these were averaged over ten minute intervals and used for the application of heat and moisture balance and for temperature distribution. Graphical representations of such data are presented in Appendix A, B, and C. After the heat and moisture balance was calculated for one month (at 10 minute intervals), the month long balance was averaged on a daily basis. For the selected periods heat balance data were collected from the two storage bins at 10 second intervals and used for the application of heat and moisture balance without averaging.

ii) Heat balance of selected periods

Earlier, it was assumed that changes in respiration rates are linked to physiological and pathological changes; quantifying respiration rate as rate heat of produced inside the storage could be used as an indicator of unusual respiratory activity. Therefore, the rate heat quantified using the heat and moisture balance has to be reasonably accurate in order to detect such changes. Therefore, heat and moisture balance were applied on short periods under imposed conditions. In contrast to the automatic mode of the system control, exhaust louvers for the two bins were kept closed, heaters and humidifiers were turned off, air was circulated between the bins and their mixing rooms at minimum ventilation rate, and no air exchange was made for periods exceeding 8 hrs per day. Data collected from the selected periods were applied in heat and moisture balance. Figures 5.12 to 5.21 show net heat produced by potatoes inside the two storage bins. Net rate of heat produced by potatoes inside each of the two bins was converted to respiration rates expressed as CO_2 produced ($ml.kg^{-1}.h^{-1}$) using the principle of the respiration equation (Eq. 3.1) and a conversion factor reported by Hardenburg, *et al.* (1990). Table 5.1 shows mean of pile temperature, rate of heat produced by potatoes (W), respiration rates ($ml.kg^{-1}.h^{-1}$) over the selected periods for the two storage bins.

The two bins maintained stable temperatures and net heat produced rate by the potatoes housed inside them. The mean of heat produced rates inside the bins within nearly a two month period were 50 and 59W for bin 1 and bin 2, respectively. There was no significant difference between the net heat produced rates in the two bins. Mean respiration rates were 3.47 and 4.08 $ml.kg^{-1}.h^{-1}$, respectively. Net heat generated rate and the corresponding respiration rate values exhibited similar trends with less variations. This indicates that applying conditions with fewer disturbances resulted in accurate estimates of the heat produced. Generally, the two bins exhibited similar heat production rates, with a few instances where heat produced rate inside the bins varied due to possible disturbance or sudden changes in the surrounding conditions that may have caused such variations.

Given the fact that under normal operation of the control system of a storage facility, air circulation without heating and humidification is applied for extended periods, during such periods, data can be collected and used for the application of heat and moisture balance. Additionally, stable periods can be periodically imposed to obtain such data for the heat and moisture balance applications.

Respiration rates measured using heat and moisture balance were compared with those reported in the literature. Several respiration studies on varieties grown in various regions and stored under different conditions have been reported in the literature. Among the large number of potato varieties tested, the variety used in this study (Chieftain) was not reported. Its respiration rate as determined in this study at 5°C ranged from 1.44 to 1.89 $ml.kg^{-1}.h^{-1}$. Details of these experiments are presented in Chapter VIII.

Respiration rate as CO_2 produced by potatoes at temperatures near 5°C have been reported. Hardenburg *et al.* (1990) reported respiration rates for mature potatoes in the range of 1.5-4.5 $ml.kg^{-1}.h^{-1}$. Dennis (1983) presented respiration rates gathered from the literature ranging from 1.38-4.4 $ml.kg^{-1}.h^{-1}$. Peterson *et al.* (1981)

reported respiration rates in the range of 0.76-1.3 $ml.kg^{-1}.h^{-1}$ for mature Russet Burbank potatoes. Schaper and Varns (1978) reported respiration rates for several varieties, measured using gas analysis methods, ranging from 0.76-1.11 $ml.kg^{-1}.h^{-1}$, as shown in Table 5.2. Comparing these respiration rates with those obtained by the heat and moisture balance, it can be clearly seen that the later fall within ranges reported in the literature. One must also consider that variations in respiration rates are attributable to factors such as variety, growing conditions, and experimental conditions.

Respiration rates reported in Table 5.1 and obtained using the heat and moisture balance method generally were higher than those measured using gas analysis (1.44 to 1.89 $ml.kg^{-1}.h^{-1}$). Such a comparison indicates that the heat and moisture balance method may overestimate respiration rates. However, it should be noted that the two methods of respiration rate estimation were carried out under different conditions. Respiration measurements using heat and moisture balance were measured under real storage conditions, whereas the gas analysis measurements were carried out under controlled conditions and hence much more stable. Nonetheless, the heat and moisture balance was aimed at assessing respiration ranges rather than obtaining an absolute values as is done under laboratory conditions using precise and well tested methods such as the gas analysis.

The accuracy of the heat and moisture balance was mainly dependent on the accuracy of temperature and relative humidity measurements; however, because of the high relative humidity conditions in the two bins and the fact that no moisture was added to the system during the selected period, error in heat rates was considered mainly due to thermocouples' error. Earlier in section (5.2.1.2.1) not only calibration procedures for thermocouples were discussed, but also their measurements were compared with a mercury thermometer (Thermometer 35/230C, Fishers Scientific)

at a normal operational temperature range. Regression analysis was made for every thermocouple and the regression models were used to correct thermocouple readings. The mean error after calibration was found to be 0.1°C. When such error was applied to the mean heat rates determined by the heat and moisture balance (Table 5.1), the maximum error was determined at 10%.

In such study one must consider the complexity of a system with real storage condition and the involvement of several factors in addition to the use of a biological material, therefore variations are normally to be expected. In general, the obtained heat rates shown in Table 5.1 exhibited stability and repeatability over a two month period as well as their agreement with ranges reported in the literature. Therefore, the rates of heat generation by potatoes were estimated within the error range that would be expected in a large scale facility.

Table 5.1. Means of pile temperature, heat generated rate inside the two bins and their corresponding respiration rates.

Day	Bin 1			Bin 2		
	Temp. (°C)	Heat rate (W)	CO_2 ($ml.kg^{-1}.h^{-1}$)	Temp. (°C)	Heat rate (W)	CO_2 ($ml.kg^{-1}.h^{-1}$)
14/01	4.8	66	4.5	5.9	72	5.0
18/01	6.4	54	3.7	7.3	80	5.5
22/01	6.8	51	3.5	7.5	58	4.0
25/02	7	60	4.1	7.1	67	4.6
28/01	5.7	55	3.8	6.2	64	4.4
02/02	4	34	2.3	4.8	39	2.7
07/02	3.8	53	3.7	4.8	49	3.3
16/02	3.9	53	3.7	4.8	56	4.0
23/02	4.0	30	2.1	4.7	58	3.9
28/02	3.9	44	3.1	4.2	49	3.4
Mean	5.03	50.0	3.74	5.73	59.2	4.08
SE	0.125	1.05	0.072	0.117	1.14	0.079

SE = standard error of the mean.

Table 5.2. Respiration rates reported in the literature

Cultivar or type	Respiration rate $ml.kg^{-1}.h^{-1}$	method	Reference
mature	1.38 - 4.4	Unknown	Dennis (1983)
mature	1.5 - 4.5	Unknown	Hardenburg *et al.* (1990)
Russet Burbank	0.76 -1.3	GA	Peterson *et al.* (1981)
Hudson	1	GA	Schaper and Varns (1978)
Reliance	1.05	GA	Schaper and Varns (1978)
Katahdin	1.05	GA	Schaper and Varns (1978)
Chieftain	1.44 -1.89	GA	In this study

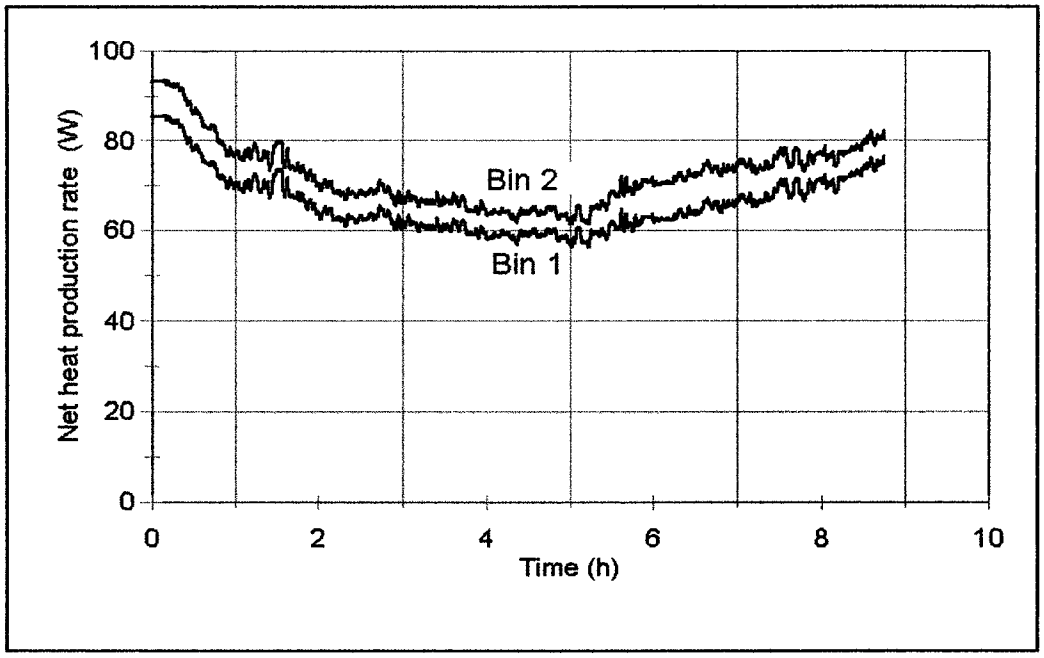


Figure 5.12. Net heat rate produced by potatoes in the two bins on January, 14th, 2001.

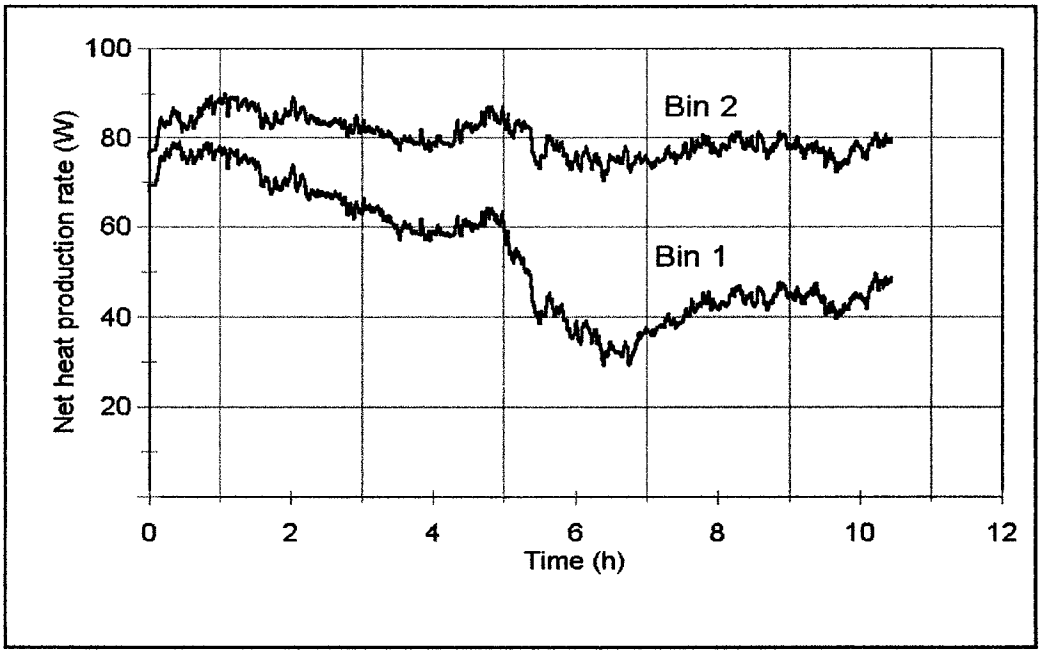


Figure 5.13. Net heat rate produced by potatoes in the two bins on January, 18th, 2001.

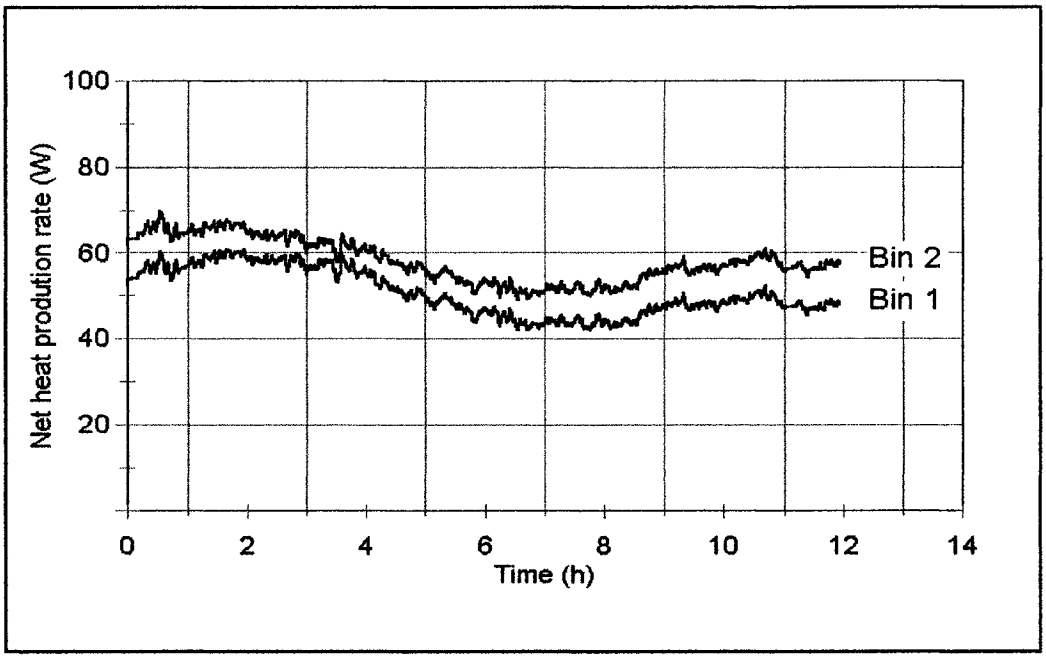


Figure 5.14. Net heat rate produced by potatoes in the two storage bins on January, 22nd, 2001.

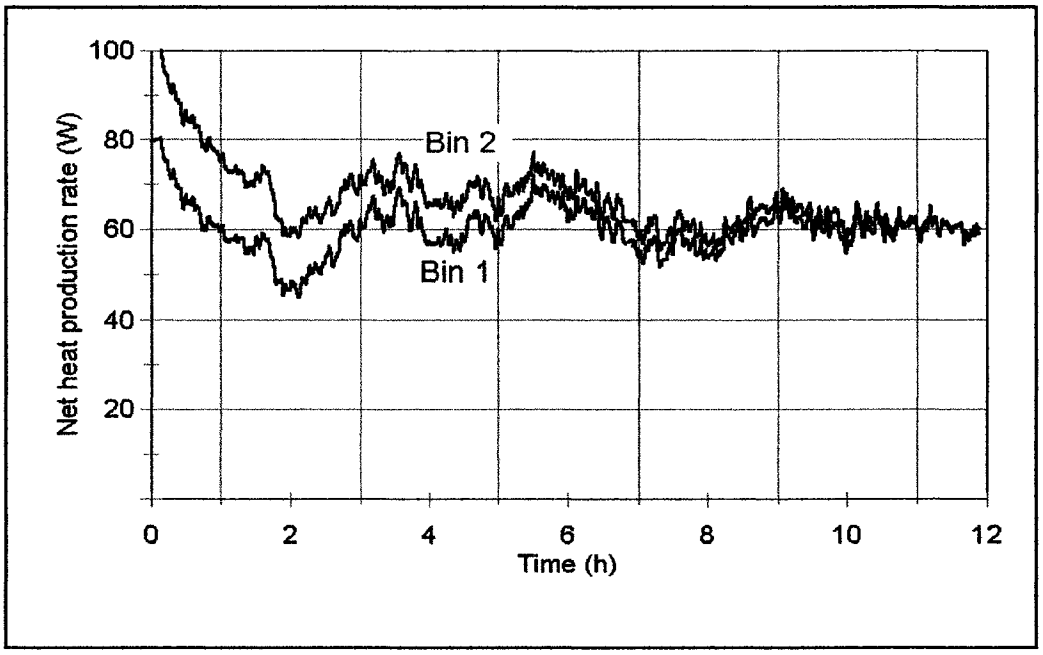


Figure 5.15. Net heat rate produced by potatoes in the two storage bins on January, 28th, 2001.

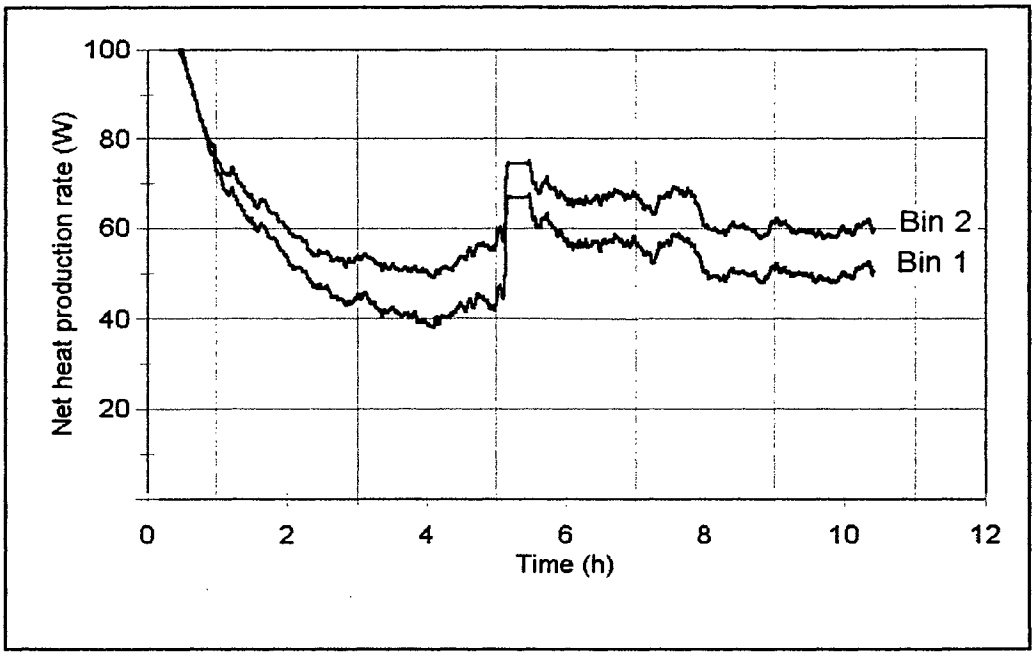


Figure 5.16. Net heat rate produced by potatoes in the two storage bins on January, 28th, 2001.

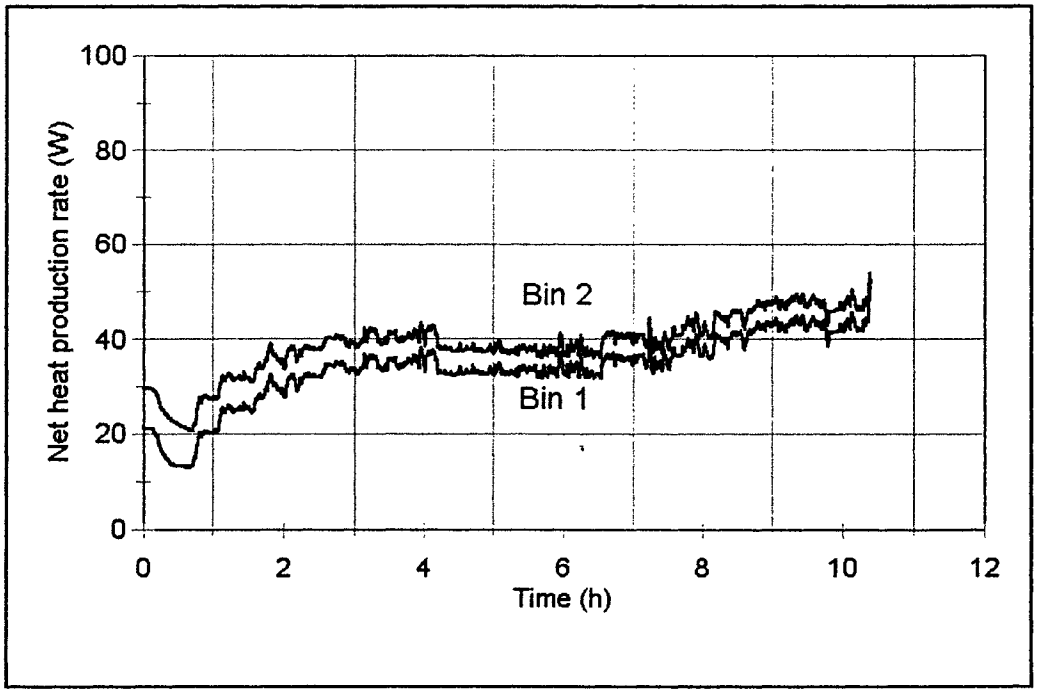


Figure 5.17. Net heat rate produced by potatoes in the two storage bins on February, 2nd, 2001.

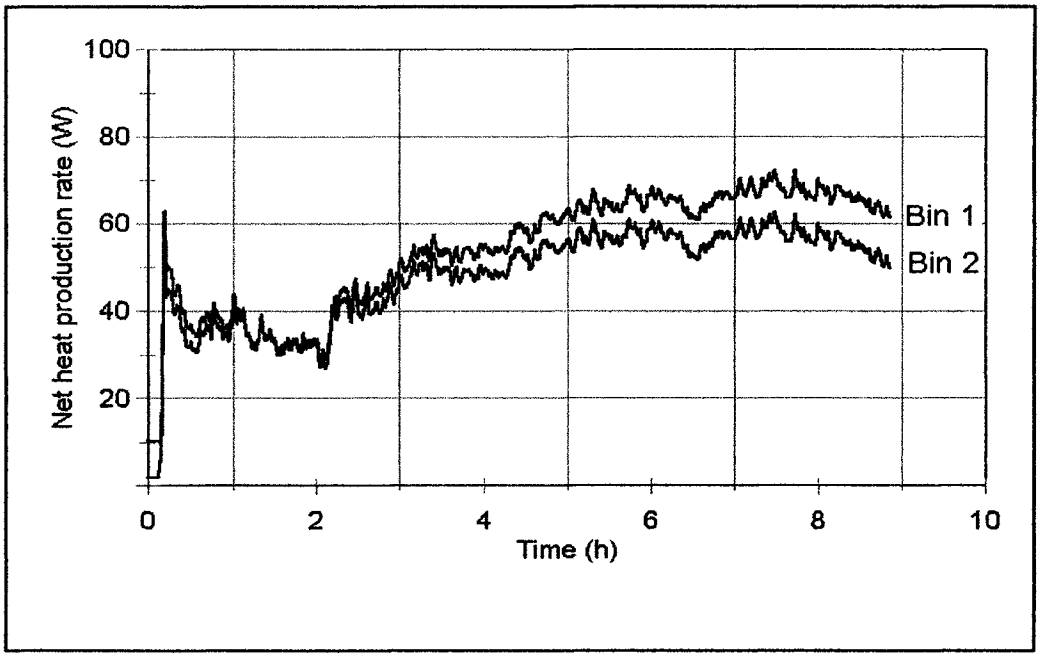


Figure 5.18. Net heat rate produced by potatoes in the two storage bins on February, 7th, 2001.

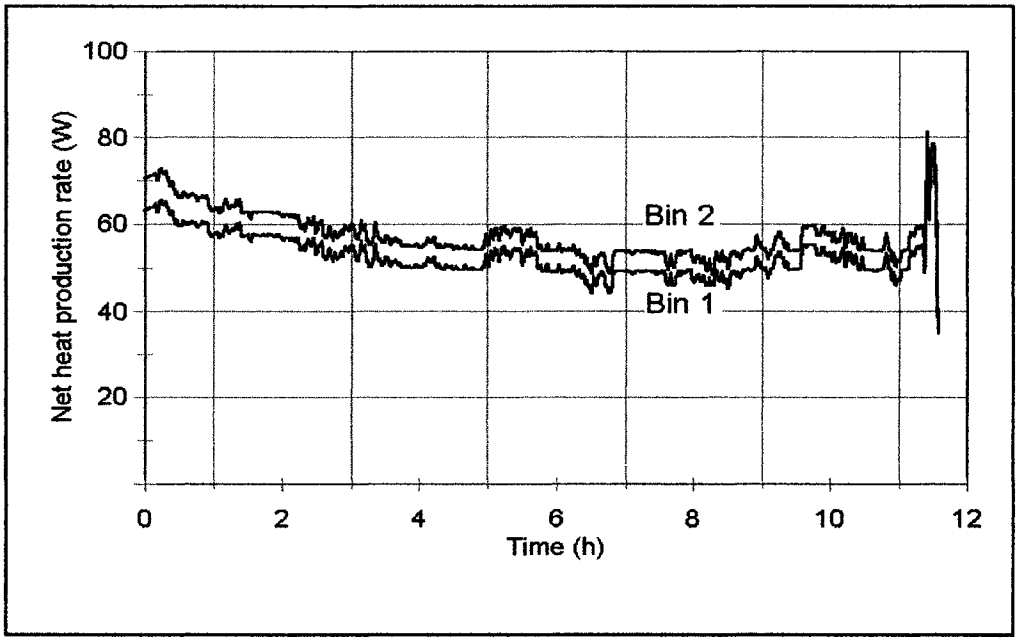


Figure 5.19. Net heat rate produced by potatoes in the two storage bins on February, 16th, 2001.

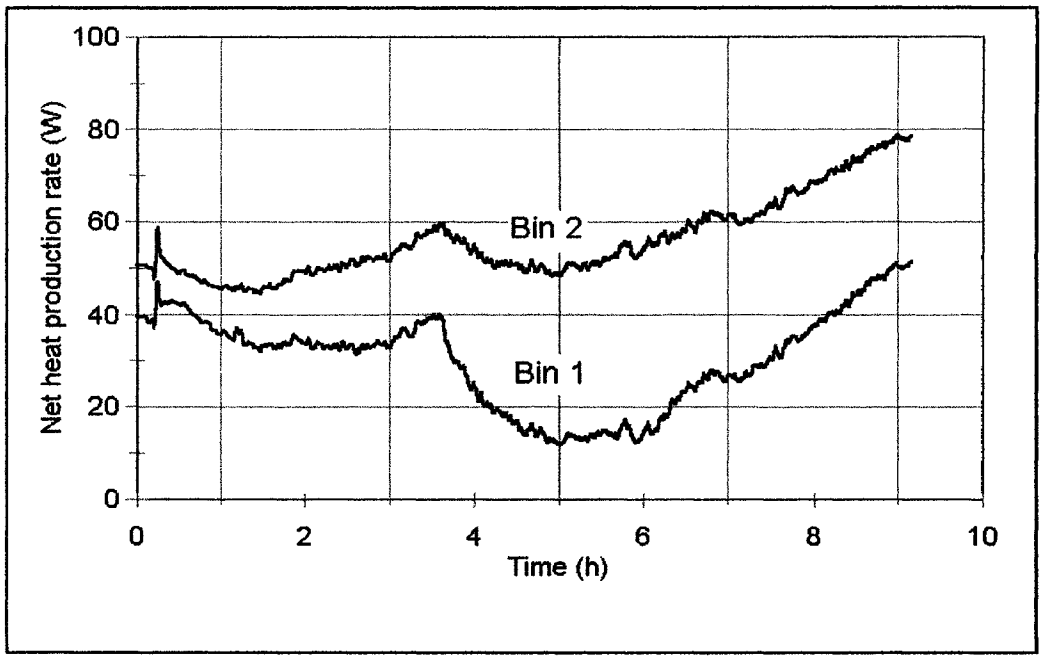


Figure 5.20. Net heat rate produced by potatoes in the two storage bins on February, 23rd, 2001.

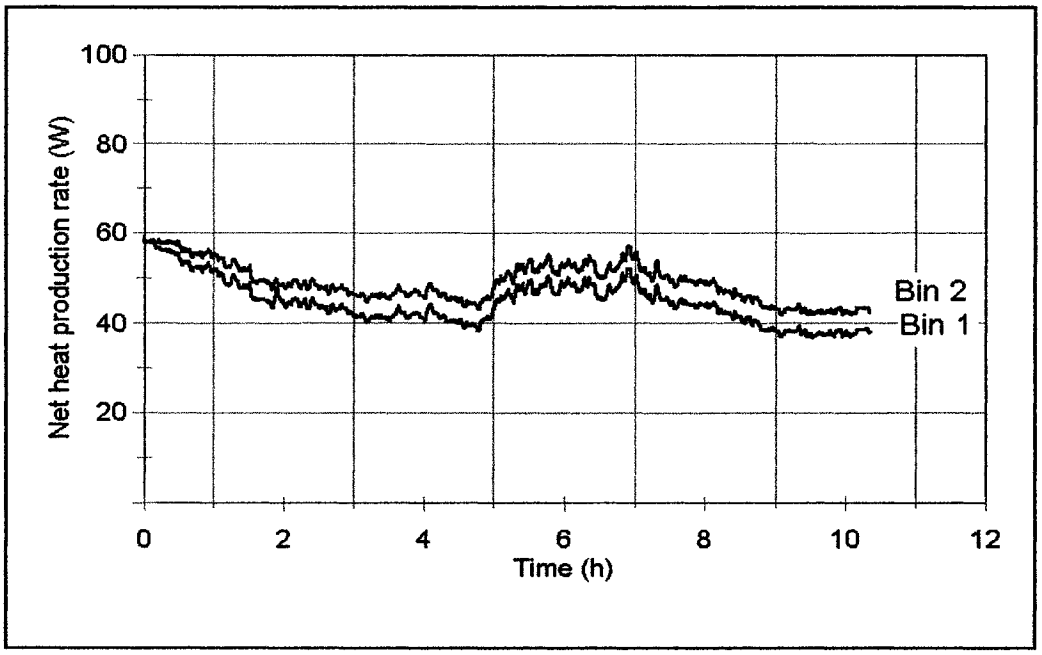


Figure 5.21. Net heat rate produced by potatoes in the two storage bins on February, 28th, 2001.

iii) Long duration and monthly heat balance

The heat and moisture balance was applied to data collected on a monthly basis and for the five month storage duration. The purpose was not to obtain accurate estimate of respiration rates but rather to obtain general trends of heat produced rate and to use the moisture balance for evaluating evaporation rates. Unlike heat production rates obtained from the selected period, rates obtained from the long durations suffered wide variations due to the unstable conditions that were mainly attributable to the effects of unquantified air changes. Table 5.3 shows means of monthly net pile temperature, its heat produced rate and corresponding respiration rate as CO_2 produced. Graphical representations of such data can also be found in Appendix C.

Estimated heat rate produced by potatoes fluctuated widely, and no specific trend in the net heat produced by potatoes was recorded. Nonetheless, the two bins exhibited similar trends in their net heat rate produced. Comparison of the heat rate produced by potatoes in the five months shows that December exhibited the highest respiration rate followed by a decline over the remaining months. This is mainly due to the higher storage temperature of 7°C at the beginning. Temperatures were then lowered to 4°C in January through April. December exhibited the greatest fluctuation in bin temperatures due to the processes of adjusting the control program and optimizing the system operations.

Table 5.3. Mean of pile temperature, heat produced in the bins and their corresponding respiration rate as CO_2 produced.

Month	Bin 1			Bin 2		
	Temp (°C)	Heat rate (W)	CO_2 ($ml.kg^{-1}.h^{-1}$)	Temp (°C)	Heat rate (W)	CO_2 ($ml.kg^{-1}.h^{-1}$)
Dec.	6.5	69	4.8	7	55	3.8
Jan.	6.6	44	3	7.3	61	4
Feb.	3.9	50	3.4	4.6	47	3.25
March	4	39	2.7	4.7	45	3.1
April	7.2	49	3.35	8	53	3.6

5.3.3. Moisture balance

Figure 5.22 presents psychrometric properties of the air measured at the mixing rooms, inside the two bins and outside the facility in December 2000 and April, 2001. Data on the moisture balance for January, February and March are not presented in this discussion because of inaccurate relative humidity measurements resulting from condensation on the humidity sensors. Humidity sensors at both mixing room became inaccurate and their recalibration required extended period of time. Instead, the relative humidity in the mixing rooms was maintained above 90% for the entire storage period. The humidity system was operated manually; two humidifiers were placed in the mixing rooms and operated at low rates. Relative humidity in the mixing rooms was measured frequently using a relative humidity probe (Model 37000.60, Tri-Sense air velocity-temperature-relative humidity transducer, Cole-Parmer Instrument Co. Vernon Hills, Illinois). Since a continuous airflow system was used, relative humidities of the mixing rooms were similar to those of the storage bins. However, relative humidity measurement inside the bins was performed throughout the storage period. Figures A.18, A.19 and A..20 in Appendix D show relative humidity for the two storage bins for January, February

and March to have been maintained above 90%.

Humidity ratios were calculated based on temperature and relative humidity measurements in the mixing rooms and storage bins. Change in humidity ratio difference ($\Delta\mu$) was used to determine the latent heat of evaporation (q_e) and applied in the heat balance. For the moisture balance, the humidity ratio difference was averaged at every four hours. A positive mean $\Delta\mu$ represented water evaporation, while a negative means $\Delta\mu$ represented condensation on produce surfaces that could be evaporated after attaining a positive $\Delta\mu$.

The net 4 hr mean $\Delta\mu$ was used to calculate water evaporation rate. However, evaporation rates do not practically represent transpiration rate, since a transpiration rate measurement requires the determination of vapour pressure at the surface of the produce surface and of its surrounding air. Alternatively, water evaporation rate was measured and compared with mass loss measurements.

Table 5.4 shows means of water evaporation rates for December and April, while Figure 5.23 shows net water evaporation rates for the same period. In April, bin 2 exhibited very low evaporation rates, attributable to the higher relative humidity applied as compared to bin 1 (Figure 5.22). Relative humidity at the mixing room connected to bin 2 was maintained higher than that in the bin itself. In contrast, relative humidity in bin1 was higher than that of its mixing room. While the humidity ratio of bin 1 was quite steady and that of its mixing room fluctuated widely most of the time. Accordingly, the calculated evaporation rates fluctuated widely.

One must consider the difficulties in measuring evaporation rates and accordingly the transpiration rates even under controlled environment and the difficulties in maintaining a steady air flow at a stable relative humidity. It is expected that under real storage conditions such measurements are likely to also be quite unstable.

Table 5.4. Means of monthly evaporation rates and their standard deviations.

Month	Evaporation rate ($g.kg^{-1}.h^{-1}$)	
	Bin 1	Bin 2
December	0.0211 ± 0.041	0.0257 ± 0.0434
April	0.0144 ± 0.0238	0.00276 ± 0.014

Mass losses were determined for both bins over the entire storage period (from start to end) and for short periods in which a daily mass loss analysis was undertaken. In general, both measurements were quite similar, the mean of short period mass losses were 0.0232 and 0.019 $g.kg^{-1}.h^{-1}$ for bin 1 and bin 2, respectively. Considering that water losses might not be steady throughout the storage period and are directly affected by variations in temperature, relative humidity and flow rate, variations from one month to another were to be expected. However, when evaporation rates presented in Table 5.4 are compared with those obtained by weight loss analysis, the two were quite similar.

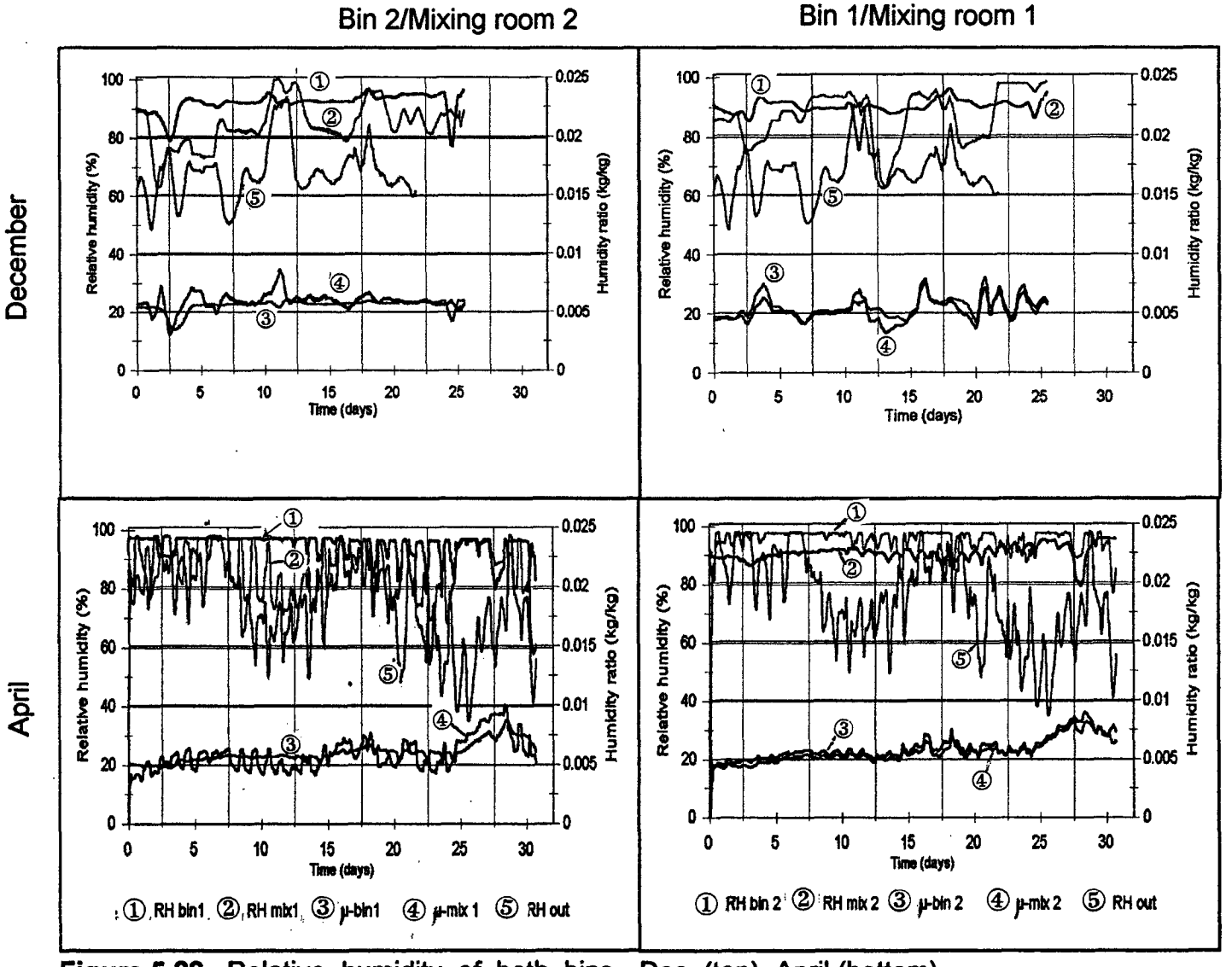


Figure 5.22. Relative humidity of both bins, Dec. (top), April (bottom).

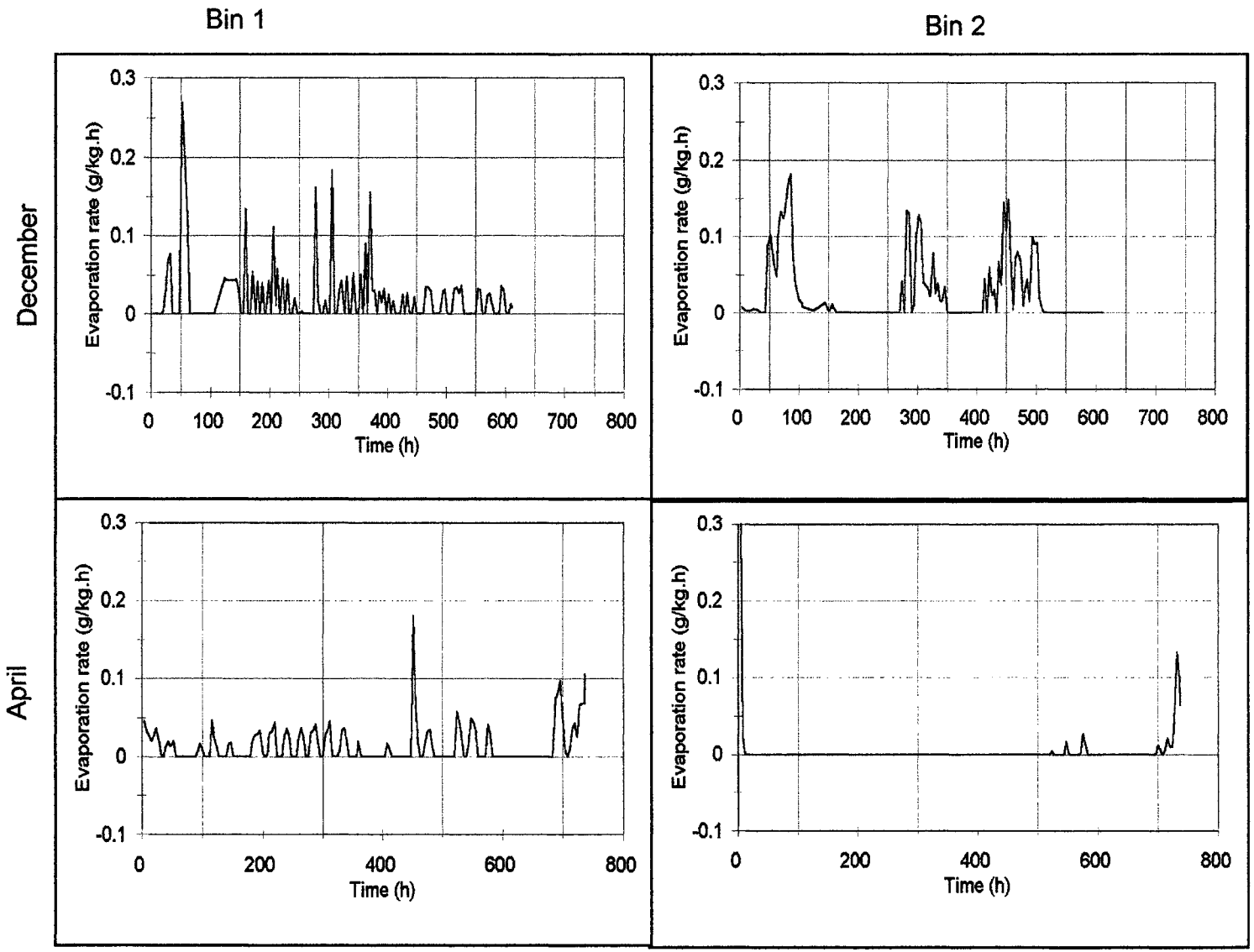


Figure 2.23. Evaporation rates for bin1 and bin2, December (top), April (bottom).

5.3.4. Determination of mass losses

Four plastic mesh bags were filled with potatoes and distributed within each storage bin. At the beginning and at the end of the storage period, the bags were weighed. Table 5.5 shows the samples mass, their mean mass loss and their percentage of fresh mass loss. The mass loss over the entire storage period was determined at 0.0176 and 0.0179 $g.kg^{-1}.h^{-1}$ for bin1 and bin 2, respectively.

Table 5.6 shows mean mass losses determined on a daily basis. Both bins exhibited linear mass loss over time with mean rates of 0.0230 and 0.0192 $g.kg^{-1}.h^{-1}$ for bin 1 and bin 2 respectively. Since the two bins were subjected to the same storage conditions, its is evident that they exhibited similar mass loss rates. Losses due to respiration and transpiration were about 1.3% per month.

Monthly mass losses were compared to those reported in the literature. Hunter (1986) gave a general estimate of weight losses in a potato storage in the range of 3-10%. In his study of several varieties at several temperatures, at 7°C the average weight loss per week was between 0.2 and 0.4%, leading to a mass loss of 1% per month. Schippers (1976) gave a mass loss estimate with an air-cooled system of 5% by the end of the storage period to be acceptable, and above that tubers exhibit signs of losing firmness. However, in the present study, no quality assessment analysis was performed after the storage, but tubers maintained good appearance and firmness. Given considerations to the variability in storage conditions and produce related factors, the mass analysis obtained in the present study acceptably agreed with losses reported in the literature.

Table 5.5. Weight loss determination for the two storage bins.

Replicates and their start and ending weights (kg)								
	Replicate 1		Replicate 2		Replicate 3		Replicate 4	
	Start	End	Start	End	Start	End	Start	End
Bin 1	2.148	2.00	2.131	1.99	2.143	2.05	2.055	1.90
Bin 2	2.137	1.96	2.152	2.04	2.162	2.015	2.132	2.015

Weight loss percentages and their means ± standard deviations					
	R1	R2	R3	R4	Mean
Bin 1	6.9%	6.62%	4.3%	7.3%	6.28 ±1.2
Bin 2	8.3%	5.4%	6.8%	5.5%	6.5 ±1.2

Table 5.6. Periodical weight loss analysis.

days	Bin 1		Bin 2	
	Sample average weight (g)	Loss ($g.kg^{-1}.day^{-1}$)	Sample average weight (g)	Loss ($g.kg^{-1}.day^{-1}$)
0	2030		2041	
2	2028.5	0.37	2039.5	0.37
4	2027	0.37	2037.5	0.49
6	2024	0.74	2035.5	0.49
8	2021.5	0.62	2034	0.37
10	2018.5	0.74	2032	0.49
12	20.16.5	0.5	2029.5	0.62
14	2014.5	0.5	2028.5	0.25
16	2012	0.62	2026.5	0.49
18	2010	0.5	2024.5	0.49
20	2007.5	0.62	2022.5	0.49
Mean		0.56 ±0.13		0.46 ± 0.096
Monthly weight loss (%)		1.66%		1.25%

5.3.5. Gas analysis

Figure 5.24 shows the storage bin respiration rates for a 40 day period measured by in-store gas analysis. While the respiration rates calculated for bin 1 fluctuated significantly, that for bin 2 were fairly steady. Mean respiration rates were 0.760 and 0.745 $ml.kg^{-1}.h^{-1}$ for bin 1 and bin 2, respectively. The stability of observed variables collected from bin 2, as discussed in previous sections, may explain the similar trend shown by gas analysis. Bin 2 exhibited more stable conditions than bin 1 due to its location. Nonetheless, apart from the fluctuating rates of bin 1, respiration rates of the two bins were quite similar. When such values were compared with those obtained by the use of the heat and moisture balance and the laboratory gas analysis, respiration rates calculated based on CO_2 measurements in the bins seemed to underestimate respiration rates. This was attributable to the lack of complete airtightness that may have resulted in CO_2 moving out of the bins. Also, the effects of infiltration were not taken into consideration as no ventilation was used. Schaper and Varns (1978) gave an infiltration estimate of 13% for a typically constructed potato storage. When respiration rates obtained using in-store gas analysis were compared with those obtained using the laboratory gas analysis method, they were relatively closer than those obtained by the heat and moisture balance method.

Attempts to measure CO_2 contents inside storage bins have been reported (Jayas *et al.,* 2001). They measured CO_2 as part of an evaluation of the performance of a control system for a commercial-scale storage facility. The authors reported a CO_2 percentage of about 0.2%, similar to these obtained in the current study. However, the authors did not use CO_2 percentages to measure respiration rates, rather they used the values as an operational parameter for the ventilation system. Similarly, Schaper and Varns (1978) reported a study that was aimed at determining CO_2 production rates during suberization of several potato varieties. Their storage

bin was specially modified for such operation. They reported higher CO_2 percentages (2-4%) because of gas analysis was made at an early stage of storage, and possibly because of the use of relatively airtight storage bins.

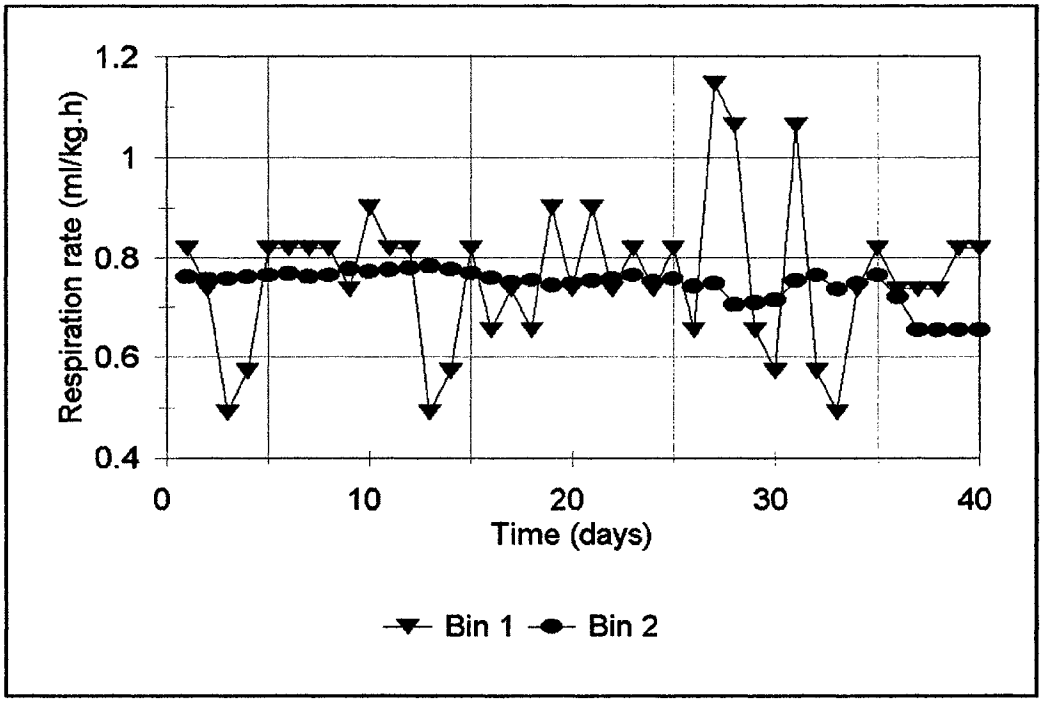


Figure 5.24. Respiration rates measured in the two bins

5.4. Summary and Conclusions

A research scale storage facility was constructed, instrumented and used for storing potatoes for a five month period. The two storage bins were filled with potatoes and their temperature, relative humidity, ventilation rates and other operational parameters were collected for the entire storage duration. Data were used for the application of heat and moisture balance to determine heat rate produced by the stored potatoes.

System performance: The system performance was in accordance with recommended storage practices. Temperature distribution and the difference

between that of ventilation air and the bin was generally kept within 1.6°C. Temperature variations through the pile remained between ±0.5°C, indicating a good performance of the ventilation and control systems. Most of the time, relative humidity was maintained at acceptable levels at or above 90%.

Application of the heat and moisture balance: The heat and moisture balance was primarily applied on selected short periods during which disturbances by air exchanges were largely eliminated: heaters and humidifiers were turned off, exhaust louvers were closed, and fans were operated to circulate air at minimum flowrate for more than 8 h/day. The heat and moisture balance determined the heat rate produced by potatoes within an acceptable accuracy for a large scale storage facility. Mean heat rate produced by potatoes over the selected period were 50 W (3.47 $ml.kg^{-1}.h^{-1}$) for bin 1 and 59.2 W (4.08 $ml.kg^{-1}.h^{-1}$) for bin 2. When these means were compared with respiration rates reported in the literature, these obtained by the heat and moisture balance fell within ranges reported in the literature. When the obtained respiration rates were compared with rates measured for the same potatoes under laboratory conditions (1.44-1.89 $ml.kg^{-1}.h^{-1}$) and in-store CO_2 analysis (0.75 $ml.kg^{-1}.h^{-1}$ for bin 1 and 0.76 for bin 2), the first were significantly higher, and such difference were attributable the fact that the measurements were performed at different storage conditions. The heat and moisture balance was also applied on monthly data collected from normal system operations, the obtained rates suffered wide variations due to unstable conditions, yet the mean rates were similar to those obtained by applying the heat and moisture balance on the short duration data.

Moisture balance and mass loss: The moisture balance was applied on two months of data. Mass loss analyses were performed for the entire storage duration

and on a daily basis. Both were within the generally acceptable losses reported in the literature. Monthly mass loss was estimated at 1.3%, slightly above the losses reported in the literature. Water evaporation rates determined by the moisture balance were generally comparable with those obtained by weight losses analysis. Mean mass loss rate for the two bins, determined by the moisture balance, was 0.0232 $g.kg^{-1}.h^{-1}$, while that determined by weight loss throughout the storage period was 0.0178 $g.kg^{-1}.h^{-1}$.

Determination of CO_2 levels in the bins : Gas analysis was performed for the two bins over a 40-day period. Measured CO_2 percentages were used to determine respiration rates. Rates obtained were near the lower limit of respiration rate ranges reported in the literature and those obtained by the gas analysis method under laboratory storage conditions, but much less than those obtained by the heat and moisture balance. Lower respiration rate values that obtained by in-store gas analysis, were attributable to lack of air-tightness of the facility that indeed led to the escaping of CO_2 from the storage bins.

CHAPTER VI

EFFECTS OF EARLY INFECTION WITH SOFT ROT (*Erwinia carotovora*) AND SPROUTING ON RESPIRATION RATE OF STORED POTATOES

6.1. Introduction

Respiration is a physiological process that continues while a produce is being stored. Between harvesting and the end of the storage period, the respiration rate generally goes through several stages. For potatoes in particular, the respiration rate starts at higher rates and declines to its lowest rates for most of the storage duration. Beside the effects of the storage conditions, disease invasion and sprouting are believed to have significant effects. While the effect of sprouting has been reported in the literature, very little, if any attention has been given to the effect of disease infestation on respiration rate.

Experiments were aimed at standardizing the methodology for disease inoculation, respiration measurement, and to assess the effects of early stages of disease infestation and sprouting on respiration rates of stored potatoes. A closed gas analysis system that used a gas chromatography for analyzing gas samples was used.

The aim of the investigation was not to conduct a long term experimental investigation, but to quantify the early effects of disease and sprouting stresses on respiration rate, and the possibility of their early detection by measuring respiration rate.

6.2. Materials and Methods

6.2.1. Potatoes

Potatoes cv. President grown in Florida were purchased from a local wholesaler. The produce was targeted for fresh table uses, as their appearance showed that no suberization or sprout inhibitor were applied. Tubers were pre-washed and filled in 22.73 kg (50 lb) capacity cardboard boxes. The boxes were taken from the wholesaler's refrigerated room and transferred to a walk-in cold room adjusted to 10°C.

Tubers of similar sizes were selected for the experiments, divided into groups weighed (≃3 kg each), marked and kept for further experimental procedures. Potato density was determined to be 1.0191g.cm^{-3} using the submergence method, the reported density was an average of 6 measurements. Potatoes density was later used for determining free volume of the storage containers.

6.2.2. Treatments

Four treatments were applied namely non inoculated (*defined as healthy, H*), inoculated (*defined as diseased, D*), sprouted & non inoculated (*defined as sprouted, S*), and sprouted & inoculated (*defined as sprouted and diseased, SD*). Table 6.1 shows the treatments and the mass of their replicates. For each treatment, four replicates were used for respiration rate measurement and a fifth replicate was added to the D and SD treatments for distinctive sampling. Experiments were carried out in two batches, the H and D treatments were tested in the first batch, and the S and SD treatments were tested in the second.

For the sprouted treatments, sprouting was initiated at the cold room and further sprouting was achieved by exposing them to light at room temperature for several days. Although tubers were newly harvested, their early sprouting may be attributed to the combination of sudden temperature change and exposure to light.

The respiration measurements were started at a sprout length of 10 mm.

Table 6.1. Disease treatments and the mass of the replicate used.

Treatment	Replicate 1	Replicate 2	Replicate 3	Replicate 4
H	3.01	3.21	3.13	3.11
D	3.12	3.02	3.12	3.09
S	3.05	3	3.99	3.16
SD	3.21	2.79	3.02	3.38

6.2.3. Inoculation process

Soft rot bacteria (*Erwinia carotovora* subsp. *carotovora*) was obtained from the plant pathology laboratory at the department of Plant Science, McGill University. The disease agent was grown on an agar nutrient in a petri plate, the agent was pure and no contaminations were observed. The plate was wrapped with paraffin and kept in a refrigerator adjusted to 5°C, and used as a stock for further inoculum purposes.

Nutrient agar was prepared by mixing the agar in distilled water at the manufacturer recommended proportions and autoclaved at 103.42 kPa (15 psi) for 20 minutes, then cooled under the hood and distributed in petri-plates. Plates were cooled and sealed with paraffin and kept in a refrigerator at 5°C for further use. At the time of transferring the inoculum, bacteria were streaked in a zig-zag fashion on the agar medium. Again, the process was performed under the hood, and plates were incubated at room temperature (~20°C) for 4 days.

A short time before inoculation of the potatoes, bacteria were washed out of the petri plate using a sterilized $MgSO_4$ (10 mM) solution. A high concentration bacterial suspension was thus obtained. The suspension was diluted to an estimated bacterial cell count of $10^7 CFU.ml^{-1}$ following the procedures reported by Ranganna

(1996). The desired colony-forming units (CFU) was obtained by adding $MgSO_4$ solution to the suspension and measuring its transmittance using a Spectrophotometer (Model 80-2088-62, Biochrom, UK).The instrument was configured to measure transmittance through the sample at 540nm wave length. The targeted bacterial CFU was achieved by gradually diluting the bacterial suspension until a transmittance of 50% was reached. For each inoculated treatment about 100 ml of the bacterial solution was prepared.

Tubers for all replicates were washed with a 0.1% Sodium Hypochlorite (NaOCl) solution and surface dried. Replicates designated for inoculation were prepared by drilling 2 to 3 holes of 5 mm in diameter and 20 mm in depth on the top surface of each tuber.

The prepared 100 ml bacterial solution was equally divided among the inoculated replicates. For each replicate the amount of solution was equally divided among the number of tubers. Then all replicates were placed in a separate airtight storage containers (as described below) and placed in a walk-in cold room adjusted to 10°C.

6.2.4. Storage container

Experimental storage containers were made from 500 mm (19.5") long and 250 mm (10") internal diameter PVC pipe sections equipped with two square plexiglass lids. For airtightness the bottom lid was screwed to the PVC pipe and the joints were filled with silicon. On the top surface of the container, a Neoprene gasket was installed. At closure the top lid was joined to the assembly using six threaded rods that ran through the top and bottom lids. On the top lid, two septa were installed to facilitate sampling of air using syringes. Figure 6.1 shows a diagram of the type of storage container used.

The containers were tested for airtightness using a digital pressure indicator

(model DPI 601, SPR Control Systems, Mississauga, ON). Each container was tightly closed, pressured to 2 kPa and observed to maintain the pressure during 30 minutes; a container was considered airtight when the applied pressure remained constant during the test period.

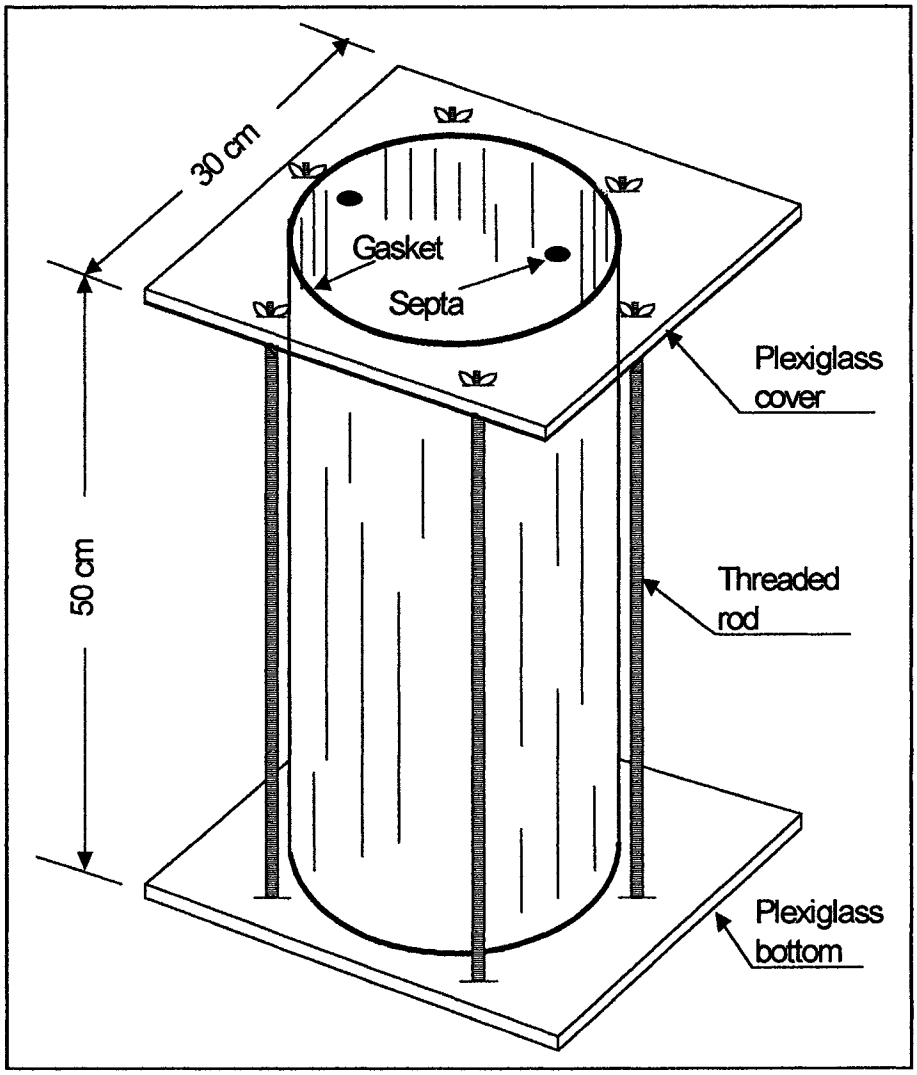


Figure 6.1. Diagram of the storage container.

6.2.5. Air sampling and analysis

Periodic gas withdrawal was made once every 24 hours. Three air samples were taken from each container using 1ml syringes and their gas composition was analyzed in a Gas Chromatograph (Model SRI 8610A, SRI Instruments, USA). The GC was equipped with a thermal conductivity detector (TCD) operating at a 45°C oven temperature and 100°C detector temperature using helium as a carrier gas. The peak areas were quantified using an HP integrator (3390A HP integrator, Hewlett Packard) which gives a printout of the three gas peaks (CO_2, O_2 and N_2) and their percentages in the sample. For every container three samples were analyzed and the two closest results were recorded and averaged.

To avoid anaerobic respiration and the effect of elevated CO_2 levels on the respiration process, containers were opened and flushed whenever CO_2 approached 3%, the threshold suggested by Schippers (1977a) for respiration measurement. For the entire experiment, containers were aerated at less than 3% CO_2 using pressurized air that was circulated inside the container for one minute.

6.2.6. Calculation of respiration rate

Respiration rate was calculated using Equation 6.1. Free volume of the container, the percentage of CO_2 and O_2, the time elapsed between consecutive gas withdrawals, and the mass of the produce were used for calculating respiration rate as CO_2 produced or O_2 consumed (ml. $kg^{-1}.h^{-1}$).

$$RR = \frac{\Delta X\ V}{\Delta t\ m_p} \qquad (6.1)$$

Where:

RR = respiration rate as CO_2 produced or O_2 consumed

$(ml.kg^{-1}.h^{-1})$,

ΔX = CO_2 or O_2 percentage change inside the container during Δt (%),

V = free volume inside the container (ml),

Δt = time between two consecutive GC analyses (h),

m_p = mass of the produce (kg).

Respiration quotient (RQ) was calculated using Equation 6.2

$$RQ = \frac{CO_2 \ produced}{O_2 \ consumed} \qquad (6.2)$$

6.2.7. Disease evaluation

Samples were taken periodically from the containers designated for sampling. A visual evaluation was made by cutting sections at the inoculated holes. Visual assessment of disease advancement were made in terms of appearance, flesh softness, color and odor.

6.2.8. Statistical analysis

Analysis of variance (ANOVA) was performed using the Statistical Analysis System (SAS) package, version 12. A statistically significant difference among the treatments was declared at 0.05 probability level.

6.3. Results and Discussion

6.3.1. Respiration measurement

Figure 6.2 shows respiration rate means for the four treatments expressed as CO_2 produced (top) and as O_2 consumed (bottom), error bars are the standard error, and Table 6.3 shows daily mean of respiration rate as CO_2 produced, O_2

consumed, and respiration quotient, and significancy using LSD analysis. Means for the entire period of the four treatments are shown in Figure 6.3 expressed as CO_2 produced (top) and as O_2 consumed (bottom). Also, respiration quotients (RQ) are shown in Figure 6.4. Numerical values of the means of CO_2 produced, O_2 consumed and RQ for the four treatments are shown in Table 6.2.

Table 6.2. Means of respiration (RR)rate and respiration quotient (RQ) for the four treatments ± standard error.

Treatment	RR (ml $CO_2.Kg^{-1}.h^{-1}$)	RR (ml $O_2.Kg^{-1}.h^{-1}$)	RQ
H	2.9 ±0.20	2.49 ±0.36	1.29 ±0.19
D	4.90 ±0.35	3.71 ±0.26	1.35 ±0.13
S	4.84 ±0.15	4.62 ±0.19	1.05 ± 0.04
SD	6.50 ±0.31	6.05 ±0.24	1.07 ±0.02

Respiration rate started high for all treatments and gradually declined, and the four treatments maintained the same trend of decline. Significant differences between the H treatment and the rest of the treatments were recorded at every data point. The SD treatment exhibited the highest respiration rate and maintained this high significant difference compared to the other three treatments. Although the D treatment showed higher respiration rates than the S treatment, the two treatment means were not statistically different.

The high respiration rate at the start of the experiment is a normal occurrence and can be attributed to the effect of preparing the treatments and the exposure of tubers to high temperature. However, the preparation had a similar effect on all treatments, as they maintained a significant difference in their respirations, despite their declining trends.

Under normal conditions, preparation and even healing of wounds does not take an extended period of time. Peterson *et al.* (1981) reported a sharp decline in

respiration rate as CO_2 produced for immature and newly harvested potatoes from 16.65 $ml.kg^{-1}.h^{-1}$ to reach an equilibrium at 3.4 $ml.kg^{-1}.h^{-1}$ 160 hours after harvesting. Based on this observation tubers were kept at 10°C for more than two weeks before the start of the experiments for this study.

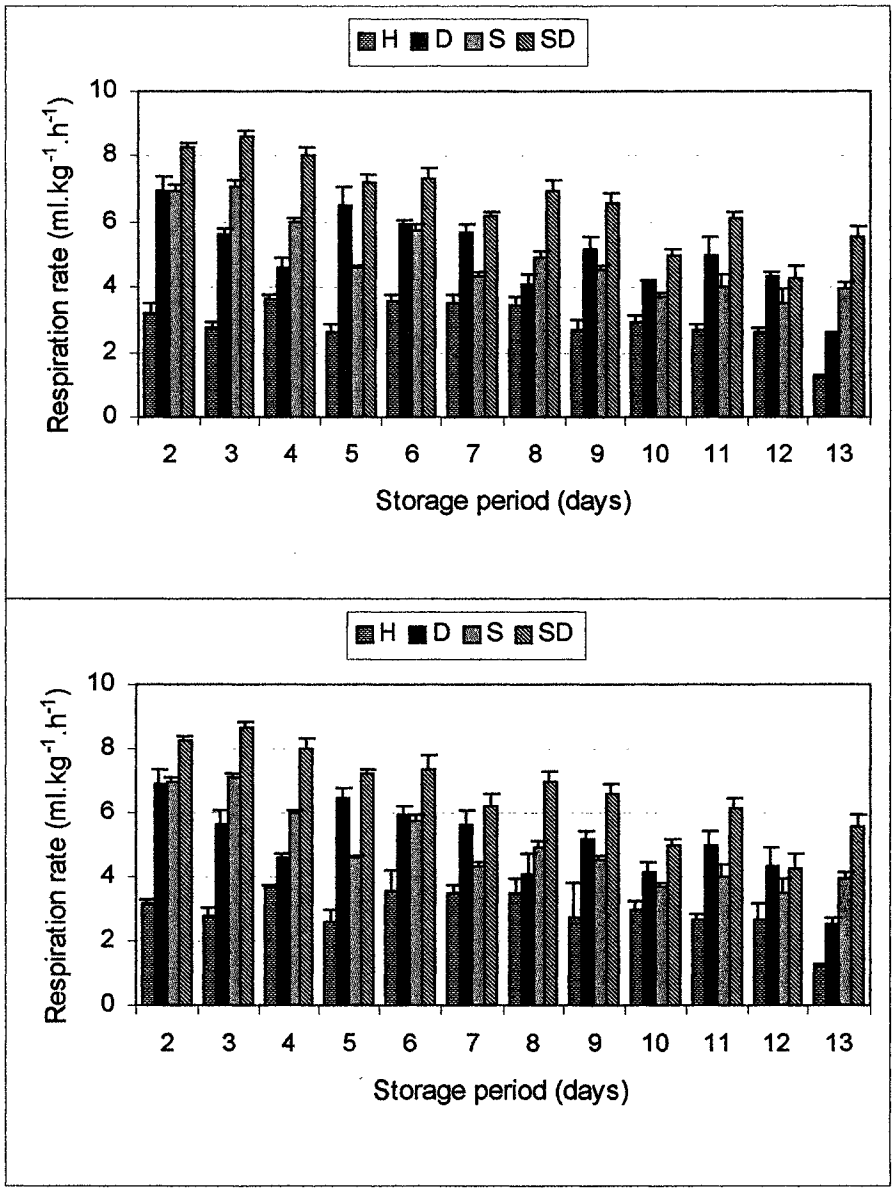


Figure 6.2. Respiration rate as CO_2 produced (top) and O_2 consumed (bottom). Error bars are the standard error.

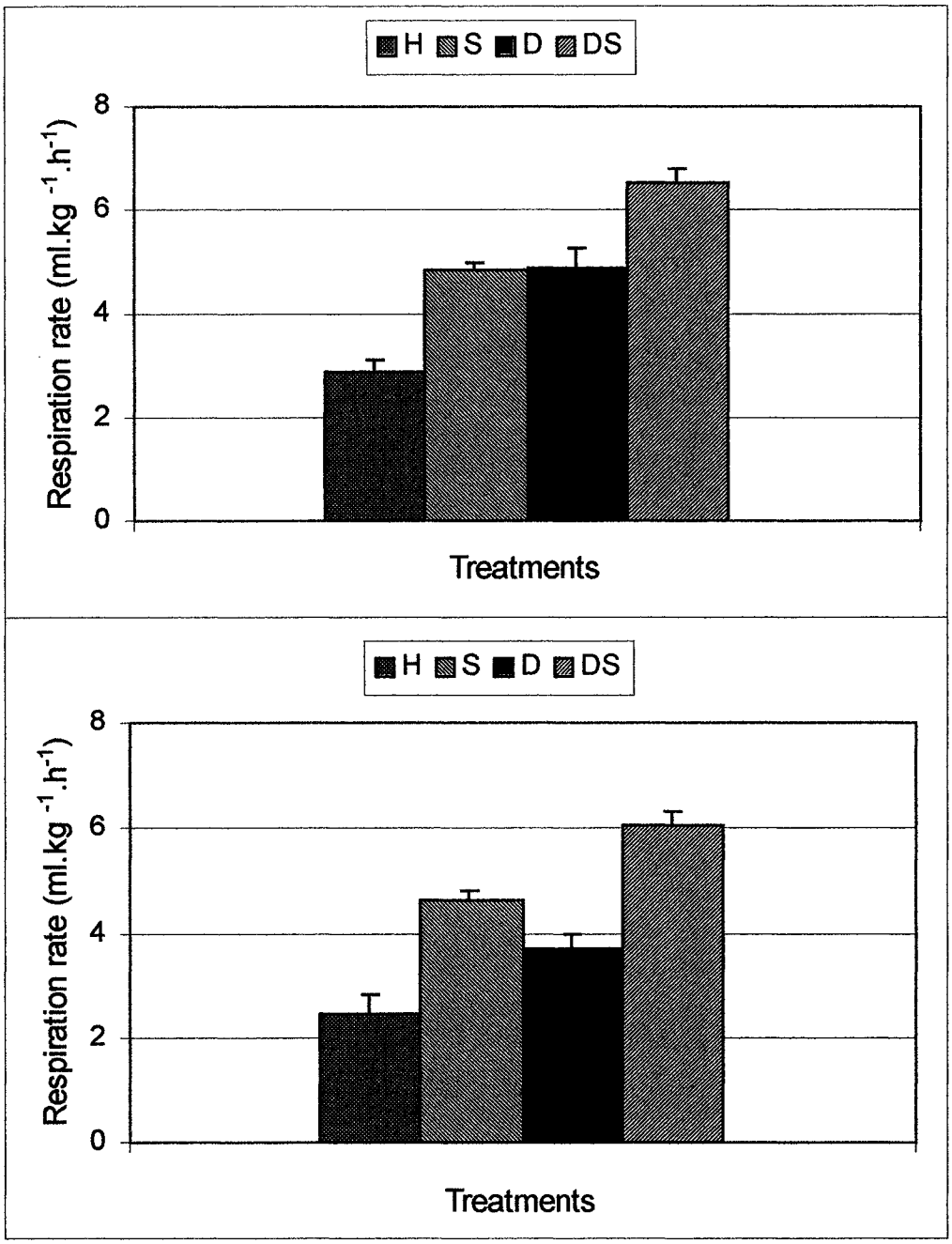


Figure 6.3. Means of respiration rate as CO_2 consumed (top) and as O_2 consumed (bottom).

Table 6.3. Means of respiration rate and RQ for the four treatments

Treatment	Storage period (days)											
	(i) Respiration rate measured as CO_2 produced ($ml.kg^{-1}.h^{-1}$)*											
	2	3	4	5	6	7	8	9	10	11	12	13
H	3.2 c	2.8 d	3.7 d	2.6 d	3.5 d	3.5 b	3.5 c	2.7 c	3.0 c	2.7 c	2.6 b	2.2 d
S	7.0 b	7.1 b	6.0 b	4.6 c	5.7 b	4.3 b	4.9 b	4.5 b	3.7 b	4.0 c	3.5 a	4.0 b
D	6.9 b	5.6 d	4.5 b	6.5 b	5.9 b	5.6 a	4.1 c	5.2 b	4.1 b	5.0 b	4.3 a	2.6 c
SD	8.3 a	8.6 a	8.0 a	7.2 a	7.4 a	6.2 a	6.9 a	6.6 a	4.9 a	6.1 a	4.3 a	5.6 a
	(ii) Respiration rate measured as O_2 consumed ($ml.kg^{-1}.h^{-1}$)*											
H	2.7 d	2.7 d	3.6 c	2.5 c	3.0 c	2.2 c	2.2 d	2.3 b	2.4 c	2.4c	2.8 b	1.2 d
S	6.6 b	6.4 d	5.4 b	5.0 b	5.0 b	4.5 b	4.3 b	4.1 b	4.0 b	3.9 b	3.4 b	3.5 b
D	5.7 c	4.2 c	4.2 c	4.8 b	4.1 b	3.9 b	3.2 c	3.5 c	3.7 c	4.1 b	2.9 b	2.2 c
SD	7.8 a	7.5 a	7.0 a	6.7a	6.8 a	5.8 a	6.3 a	6.0 a	5.4 a	5.5 a	4.5 a	4.8 a
	(iii) Rrespiration quotient (RQ)*											
H	1.2 a	1.0 b	1.0 a	0.9 b	1.5 a	1.7 a	1.8 a	1.9 a	1.2 b	1.1 a	1.1 ab	1.0 a
S	1.2 a	1.1 b	1.1 a	0.9 b	1.1 a	1.0 b	1.1 b	1.1 b	0.9 c	1.1 a	1.1 ab	1.1 a
D	1.3 a	1.3 a	1.1 a	1.4 a	1.5 a	1.5 a	1.3 ab	1.5 a	1.1 a	1.2 a	1.5 a	1.2 a
SD	1.1 a	1.2 a	1.2 a	1.1 b	1.1 a	1.1 b	1.1 b	0.9 b	0.9 c	1.1 a	0.9 b	1.2 a

(*) Means in the same column that are followed by the same letters are not significantly different at 0.05 level using LSD test.

Delaying of the experiment after receiving the potatoes was due to setup preparation for the D and H treatments, and to allow sprouting for the S and SD treatments. However, it is estimated that experiments were started within 30 days from harvest. In such a case, one can be certain that respiration rate increase due to harvesting and field conditions had no effect on the measured respiration rate. When the respiration rates of the H treatment were compared with the respiration rates reported by Peterson *et al.* (1981), and giving due consideration to variety and field conditions, results are within an acceptable range.

Schippers (1977b) reported average respiration rates as CO_2 produced for several potato cultivars harvested in October at 1 $ml.kg^{-1}.h^{-1}$. However, such a low respiration rate at such an early stage of storage is very much questionable. In a previous article (Schippers, 1977a) reported an average respiration rates as CO_2 produced gathered from the literature in the range of 1.62 to 5.4 $ml.kg^{-1}.h^{-1}$. Also, the general tendency for the respiration rate of all harvested agricultural products is to start high at harvesting and decline with time in storage.

Hardenburg *et al.* (1990) reported respiration rates as CO_2 produced in the range of 7.5 to 11.4 $ml.kg^{-1}.h^{-1}$, for immature tubers and 3.8 to 5.4 $ml.kg^{-1}.h^{-1}$ for mature potatoes. Evaluating respiration rates reported in the three articles, and giving considerations to variety and other conditions, respiration rates reported in the current experiment are within an acceptable range. Moreover, such results suggest that difference between the treatments in their respiration rates was due to the effects of the treatments applied and not due to preparation.

The S treatment exhibited a respiration rate significantly higher than that of the H treatment and significantly lower than that of the SD treatment. When a comparison between S and H treatments was made, the respiration rate of the S treatment was 69% higher. van Es and Hartmans (1987) suggested that an increase in respiration of more than 50% could occur due to an early stage of sprouting and

as sprouts grow, respiration rates could increase by 4 to 5 folds. In this experiment nonetheless, sprouts did not grow to an advanced stage, mainly due to low storage temperature. Thus, such a comparison suggests that sprouting indeed increased respiration and such trend could be expected to continue with time.

For the inoculated treatment D, no data was found in the literature for comparison. The D treatment showed a significantly higher respiration rate than the H treatment, and also showed a slightly higher respiration rate than the S treatment, but not statistically significant. Such comparison suggests that an early disease infection may have an effect similar to that of sprouting on respiration rates. Nonetheless, disease applied in this experiment was tested at early stages and no physical development of the disease was observed. Although the presence of disease in the tubers showed an increase in respiration rate such a finding has to be verified with further experiments.

Figure 6.4 shows means of respiratory quotient (RQ) for the four treatments. The RQ values showed mixed trends and wide variations were observed. Although the means for the four treatments did vary, they were not significantly different at the 0.05 level. van Es and Hartmans (1987) reported RQ values between 1.1 to 1.25 at early storage and down to 0.7 at the sprouting stage. Schippers (1977a) in an extensive literature review, reported RQ values of higher than one at the start of storage, between 0.9 and 1 during the main storage period, and higher than one again at sprouting. In this work however, RQ values were 1.29, 1.35, 1.05 and 1.07 for H, D, S, and SD treatments, respectively. Although such values agree with those reported by van Es and Hartmans (1987) and Schippers (1977a) for H and D treatments, they are quite different for the S and the SD treatments. Also, no significant difference of RQ among the treatments was found, which may not be a normal occurrence. One may suspect that the low RQ for sprouted tubers may be due to early sprouting, yet no published data was found to support such a claim, and

thus no conclusive interpretation can be made. However, further experiments may explain such findings.

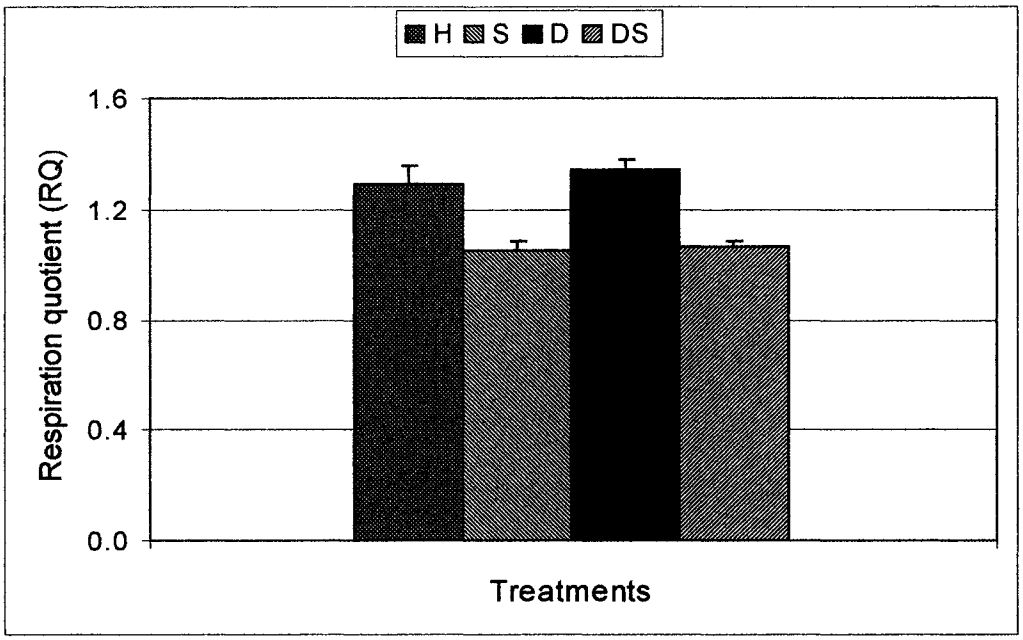


Figure 6.4. Means of the respiratory quotient (RQ) for the four treatments.

6.3.2. Disease progression

A visual evaluation of the disease progression was made daily. One tuber was taken, a cross sectional cut was made through the infected sites and a visual inspection was made for signs of changes in flesh color and tissue softness.

For the entire experiment period, no obvious signs of infections such as tissue softness were observed. However, a slight color change surrounding the inoculated site within a 10 to 20 mm radius was observed, implying early stages of infection as described in section 3.4.1. When the infected sections were left at room temperature, infection started within the color marked area (10-20 mm radius) within hours. Since the aim of the experiment was not to study disease development, but

rather to measure changes in respiration rate at an early stages of infection; inspection of inoculated tubers suggested that although disease symptoms did not physically develop, yet the disease did have a significant effect on respiration rate. For the sprouted tubers, slow development of sprouts was noticed. Because of the low temperature, low sprout growth rate was expected. However, the average sprout length did not exceed 20 mm, and therefore, no sharp increase in respiration was observed.

6.4. Summary and Conclusions

The effects of early disease and sprout stress on respiration rate of potatoes stored at 10°C showed significant difference among the four applied treatments. the inoculated treatment (D), sprouted (S) and sprouted & inoculated treatments (SD) showed significantly higher respiration rates than the control treatment (H). The SD treatment showed significantly higher respiration rate than the other treatments, while the D and S treatments were not significantly different. Respiration rates for the H and S treatments were comparable to values reported in the literature, but no data were available for comparing disease effect.

Respiration quotient (RQ) showed no significant difference among the four tested treatments. The RQ value for the H treatment was comparable with those in the literature, while that for the S treatment was lower than what was reported. No conclusion can be drawn on RQ as affected by the treatments and thus further study will be useful.

Besides the investigation of the effects of disease and sprouting on respiration rate, the performance of the gas analysis system using the GC was also evaluated. Since a respiration rate study requires several treatments and accordingly, the use of a large number of experimental containers, in a multi-container setup, the time required for analysis is an important consideration. In this

study, time required for analysing one air sample in the GC was determined to be 6 minutes. Based on this time, the total time needed for analysing three samples from each container of the four treatments with four replicate each (4×4×3) was 4.8 hours. Further, giving due considerations to sampling time, the GC method is a highly time consuming method.

CHAPTER VII

DEVELOPMENT AND TESTING OF AN AUTOMATED 24-CONTAINER EXPERIMENTAL STORAGE SYSTEM FOR RESPIRATION STUDY

7.1. Introduction

A respiration rate study is generally performed by storing the produce in an airtight container and periodic air sampling and analysis are made. The CO_2 and O_2 contents of the air samples are determined and used for calculating respiration rate. Several methods are available for measuring respiration rates of agricultural products; the most commonly used is the gas analysis method. Existing methods for respiration measurement were extensively discussed in Chapter III, including their attributes of variability, accuracy, cost and convenience.

For most respiration rate and controlled atmosphere storage studies, the use of multi-container setup is essential; also such studies require long term storage and frequent gas analysis. Thus, it was realized that a setup with multi-container and automated air sampling system was necessary for this study. The system must be accurate, fast, reliable and easy to use.

This work was aimed at developing and testing a gas analysis method that requires less analysis time, is easy to use, and convenient while offering high accuracy. The system was intended to be used for long term respiration study of agricultural products in general, and in this study will be used for potatoes respiration. Giving importance to the reliability of the developed system, its measurements were compared with an existing gas system that uses Gas Chromatograph for analyzing air samples.

7.2. The Gas Analyzer System Components

7.2.1. Storage container

In total, 24 identical storage containers were fabricated from a 9.5 mm (⅜") thick PVC pipe sections of 254 mm (10") internal diameter (ID) and 533 mm (23") in length. The bottom was assembled to the main pipe section by setting it on a 25.4 mm (1") high PVC ring that was inserted in the pipe section, levelled with the bottom ring and glued. For airtightness, the side surfaces of the bottom cover and the pipe walls were covered with silicon paste. Figure 7.1 shows a sectional view of the container and Figure 7.2 shows the 24 containers inside the cold room and the system components outside the cold room.

For closing the container, a top cover was also inserted in the pipe section and rested on a similar ring located at a distance of 63.5 mm (2½") from the top edge, and for airtightness, a rubber gasket was installed between the cover and the ring. For an airtight closure, a 4.67 mm (3/16") thick, 50 mm (2") wide, and 279.4 mm (11") long metal plate was passed centrally sideways and rested in two passages located symmetrically on the two opposite sides of the pipe section walls at distances of 50.8 mm (2") below the top edge and 12.7 mm (½") above the cover. Figure 7.3 shows the top view of the storage container.

For an airtight closure, a T-shape handle was screwed at the centre of the metal beam, pushing the cover downward, creating a uniformly distributed pressure on the gasket. The handle, the solenoid, and the pipe connection were located at 54 mm (2⅛") below the container edge. Combining the above design features, the introduced storage containers facilitate easy opening and closing, are very durable, and offer stackability inside the cold room.

On the top cover, two threaded holes were made, on the first a connection was installed and connected to a sampling sequencer via a rigged plastic hose 6.35 mm (¼") OD and 4.572 m (15') long, and on the second, a one-way solenoid valve

was installed (Figure 7.3). Once activated, the solenoid valve allowed air to enter the container replacing the air volume taken for analysis. Solenoid opening scheme was arranged in such a way that the solenoid of the container being sampled was kept closed during air sampling, and the solenoid of the previously sampled container was opened to replace an air volume of 944 ml drawn for analysis. Thus, mixing the container's air with fresh air during gas analysis was prevented. Since the sampled air volume is quite large (3.9%) of the total free volume of the container (24.5 liter) and the percentage of sample size out of container volume increases as produce mass increases. A CO_2 correction procedure that took into account the CO_2 mass used for analysis was applied. Details of the procedure is presented in section 7.3.2.2.

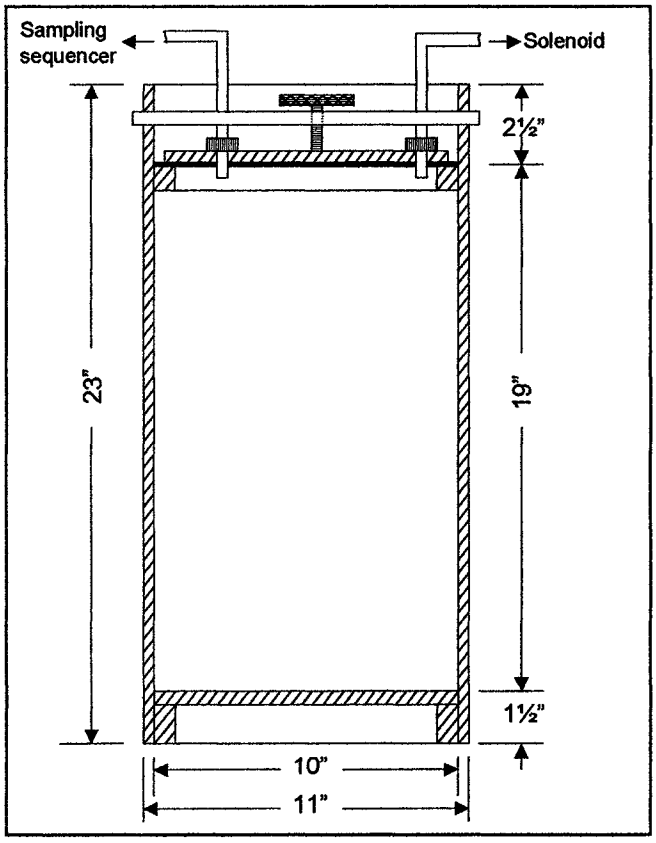
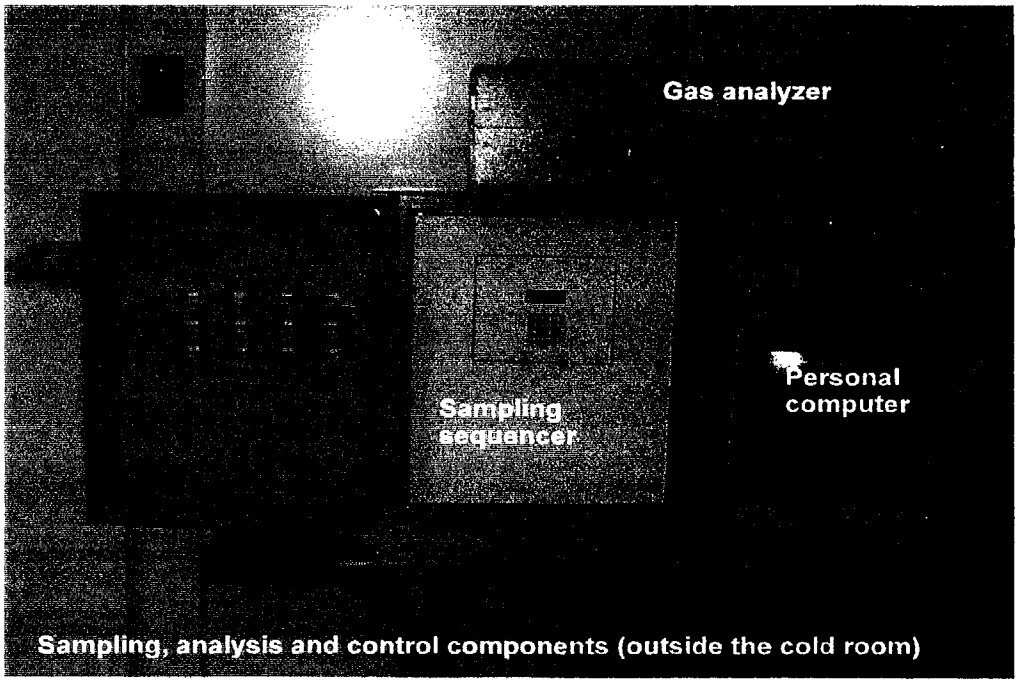


Figure 7.1. Sectional view of a storage container.



The 24 storage containers (inside the cold room)

Figure 7.2. Outside the cold room components (top) and inside the cold room components (bottom) of the system.

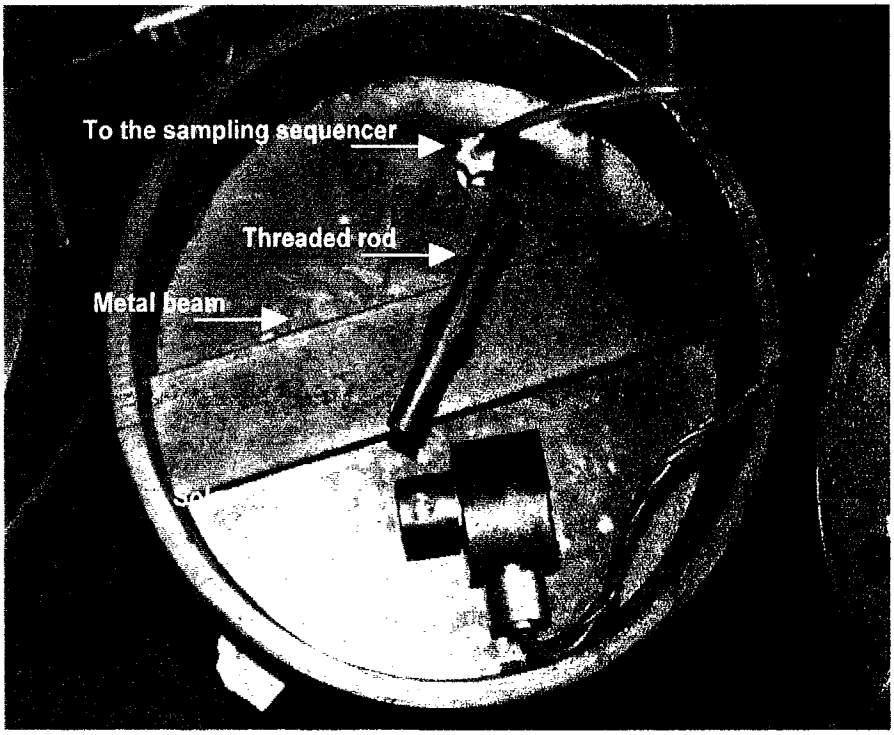


Figure 7.3. Top view of the storage container.

7.2.2. Microprocessor based automatic sequencer

For sampling from several containers, the system was connected to a 402AS-24 microprocessor automatic sequencer (NOVA Analytical Systems Inc., Hamilton, ON). At the inlet, the sequencer was equipped with 24 channels to which the 24 containers were connected via 6.35 mm (¼") OD rigged plastic pipes. To prevent water from entering the gas analyzer, filters were individually installed on the 24 channels. On each channel a solenoid valve was installed and controlled through the microprocessor, with a sampling time between 0 and 255 seconds. Parallel to the activation of the channel solenoid, a solid state relay (SSR) activated a solenoid valve that was installed on the respective container and facilitated replacing the sampled air. The solenoid facilitated air to enter the container replacing that drawn for analysis, and hence low pressure inside the containers caused by sampling was prevented.

The sequencer was connected to a 486 IBM PS/2 personal computer via an RS-232 port. A BASIC program was written to convert the analyzer analog output into percentages of CO_2 and O_2, displayed the results a computer screen and saved them into an ASCII file. Figure 7.4 shows internal view of the components of the sampling sequencer.

7.2.3. Gas analyzer

A portable infrared CO_2 and O_2 gas analyzer, model 309BT (NOVA Analytical Systems Inc., Hamilton, ON) was used. It detected CO_2 within a range of 0-10% using a sensitive infrared detector, and O_2 within a range of 0-25% using an electrochemical sensor. The analyzer had a response time of 10 seconds at 90% of the reading with accuracies of ±1% and ±0.5% full scale, for CO_2 and O_2, respectively. However, for this setup, sampling time was set to 30 seconds. The analyzer was equipped with an internal vacuum pump that drew air from the storage

containers at a flow rate of 31.5 cm^3/s (4 CFH), passing it through the CO_2 and O_2 detectors and venting it out. It was also equipped with air filters installed prior to the sensor and air flowmeter.

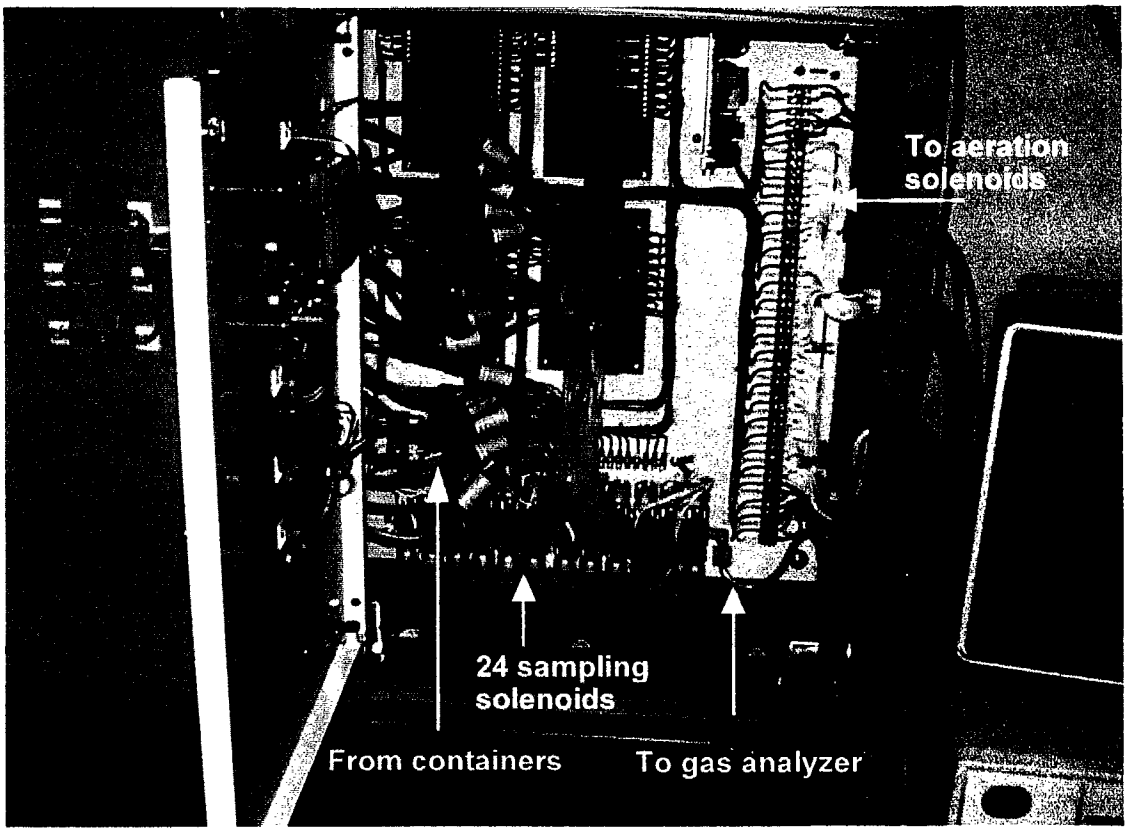


Figure 7.4. Inside view of the sampling sequencer.

7.3. Comparing the developed system with an existing GC system

7.3.1. Materials and methods

For the purpose of comparing the two systems, three storage containers for each system were prepared for storing a potato mass of about 3 kg, and gas analysis was performed daily using the tested method (gas analyzer) and the reference method (GC method) for a period of 10 days. The following subsections

discuss the results of the two systems.

7.3.1.1. The Gas Analyzer system

Components of the gas analyzer system described earlier were assembled, and the system was prepared for comparison with the GC system.

7.3.1.2. The Gas Chromatograph system

The system relies on the use of a Gas Chromatograph as the prime analytical instrument for the determination of CO_2, O_2 and N_2 contents in the air sample taken from the airtight storage containers. The storage containers used in these experiments are described in section 6.2.4 of Chapter VI and shown in Figure 6.1, they were quite difference from these used for the GA system (Figure 7.1).

The GC used was an SRI 8610A Gas Chromatograph (SRI Instruments, USA) equipped with a thermal conductivity detector operating at a 45°C oven temperature and 100°C detector temperature, using helium as a carrier gas. The GC was connected to a personal computer equipped with a software that integrated the three gas (CO_2, O_2 , and N_2) peaks and displayed their percentages in the gas sample.

7.3.2. Experimental procedure

7.3.2.1. Preparing storage containers

Three containers of each type were prepared for the experiment. Containers were washed with chlorinated water and tested for airtightness. Containers for both systems were tested for airtightness by pressurizing them at 2 kPa and monitoring pressure for 30 minutes using a digital pressure indicator (model DPI 601, SPR Control Systems, Mississauga, ON). A container was considered airtight when no pressure drop was observed.

Potato tubers, cv. Chieftain stored at 10°C were weighed and placed inside the containers. Produce density was determined to be 1.062 $g.cm^{-3}$ using the submergence method. Three containers for each system, GA and GC, were filled with potatoes at known mass, closed tightly and placed inside a walk-in cold room adjusted to 10°C. Table 7.1 shows produce mass, produce volume, and free volume of each container. Since the potato volume was a small percentage of the container volume, variations of potato mass was considered to have a negligible effect on respiration rate. Further, CO_2 percentages of the containers were kept below 3% throughout the experiment.

Gas analysis was performed daily for 10 days using both the gas analyzer (GA) and the GC systems. For the GA system, air analyses from the three containers was performed in two runs. Meanwhile, three samples of 1 ml of air from the containers were obtained using syringes and analyzed in the GC. The two closest readings were recorded and averaged.

Table 7.1. Mass and volume of potatoes and free volume of the storage containers.

Container	Potato mass, kg	Potato volume, cm^3	Free volume, cm^3 *
GA-1	3.1	2902.4	21512.1
GA- 2	3.2	2964.6	21449.9
GA- 3	3.2	2999.4	21415.1
GC-1	3.5	3253.4	21200.3
GC-2	3.3	3108.1	21345.7
GC-3	3.4	3203.8	21249.9

* Free volume is based on container volume of 24414.5 cm^3 for the GA method, and 24453.7 cm^3 for the GC method.

7.3.2.2. Correcting the CO_2 percentage inside containers of the GA system

While in the case of the GC method a small air volume was taken for analysis (3 samples of 1 ml each), the GA system used much larger air volume; air was drawn at a flow rate of 31.5 $cm^3.s^{-1}$ (4 CFH) for a 30 second analysis time. Thus, 944ml were drawn from the container at every gas analysis, and this volume must be taken into consideration in the calculation of the respiration rate. A correction procedure was established to add the volume of CO_2 in the 944 ml to the free volume of the container before calculating respiration rate. A linear regression relation was developed to take into account the amount of sampled air is shown in Figure 7.5.

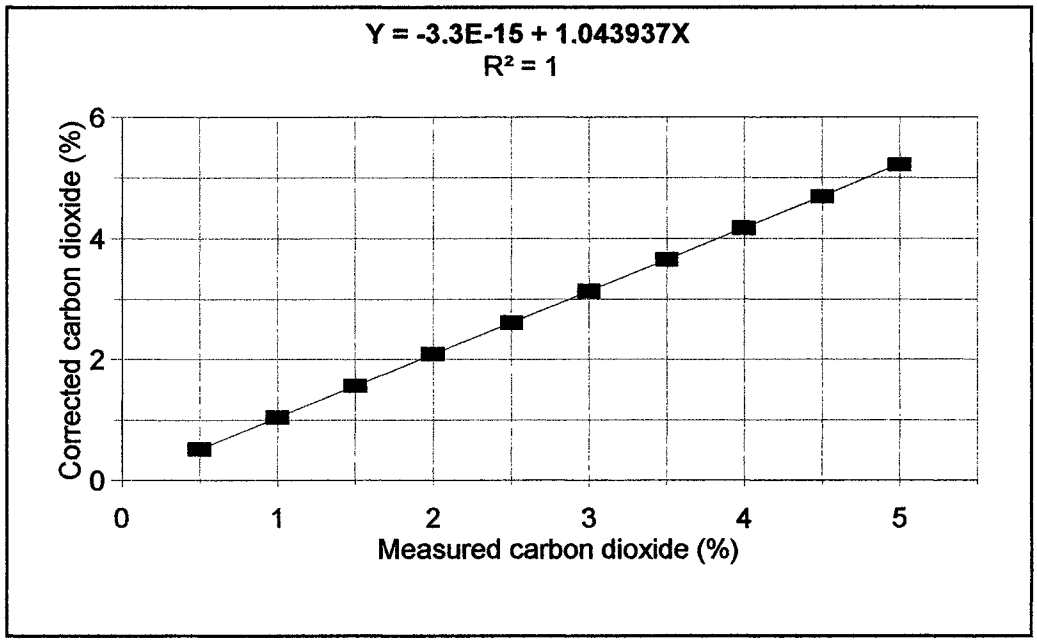


Figure 7.5. Corrected versus measured CO_2 percentages for a storage container being sampled by the GA system.

7.3.2.3. Calculating respiration rate

Respiration rate was calculated using equation 7.1. Free volume of the container, the percentage of CO_2 and O_2, the time elapsed between consecutive gas

withdrawals, and the mass of the produce were used for calculating respiration rate as CO_2 produced or O_2 consumed (ml. $kg^{-1}.h^{-1}$).

$$RR = \frac{\Delta X\ V}{\Delta t\ m_p} \qquad (7.1)$$

Where:

RR = respiration rate as CO_2 produced or O_2 consumed ($ml.kg^{-1}.h^{-1}$),

ΔX = CO_2 or O_2 percentage change inside the container during Δt (%),

V = free volume inside the container (ml),

Δt = time between two consecutive GC analyses (h),

m_p = potatoes mass (kg).

7.3.3. Results and discussions

The produce volume for all treatments was a small percentage (12- 13%) of the container volume (see Table 7.1). This facilitated the closure of the containers for 48 hours without reaching a CO_2 percentage of 3%, the threshold at which aeration must be performed. However, in this study an air exchange was performed when CO_2 percentage exceeded 2% by circulating pressurized air inside the containers for one minute.

Respiration rates for both systems are presented in Figures 7.6 and 7.7, for CO_2 produced and O_2 consumed, respectively. Respiration rates measured by both systems followed similar trends throughout the experimental period. Respiration measurements were performed for 10 days, and were realistically considered adequate for testing the performance of the two systems. Figures 7.6 and 7.7

show that respiration rates measured with the two systems were at rates below 2.5 $ml.kg^{-1}.h^{-1}$ throughout the storage period.

Tables 7.2 and 7.3 show the analysis of variance results (ANOVA), comparing the two data sets of respiration rates as CO_2 produced and O_2 consumed, respectively, and the interaction between measurements and method. Results showed no significant difference between the two methods at the 0.05 level. Also, interactions between the method and the daily measurements were also not significant. However, high significancy was observed between day to day measurements. Such observation is expected, since respiration rate was not expected to be absolutely constant.

Time taken for analysis was also observed throughout the experiment. It took 30 seconds to complete one analysis for the GA system, making the time required to complete two analyses one minute. On the other hand, it took 6 minutes to analyze one sample on the GC system, making the time required for analysing one container either 12 or 18 minutes, depending on how similar the first two air analyses were. Moreover, the GA system is fully automated while the GC system is not. Variations in measuring CO_2 and O_2 percentages for samples taken from the same container were also observed; accordingly, the three samples taken were mostly analysed, making the time required to complete the analysis of one container more than 18 minutes. In contrast, because of the larger volume of the sample, gas analysis results from the GA system did not vary and therefore, two gas samples for analysis per container were sufficient.

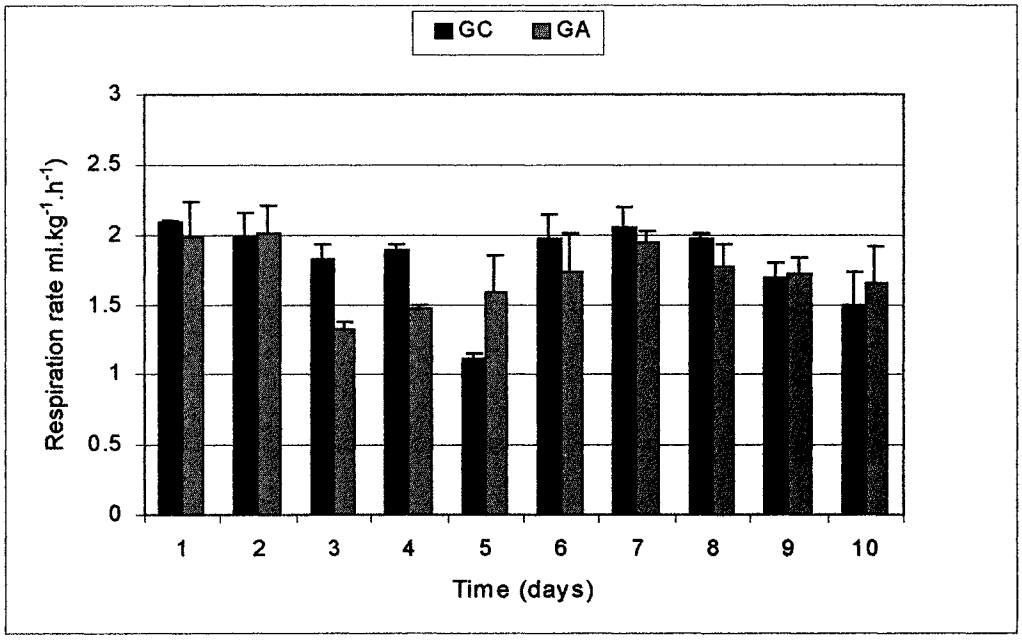


Figure 7.6. Respiration rates as CO_2 produced from potatoes measured by the GA and the GC systems. Error bars are the standard error.

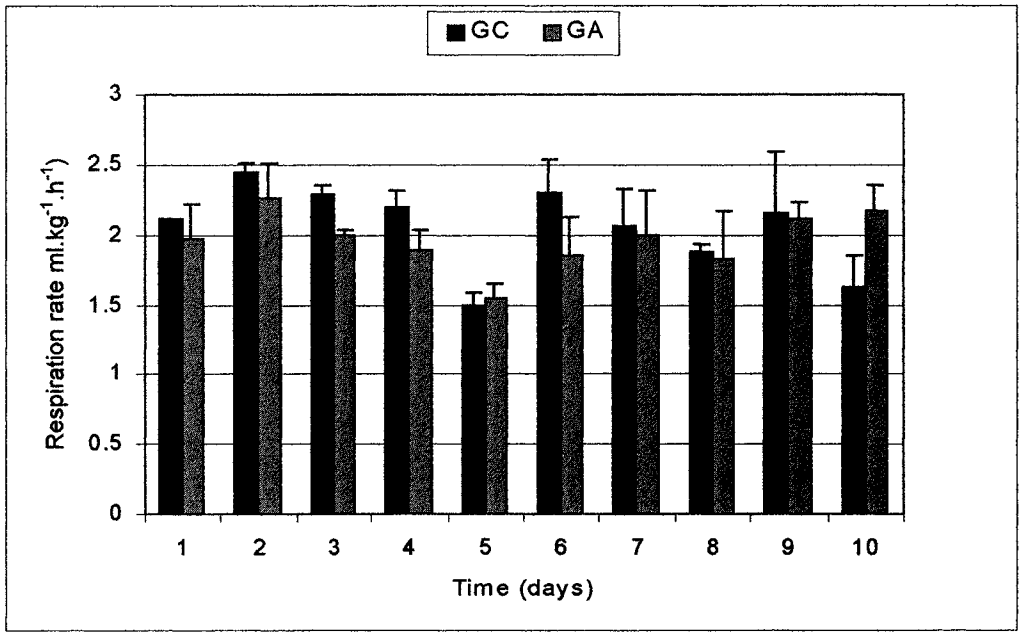


Figure 7.7. Respiration rates as O_2 consumed from potatoes measured by the GA and the GC systems. Error bars are the standard error.

Table 7.2. ANOVA Results for GA and GC methods, CO_2 produced.

Source	DF	SS	MS	F- value	Pr > F
Methods	1	0.11407	0.11407	1.41 $^{n.s}$	0.2414
Days	9	2.68343	0.29816	3.7	0.0019
M x D	9	1.09774	0.12197	1.51 $^{n.s}$	0.1771
Error	40	3.22697	0.080674	-	-

Table 7.3. ANOVA Results for GA and GC methods, O_2 consumed

Source	DF	SS	MS	F- value	Pr > F
Methods	1	0.13782	0.13782	1.01 $^{n.s}$	0.3209
Days	9	2.5963	0.28848	2.11	0.051
M x D	9	0.9751	0.10834	0.79 $^{n.s}$	0.6234
Error	40	5.4565	0.13641	-	-

7.4. Summary and Conclusions

A new gas analysis system was assembled and tested for measuring the respiration rate of agricultural products. The system was tested by measuring respiration rate of potato tubers stored at 10°C. The GA system was compared with an existing GC gas analysis system. Results showed no significant difference in the measurement of respiration rate expressed as CO_2 produced and O_2 consumed between the two systems. The newly tested system was more convenient and easier to use. Also, the study showed GA measurements to be reliable and fast. Further, it was observed that two gas analysis runs for one container were sufficient to have a reliable gas analysis using the GA system. Time-wise, the gas analysis from each container took one minute with the GA compared to 12 -18 minutes needed for the GC system to analyze one container. Additionally, the automatic air sampling

eliminated sample taking and preparation, compared to the GC system in which sampling and preparation time can be up to 3 minutes. The new system can be used with high confidence to carry out multi-container and lengthy respiration experimental investigations.

CHAPTER VIII

EFFECT OF DISEASE ON RESPIRATION RATE OF POTATOES STORED AT VARIOUS TEMPERATURES

8.1 Introduction

Respiration is a biochemical process which continues during the storage of produce. Measuring respiration rates of agricultural products is generally considered as invaluable information for determining storage conditions of regular and modified atmosphere storage systems, and the design of modified atmosphere packaging.

The respiration process is affected by several factors, generally classified as produce-related factors and storage environment-related factors. Over the years, numerous respiration studies have been conducted and have led to a significant improvement in produce quality and storeability. For potatoes, in particular, respiration rate has been investigated in relation to maturity, injuries, sprouting and as affected by storage conditions (Chapter III). However, it is apparent that little if any attention has been given to quantifying the respiration rate of potatoes as affected by disease infestation.

Earlier, in Chapter VI, effects of early disease infestation and sprouting on respiration were reported. Results showed a significant increase in respiration rates due to the effects of sprouting and disease infestation. In this Chapter, inoculated treatment similar to that described in Chapter VI as D treatment was used and defined as inoculated with no incubation (I0). Such comparison was intended to further investigate the effect of disease on respiration rate during early infection besides observing disease effect on respiration rate for a longer period of time and at various temperatures. Experiments were designed to investigate the effect of disease on respiration rate at three storage temperatures, 5, 10, and 15°C, covering

temperature range that are commonly encountered in a potato storage operation.

8.2. Materials and Methods

8.2.1. The gas analysis system

The gas analysis system used in this experiment and the storage containers have been described in Chapter VII. Before the start of the experiment, containers were washed with chlorinated water. They were then tested for airtightness using a digital pressure indicator (DPI) to detect any leaks. Each container was tightly closed, pressurized to 2 kPa and monitored for 30 minutes. A container was considered airtight if no pressure drop was observed within the test period. Containers were arranged inside a walk-in cold room equipped with an on-off temperature control system that facilitates the maintenance of storage temperatures between 0 and 17°C.

8.2.2. Potatoes

Potato tubers cv. Chieftain were obtained from a grower in mid-December, 2000. They were received in 22.73 kg (50 lb) bags, suberized and treated with a sprout inhibitor. Most of the potatoes were kept in the storage facility for the heat and moisture balance experiment, and the reminder were kept at lower storage temperatures in a walk-in cold room adjusted to 5°C and humidified to over 90%. Before every disease experiment, several bags were opened and undamaged medium to large tubers were selected. At every storage temperature, about 75 kilograms were used for all five treatments combined.

8.2.3. Inoculation Process

8.2.3.1. Preparing the tubers and storage containers

Tubers of each treatment and its replicates were weighed and marked prior

to further experimentation. For each treatment tubers were washed by soaking in (0.1%) chlorinated water. Tubers were then individually wiped with a soft sponge, dried on paper towels, and kept overnight in a dark place. Healthy treatment replicates were transferred to the containers prior to the start of inoculating the diseased treatments. For the non-inoculated treatment with holes (HW), the holes were made prior to the inoculated treatments, and tubers were placed in the containers to prevent contamination. For inoculated treatments with no incubation (I0), tubers were placed in the containers soon after their inoculation. For the other two treatments, inoculated and incubated for one day (I1) and inoculated and incubated for two days (I2) tubers were placed in the storage containers after 24 and 48 hours, respectively. For all treatments, after placing the tubers in the tightly closed containers, gas analysis was started.

8.2.3.2. Inoculum and inoculation process

The soft rot bacterial agent *Erwinia carotovora* subsp. *carotovora* was obtained from the Agriculture Canada Research Station, St-Jean-sur-Richelieu, QC, Canada, and grown in petri-dishes following the procedures described in Chapter VI. For each inoculated treatment about 100 ml of the bacterial suspension was prepared and divided equally among the five replicates (≈20 ml per replicate) and applied to the tubers.

While no holes were made on tubers of the healthy treatments (H), tubers of the healthy treatment with holes (HW) were drilled in a manner similar to that of the inoculated treatments; however no inoculation was made. For every inoculated treatment, the process began by drilling 2 to 3 holes in each tuber. Number of holes for all treatment was similar, since the weight of all treatments and their replicate did not vary greatly. However, for the fifth replicates of HW, I0, I1, and I2 treatments, designated for sample taking, and to facilitate disease progression evaluation, only

two holes were made in each tuber.

A low speed hand drill equipped with a 5 mm diameter bit modified to make a 25 mm deep hole, was used for making the inoculation holes. To avoid cross contamination between the inoculated treatments, the drill bit was kept disinfected throughout the inoculation process by keeping it in ethanol. After drilling and to facilitate applying a similar inoculum volume for all treatments, holes were cleaned with a sterilized wire hook, then filled with the bacterial suspension using a sterile 1 ml syringe. Again, to assure perfect filling, inoculum was applied gradually and tubers were tapped several times. While loading the container, tubers were placed in the holes-up position, to avoid spilling of the inoculum. For the incubated treatments, tubers were placed holes-up in a plastic bag which was closed for the entire incubation period. Incubation occurred in a room equipped with a heater with the thermostat adjusted to 25°C. For the I1 treatment, tubers were incubated for 24 hours, while for the I2 treatment tubers were incubated for 48 hours. Afterwards, potatoes were transferred to the storage containers and these were tightly closed.

Once tubers were placed in storage containers, they were expected to reach the storage temperature. In addition, at the three temperature treatments, relative humidity inside the containers was near saturation, since they were airtight and kept closed most of the time throughout the experiment, except a short time for aeration.

8.3. Gas analysis

Gas analysis was performed daily over the entire experimental period. At every analysis, air was withdrawn continuously for 30 seconds on two occasions in each run. CO_2 content inside the container was kept below 3% and once this threshold was recorded, the containers were opened, and aerated for one minute using pressurized air. For the 5 and 10°C storage temperatures, CO_2 levels approaching 3% occurred after 24 hours of storage, while for the 15°C storage

temperature, the threshold was reached within less than 12 hours, and therefore, containers were kept closed for less than 12 hours.

8.4. Evaluation of disease progression

Starting from the first day of incubation and throughout the experiment, a sample was taken periodically from the storage containers designated for sampling. A cross-sectional cut was made through the middle of every hole on the tuber, and the infected area, mainly the softened tissue developed around the infected hole was carefully removed, and diameters and depths of infected area were measured and recorded.

For most treatments, at advanced stages of disease progression, the determination of the volume of the infected area was not possible because of the way in which disease spread. Although large size tubers were used, infected holes became larger and joined together, and at more advanced stages, most of the inspected tuber was decayed. At such a stage, the uninfected part was weighed and the percentage of volume was determined. At every disease progression evaluation day, the progression of the infected area was compared with the calculated respiration rate within their respective time interval.

8.5. Experimental Design

For the respiration rate investigation, a factorial design of 3×5 was used and the analyses followed the procedure suggested by Littell, *et al.,* (1998). Three storage temperatures were applied: 5°C, 10°C and 15°C. At every storage temperature, five disease treatments were applied: *healthy (H)*, *healthy with hole (HW)*, *inoculated + no incubation (I0)*, *inoculated + incubated for 24 hours (I1)*, and *inoculated + incubated for 48 hours (I2)*. Four replicates were used for each treatment. Statistical analyses were performed using the Statistical Analysis System

(SAS) software version 12.

For the investigation of disease progression, a single tuber was taken from the fifth container of the inoculated treatments and a disease progression test was performed at five-day intervals.

8.6 Results and Discussion

8.6.1.Respiration rate and disease progression at 5°C

8.6.1.1. Respiration rate

Figures 8.1shows respiration rates as CO_2 produced for the five treatments at 5°C. The five treatments were divided into two groups, a low respiration group (includes H, HW and I0 treatments) and high respiration group (includes I1 and I2). The first group of treatments exhibited steady respiration rates of less than 2 $ml.kg^{-1}.h^{-1}$, with mean over the entire period of 1.64, 1.83 and 1.69 $ml.kg^{-1}.h^{-1}$ for H, HW and I0 treatments, respectively. The respiration rates were measured over 41 days, yet no changes in their trends were recorded, and the three treatments were not significantly different at the 0.05 level.

Inspecting the inoculated sites of the I0 treatments throughout the experiment showed no obvious signs of disease development. Internal surfaces of the infected hole developed dry corky-like tissues. Moreover, no visual differences between the infected sites of the I0 and HW treatments were observed. Such observations indicate that although bacteria were present inside the tubers, they did not invade the tuber tissue at such low temperatures as described in section 3.4.1. Respiration-wise, the insignificant difference between the H and HW treatments throughout the experiment indicated that wounding mature tubers had no significant effect on respiration rate, unlike results reported by Peterson *et al.* (1981) that showed wounded immature tubers to exhibit high respiration rates.

The I1 and I2 treatments exhibited gradually increased respiration rates, reaching above 9 $ml.kg^{-1}.h^{-1}$ at the end of the storage period. A sudden drop in respiration rate in term of both CO_2 produced and O_2 consumed was recorded on the 17th day due to improper closure of some containers. Also, later fluctuations may be attributed to measurement error and disease development. Nonetheless, the respiration increase trend was maintained.

Data collected up to the 41st day showed relatively stable respiration rates for the I1 and I2 treatments. Trends in respiration rates for the I1 and I2 treatments showed that at the beginning, these exhibited rapid respiration rates immediately after disease infection. The respiration increase was maintained for an extended period of time, mainly because of low temperatures. Low temperatures slowed the disease development and accordingly, a slow increase in respiration rates was recorded. Under low storage temperatures the steady respiration trends may be expected to continue for an extended period of time.

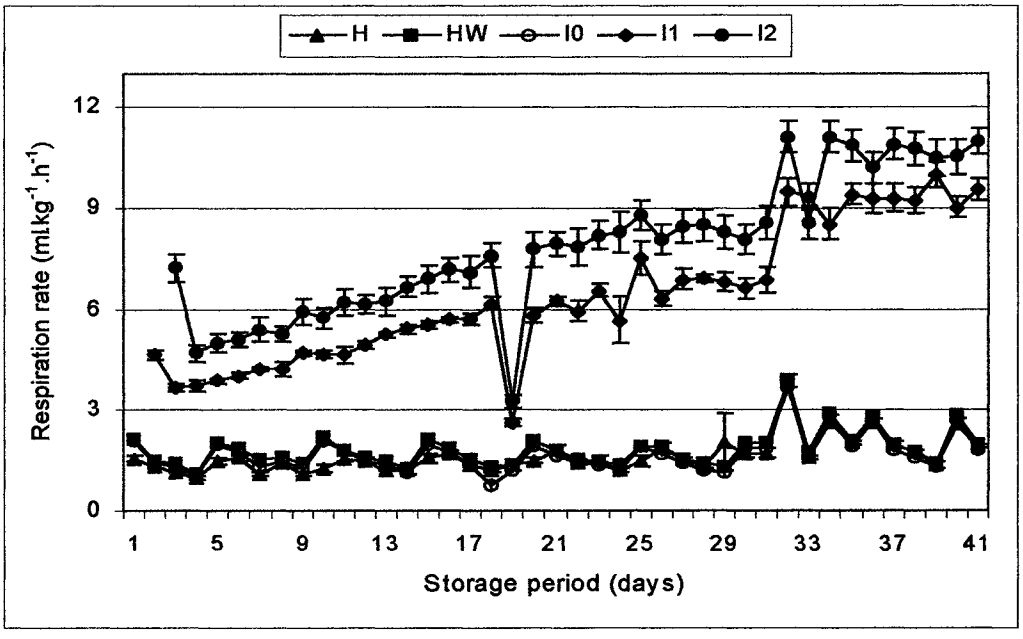


Figure 8.1. Respiration rates as CO_2 produced for the five treatments, stored at 5°C. Error bars represent ± standard error.

The I1 and I2 treatments exhibited significantly higher respiration rates than the H, HW and I0 treatments at the 0.05 level. The I2 treatment showed a significantly higher respiration rate (7.84 $ml.kg^{-1}.h^{-1}$) than that of the I1 treatment (6.37 $ml.kg^{-1}.h^{-1}$). Since tubers of the I2 treatment were incubated for 48 hrs, while these for the I1 treatment were incubated for 24 hrs; the higher respiration rates of the I2 treatment may be attributable to the higher microbial activities and the more advanced infection stage, both effects led to a significantly higher respiration rate.

When the means of respiration rates for the I1 and I2 were compared with that for the H treatment, the respiration rate of the I1 treatment was three-fold higher than that for the H and HW treatments rate, while the I2 respiration rate was four-fold higher than the H and HW treatments rate. Since the H and HW showed no significant difference in their respiration rates, the higher respiration rates of the I1 and I2 treatments are attributable to the disease infestation and not to the wounds.

When a comparison between I1 and I2 treatments was made, the higher respiration rate of the I2 treatment was mostly due to the effect of pre-storage incubation, since tubers were incubated twice as long as the I1 treatment. Thus, disease advanced more and led to higher respiration rates. When respiration rates of the I1 and I2 in Figure 8.1 were compared, a difference of about 1.25 $ml.kg^{-1}.h^{-1}$ between the two treatments was maintained throughout the experiment. Such observations have clearly demonstrated that incubation prior to 5°C storage temperature has a significant effect on disease development and thus on respiration rate.

From a disease development perspective, respiration rate of the I0 treatment suggested that disease development was practically inhibited at 5°C as described in section 3.4.1. Thus, under such storage conditions, it may take an extended period of time for infected tubers to develop disease symptoms. At early infestation stages, low temperatures slow or prohibit disease development. However, once

disease starts, it may take an extended period of time for the disease to become physically noticeable. Early signs of disease could clearly be detected as increases in respiration rate.

In practice, where the storage environment is maintained at low temperature after tubers are subjected to high temperature, disease may initiate without further spread. Thus, low temperatures indeed suppress the disease advancement, and maintaining low temperatures is absolutely essential. Under such conditions, disease progresses at very slow rates. Also, it has been demonstrated that although disease develops at slow rates, its effects on respiration rate is significant; and respiration rate can be used as a sign for detecting the existence of disease activities.

Figure 8.2 showed the respiration rate (as O_2 consumed) for the five treatments, and Figure 8.3 shows the respiratory quotient (RQ). The O_2 consumption followed a similar trend to that of CO_2 production. Treatments again fell into two groups; low and high respiration rates as seen before. However, mean respiration rates (as O_2 consumed) over then entire period were slightly higher than those measured as CO_2 produced averaging 2.07, 2.18 and 2.08 $ml.kg^{-1}.h^{-1}$ for the H, HW and I0 treatments, respectively. Similar to the CO_2 production rates, the O_2 consumption rates for the three treatments showed no significant difference throughout the experiment at the 0.05 level. Using the measured CO_2 produced and O_2 consumed, the respiratory quotients (RQ) for the three treatments were determined to be 0.81, 0.85, and 0.87 for H, HW and I0 treatments, respectively. The RQ for the three treatments were not significantly different.

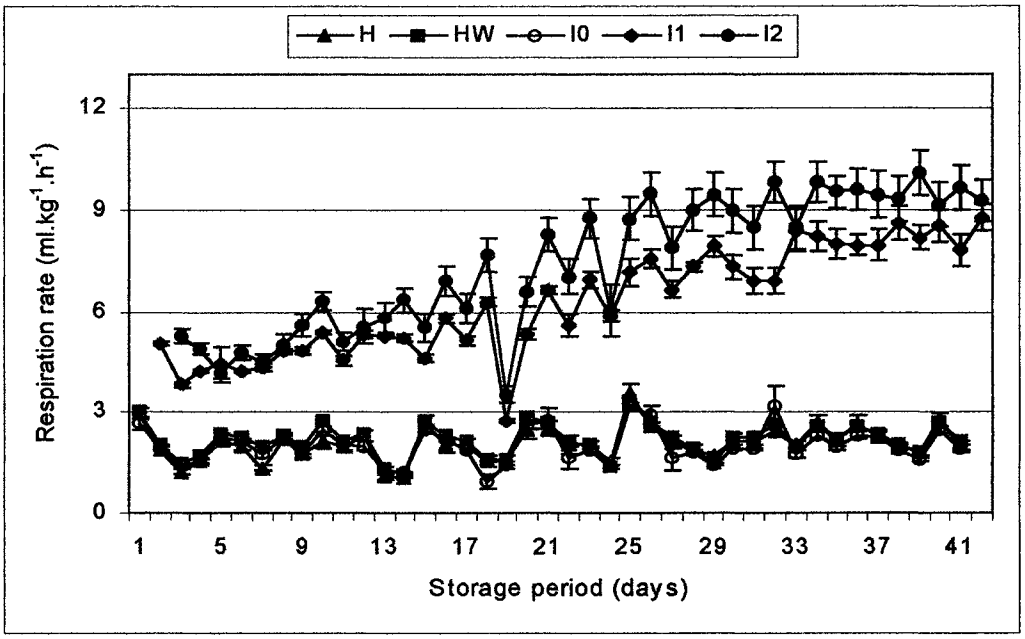


Figure 8.2. Respiration rates as O_2 consumed for the five treatments at 5°C.

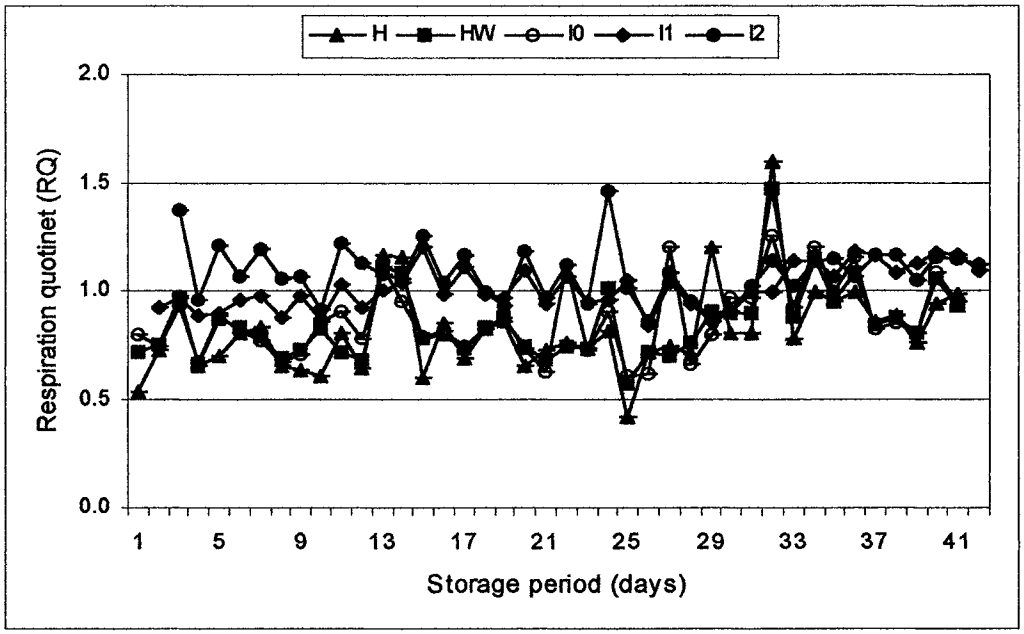


Figure 8.3. Respiratory quotient (RQ) for the five treatments at 5°C.

The I1 and I2 treatments at 6.26 and 7.40 $ml.kg^{-1}.h^{-1}$, respectively, showed significantly (over three-fold) higher O_2 consumption rates than the H, HW and I0 treatments. Respiration rates as O_2 consumed followed similar trends to those exhibited for CO_2 produced. The I1 treatment was found to be significantly different from the I2 treatment. Respiration rates as O_2 consumed for I1 and I2 treatments were quite similar to those measured as CO_2 produced. Mean RQ values calculated were slightly above unity at 1.01 and 1.08 for I1 and I2, respectively.

Figure 8.3 shows RQ values for the five treatments. It clearly shows that treatments again fell into two groups. The low RQ group included the H, HW and I0 treatments, while the high RQ group included the I1 and I2 treatments. In the literature, it is generally assumed that the RQ of healthy tubers is unity (Schippers, 1977b). RQ values for the H, HW and I0 treatments ranged from 0.6 to 1.2, 0.65 to 1.47, and 0.67 to 1.25, respectively; mean values being 0.81, 0.85 and 0.87. However, the three treatments were not significantly different.

The high RQ group included the I1 and I2 treatments; RQ for the I1 and I2 treatments ranged from 0.84 to 1.20 and 0.88 to 1.46, respectively; with mean values being 1.01 and 1.08, respectively. A comparison of the low and high RQ groups showed that not all treatments showed a steady RQ, rather the RQ value of each treatment varied within its range. Fluctuations in respiration quotient were uneven as observed during the study period and they did not exhibit any specific trends. Data on RQ of infected tubers were not available in the literature and therefore a comparison of the results of this study was not possible.

8.6.1.2. Disease progression analysis

Analysis of disease progression was made for the three inoculated treatments I0, I1 and I2 and the HW treatment. Inspecting the HW treatments was for the purpose of comparing the infected sites with a non-inoculated tubers. However,

since no inoculation was made in the HW and contamination was avoided, no infections by *Erwinia carotovora* or a secondary fungus infections were observed.

The HW samples showed wound healing after few days as surfaces developed dry tissues. This suggests that tubers are able to heal their injuries even after reaching maturity. Besides no disease symptoms were observed, the H and HW treatments showed no significant difference in their respiration rates and both followed similar trends (Figure 8.1).

Figure 8.4 shows disease progression for the I0, I1 and I2 treatments at 5°C. Disease did not develop on the I0 treatment for the entire experimental period of 41 days, whereas the I1 and I2 treatments showed disease progression up to about 60% of the tuber volume by the end of the experiment. Similar disease progression was observed for both treatments (I1 and I2 treatments). Such observations suggest that once disease has developed at low storage temperatures, it will continue progressing but at a slower rate.

The I0 treatment was visually normal at the inoculated sites; also there were no changes in colour or physical appearance. Inoculated sites (holes) developed dry surfaces without any signs of disease. This observation suggests that low storage temperature generally suppresses disease progression, and early infected tubers may not develop disease rapidly.

Comparing disease progression at 5°C (Figure 8.4) with the respiration data (in Figure 8.1), one could observe a similar trends between the two curves. Respiration rates for the I1 and I2 treatments gradually increased with time, accompanied by disease progression, although disease progression and respiration data showed similar trends. The disease progression analysis did not differentiate between the two treatments (I1 and I2), showing quite similar trends. In contrast, the respiration data (Figure 8.1) showed the I2 treatment with higher respiration rates than the I1 treatment throughout the experimental period. This suggests that the

respiration rate was in fact more accurate and reliable in differentiating between the two treatments than the disease progression analysis.

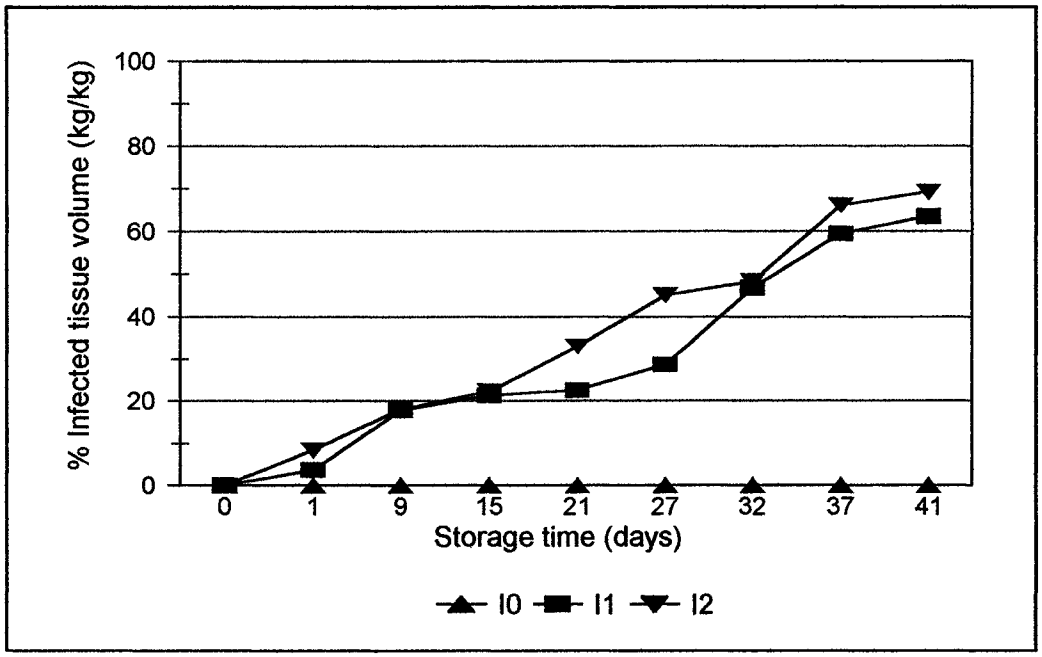


Figure 8.4. Disease progression of the I0, I1 and I2 treatments at 5°C.

8.6.2. Respiration rate and disease progression at 10°C

8.6.2.1. Respiration rate

Figures 8.5 shows respiration rates for the five treatments measured as CO_2 produced at 10°C. Respiration rates for the H and HW treatments began at less than 3 $ml.kg^{-1}.h^{-1}$ and declined gradually to maintain steady rates below 2 $ml.kg^{-1}.h^{-1}$ throughout the experiment. The I0 treatment exhibited respiration rates slightly higher than 3 $ml.kg^{-1}.h^{-1}$ at the beginning of the experiment and gradually declined to a steady rate of 2 $ml.kg^{-1}.h^{-1}$ after 11 days of storage. Means of respiration rate as CO_2 produced for the entire period were 1.89, 2.28 and 2.66 $ml.kg^{-1}.h^{-1}$ for the H, HW and I0 treatments, respectively. Although the I0 treatment showed a significantly higher respiration rate than that of the H or HW treatments

at the beginning of the experiment (up to 10 days), for the rest of the experimental period the three treatments were not statistically different. This suggests that although no physical disease infection symptoms were observed, the disease still resulted in higher respiration rates.

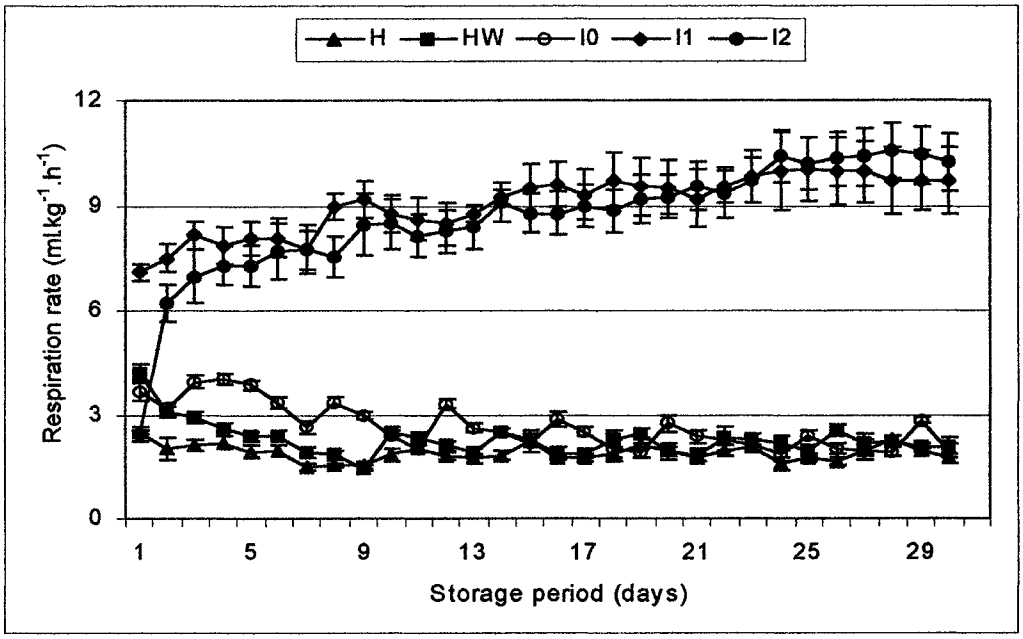


Figure 8.5. Respiration rates as CO_2 produced for the five treatments at 10°C.

When mean respiration rates of the H, HW and I0 treatments were compared, the H and HW treatments reached their steady respiration rates long before the I0 treatment. This shows that the increase in respiration rate of the I0 treatment was due to the higher bacterial respiratory activities before they reached dormancy at low temperature conditions.

Respiration rates obtained at 10°C for the H and I0 treatments were also compared with the similar treatments described in Chapter VI (H and D treatments). In both cases, treatments were similar in their bacterial loads and stored at the same

temperature, but two different varieties of potatoes were used. In Chapter VI the tubers were freshly harvested President variety while those in this Chapter were 8-month old Chieftain variety. Bearing this varietal difference in mind, the comparison was made for the entire data of the D treatment of Chapter VI and their corresponding values in the I0 treatment (the first 13 respiration measurements). Figure 8.6 shows respiration rates measured for the D and I0 treatments expressed as CO_2 and O_2 consumed, respectively, and Figure 8.7 shows the respiration rates for their corresponding healthy treatments (H1 for the D treatment and H2 for the I1 treatment). Also, Table 8.1 shows mean respiration rates as CO_2 produced and O_2 consumed and RQ for the D, I0, H1 and H2 treatments. Respiration rate as CO_2 produced for the D treatment was higher than the I0 treatment for all the reported respiration rates, but the O_2 consumption rates for the two treatments were quite similar. Similar observations were reported for their corresponding healthy treatments (H1 and H2) as shown in Figure 8.7. This could be attributed to variety and age differences between the two treatments. In fact young tubers are expected to respire at a rate higher than the mature ones. The respiration trends for both pairs (D & I0 and H1 & H2) were quite similar. Moreover, Table 8.1 shows that respiration quotient for both diseased treatments were higher than their corresponding healthy ones, but the RQ values for the Chieftain potatoes were lower than those for the President variety. Again, this maybe due to variety and age differences.

Table 8.1. Mean Respiration rates ($ml.kg^{-1}.h^{-1}$) as CO_2 produce and O_2 consumed and their corresponding RQ for similar diseased and healthy treatments applied in Chapter VI and Chapter VIII, ± standard deviations.

	Healthy treatments		Inoculated treatments	
	Chapter VI, (H)	Chapter VIII (H)	Chapter VI (D)	Chapter VIII (I0)
CO_2	2.90 ±0.39	1.91 ±0.28	5.03 ±0.73	3.23 ±0.25
O_2	2.49 ±0.72	2.39 ±0.34	3.78 ±1.54	3.61 ±0.28
RQ	1.29 ±0.37	0.84 ±0.11	1.36 ±0.25	0.90 ±0.07

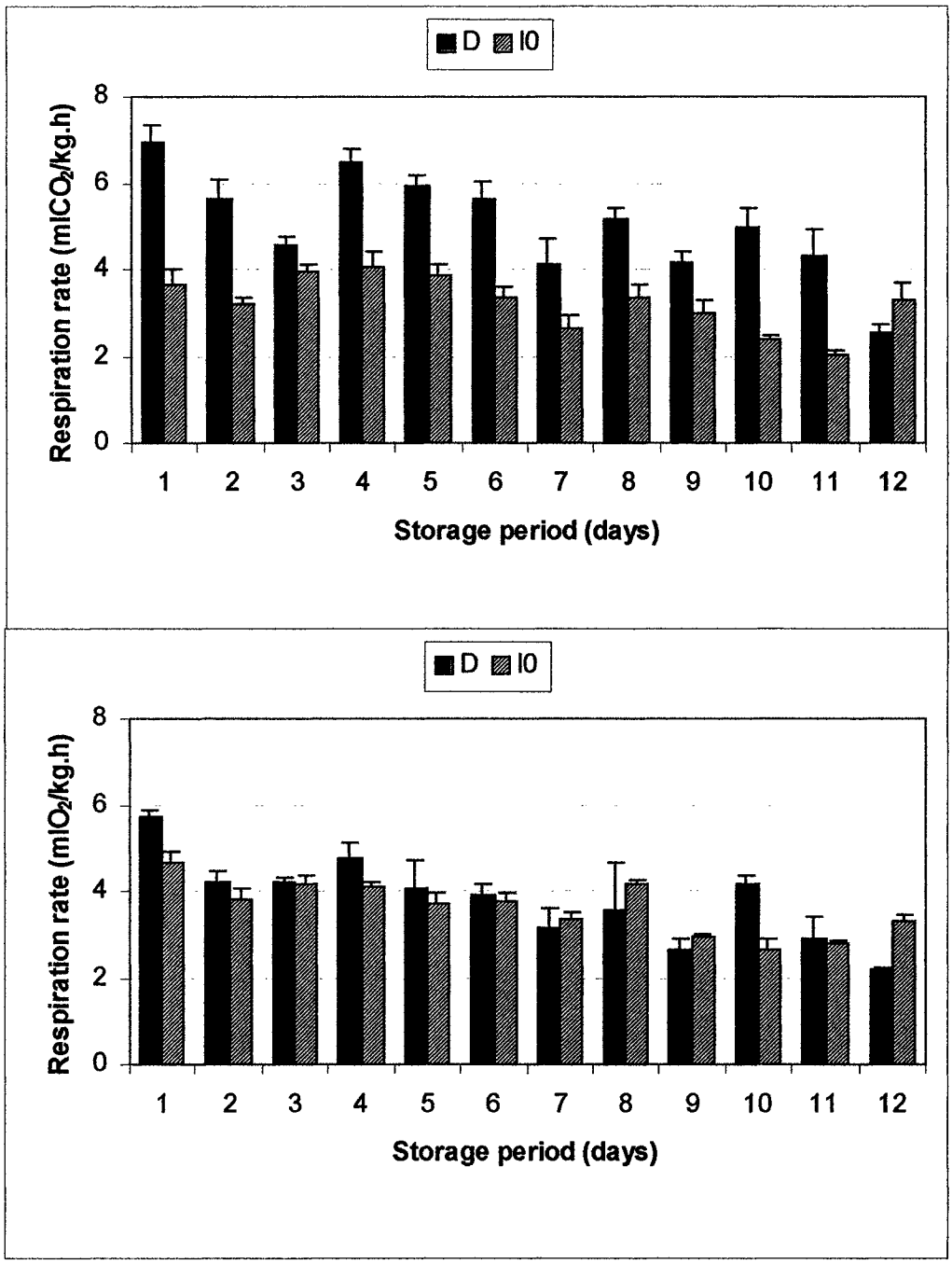


Figure 8.6. Respiration rate as CO_2 produced (top) and O_2 consumed (bottom) for the D and I0 treatments. Error bars are the standard error.

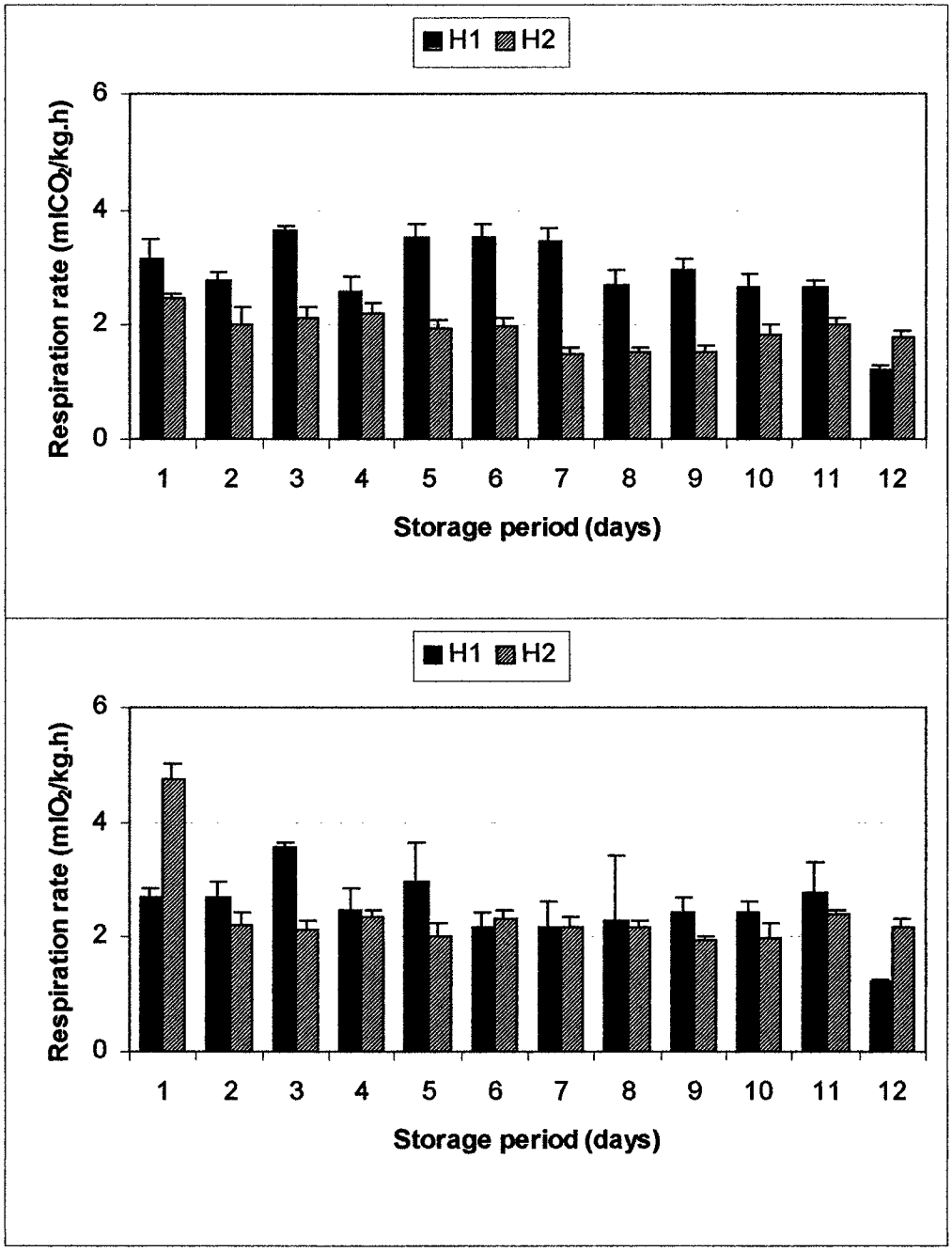


Figure 8.7. Respiration rates as CO_2 produced (top) and O_2 consumed (bottom) for the healthy treatments corresponding the D and I0 treatments.

The I1 and I2 treatments showed rapidly increasing respiration rates at the beginning of the experiment followed by stable rates. Mean respiration rates over the entire period were 9.05 and 8.64ml.kg^{-1}.h^{-1} for the I1 and I2 treatments, respectively. Throughout the experiment, the two treatments exhibited significantly higher respiration rates than H, HW or I0 treatments. However, a comparison between the I1 and I2 showed that the two treatments were not statistically different at the 0.05 level.

Mean respiration rates of the I1 and I2 treatments versus that of the H treatment showed that the disease infection led to an increase in respiration rate by more than four-fold, a magnitude similar to that at 5°C. Nonetheless, at 10°C, the pre-storage incubation of the disease did not have a significant effect on its progression in storage. This indicates that at 10°C, disease develops faster making one day of pre-storage incubation less significant. Further, it suggests that once disease starts, it develops rapidly, and faster than at 5°C.

Figure 8.8 shows respiration rate for the five treatments as O_2 consumed. The O_2 consumption rate followed similar trends to that of CO_2 production rate. Respiration rate as O_2 consumed for the H, HW and I0 treatments were quite low and steady, whereas that for the I1 and I2 progressively increased and maintained steady rates until the end. Again, the I1 and I2 treatments showed significantly higher O_2 consumption rates than the H, HW or I0 treatments. The I1 and I2 treatments showed no significant difference at the 0.05 level. Means of O_2 consumption over the entire storage period were 2.33, 2.76, 3.18 ml.kg^{-1}.h^{-1} for the H, HW and I0 treatments, respectively. Whereas those for the I1 and I2 treatments were 7.86 and 7.42 ml.kg^{-1}.h^{-1}.

Figure 8.9 presents RQ for the five treatments. Again, the five treatments were divided into high and low RQ groups. The H, HW and I0 exhibited lower RQ values than those for the I1 and I2 treatments. RQ values for the H, HW and I0

treatments ranged from 0.71 to1.02, 0.65 to 1.29, and 0.64 to 1.14, respectively, with mean values of 0.84, 0.84 and 0.85. Whereas those for the I1 and I2 treatments ranged from 0.95 to1.41, and 0.98 to 1.51, respectively, with mean value of 1.16 and 1.2. Respiration quotient for treatments at 10°C were quite a bit higher than those for treatments at 5°C.

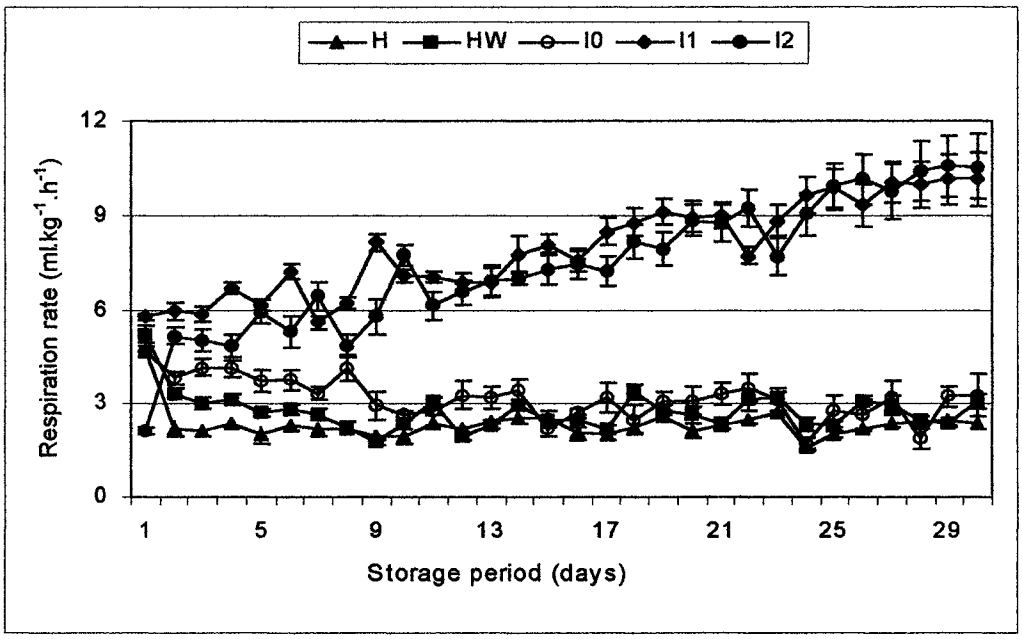


Figure 8.8. Respiration rates as O_2 consumed for the five treatments at 10°C.

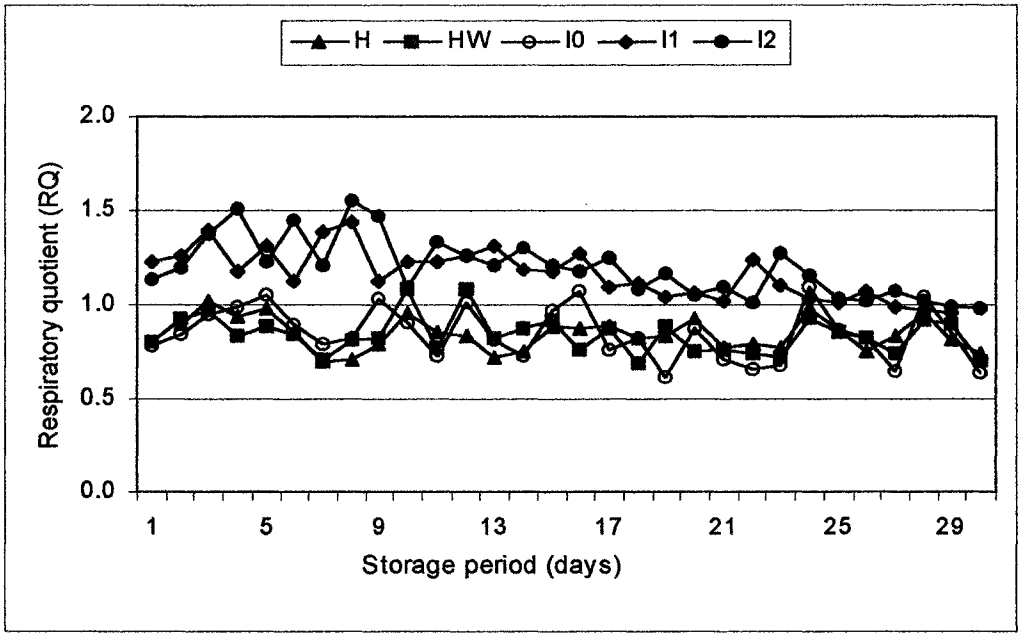


Figure 8.9. Respiration quotient (RQ) for the five treatments at 10°C.

8.6.2.2. Disease progression analysis

Figure 8.10 shows disease progression for the I0, I1 and I2 treatments at 10°C. Again, disease did not progress in the tubers subjected to the I0 treatment, but disease did spread in the tubers of the I1 and I2 treatments. Incubation time again did not have a significant effect on disease progression as seen in the I1 and I2 treatments. As expected, disease progressed faster than at 5°C, resulting in decomposition of above 75% of the tuber volume after 24 days of storage, compared with less than 40% volume after the same storage period at 5°C.

Comparing Figures 8.10 and Figure 8.5 (respiration rate curves), a progressive increase in respiration rates and disease infestation can be seen up to the 25th day of storage, then steadier respiration rates resulted at which above 75% of tuber volume was decomposed. Both curves became smooth for the rest of the storage period and maintained the same trend.

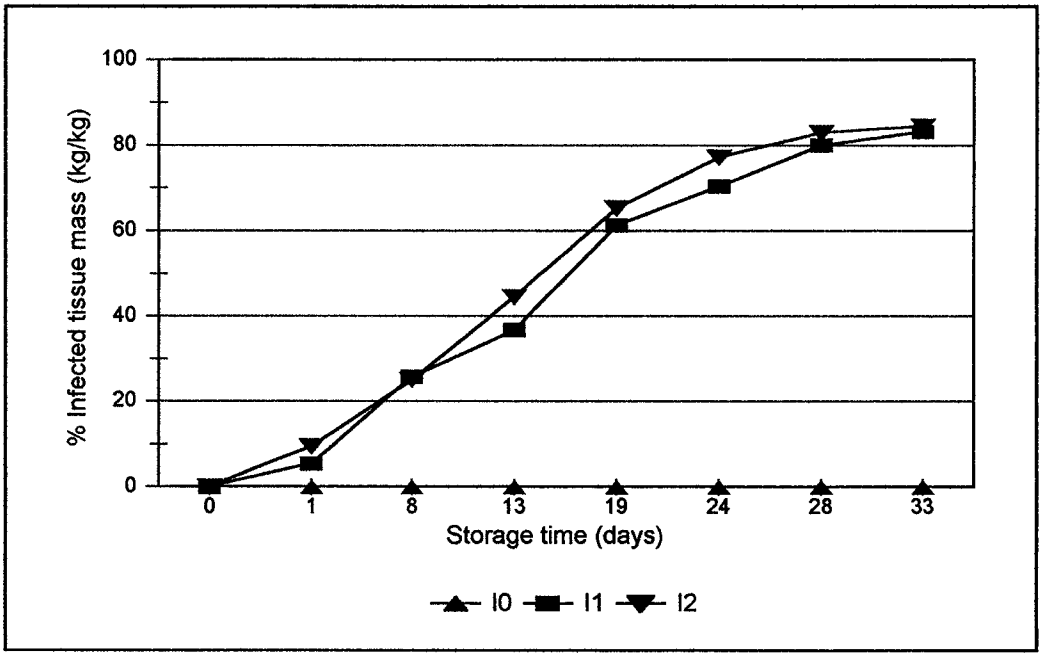


Figure 8.10. Disease progression of the I0, I1 and I2 treatments at 10°C

8.6.3. Respiration rate and disease progression at 15°C

8.6.3.1. Respiration rate (RR)

Figure 8.11 shows respiration rate as CO_2 produced for the five treatments at 15°C. The H and HW treatments exhibited the lowest respiration rates. At the beginning the two treatments showed a decline from above 6 $ml.kg^{-1}.h^{-1}$ to reach steady rates of less than 5 $ml.kg^{-1}.h^{-1}$ which were maintained until day 23, when a gradual increase began. Inspection of the tubers showed that sprouting of the H and HW started at the beginning of the third week in storage. Sprouting was to be expected because of the sudden exposure of the mature tubers to higher temperatures. The H and HW treatments were not statistically different at the 0.05 level, their means for the entire period being 6.01 and 7.57 $ml.kg^{-1}.h^{-1}$, respectively.

The I0 treatment exhibited a progressively increased respiration rate up to

day 21 in storage, where it peaked at 30 $ml.kg^{-1}.h^{-1}$, then began a declining trend similar to the trends of the I1 and I2 treatments, but at a slower respiration rate. The I1 and I2 treatments reached their peaks of 30 $ml.kg^{-1}.h^{-1}$ at 12 days of storage and both treatments began declining long before the I0 treatment. For the three treatments, the increase in respiration rate was mainly due to the effects of disease progression up to the level at which most of the potato mass had decayed, then respiration rates began to decline. In fact, the peak corresponded with the maximum decomposed mass. Thus, for the I0 treatment, it took longer before the decline could occur, while for the I1 and I2 treatments, disease advanced more rapidly due to the effect of incubation. Visual observations of tubers showed severely decayed tubers with no perceivable difference among the three treatments.

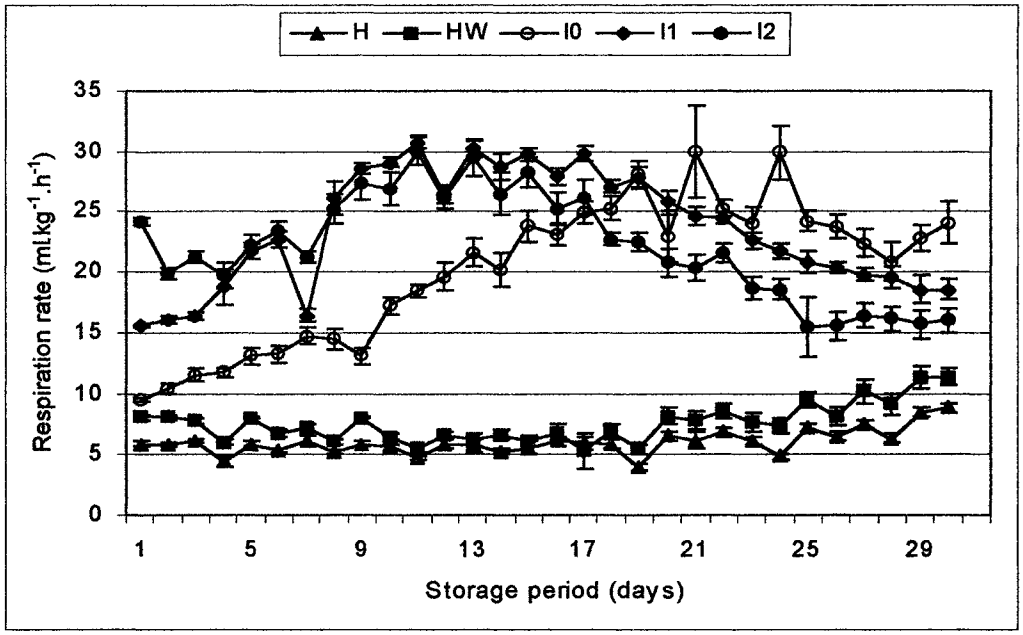


Figure 8.11. Respiration rates as CO_2 consumed for the five treatments at 15°C.

From the start of the experiment, the I1 and I2 treatments showed no significant difference in respiration rate at the 0.05 level, both showed significantly

higher respiration rates than the I0 treatment. Mean respiration rates for the entire period were 20.14, 23.47 and 22.1ml.kg^{-1}.h^{-1}, for the I0, I1 and I2 treatments, respectively. Comparing these rates with the respiration rate of the H treatment (6.01ml.kg^{-1}.h^{-1}) indicated an increase in respiration rate of more than three-fold. When the respiration rate of the H treatment was compared with the respiration rate peaks of the I0, I1 and I2 treatments, the increase was five-fold.

Figure 8.12 shows the respiration rates as O_2 consumed for the five treatments. It followed similar trends to the CO_2 produced but the respiration rate values as O_2 consumed were lower. The H and HW treatments showed no significant difference at 0.05 level, whereas the I0, I1, and I2 treatments showed significantly higher rates than the H and HW treatments. A comparison between the inoculated treatments in the increasing portion of the curve showed no significant difference between the I1 and I2 treatments, but the two were significantly higher than the I0 treatment. However, in the declining portion of the curve the I0 treatment was higher than the I1 and I2 treatments. This could be attributed to the faster decay rates of the I2 and I1.

Mean O_2 consumption rates over the entire storage duration for the H and HW were 5.12 and 6.96 ml.kg^{-1}.h^{-1}, respectively, while those for the I0, I1 and I2 were 17.39, 19.43 and 18.92ml.kg^{-1}.h^{-1}, respectively. Again treatments were divided into two groups, high and low respiration rate groups: in the first the H and HW and in the second the I0, I1 and I2 treatments. The H and HW treatments were not significantly different throughout the storage period. The I0 showed significantly lower respiration rates that the I1 and I2 treatments at the beginning of the experiment, followed by a period of similarity between the three treatments, and in the last portion, the I0 was higher than that of the I1 and I2 treatments. However, means over the entire period were quite similar.

Respiratory quotient for the H and HW treatments ranged from 0.86 to 1.56,

and 0.82 to 1.31, respectively, with mean values of 1.21 and 1.11. Whereas RQ for the I0, I1 and I2 ranged from 0.95 to 1.68, 0.97 to 1.62, and 0.91 to 1.65, respectively, with mean values of 1.23, 1.26, and 1.20, respectively. Unlike the RQ values reported at 5 and 10°C, those at 15°C were all above unity.

Observing the RQ for the five treatments at the three storage temperatures shows that the RQ increases due to disease infestation. Also, for the same treatment, temperature increase tends to increase RQ. Table 8.2 shows the means for the entire storage period of all treatments at the three storage temperatures. RQ increased as affected by both temperature and disease infestation.

Table 8.2. RQ means of the five treatments at the three storage temperatures (± standard error)

Temp. (°C)	H	HW	I0	I1	I2
5	0.81±0.03	0.85 ±0.03	0.87 ±0.07	1.01 ±0.03	1.08 ±0.04
10	0.84 ±0.05	0.84 ±0.05	0.85 ±0.05	1.16 ±0.05	1.20 ±0.03
15	1.21 ±0.07	1.11 ±0.05	1.23 ±0.05	1.23 ±0.05	1.20 ±0.04

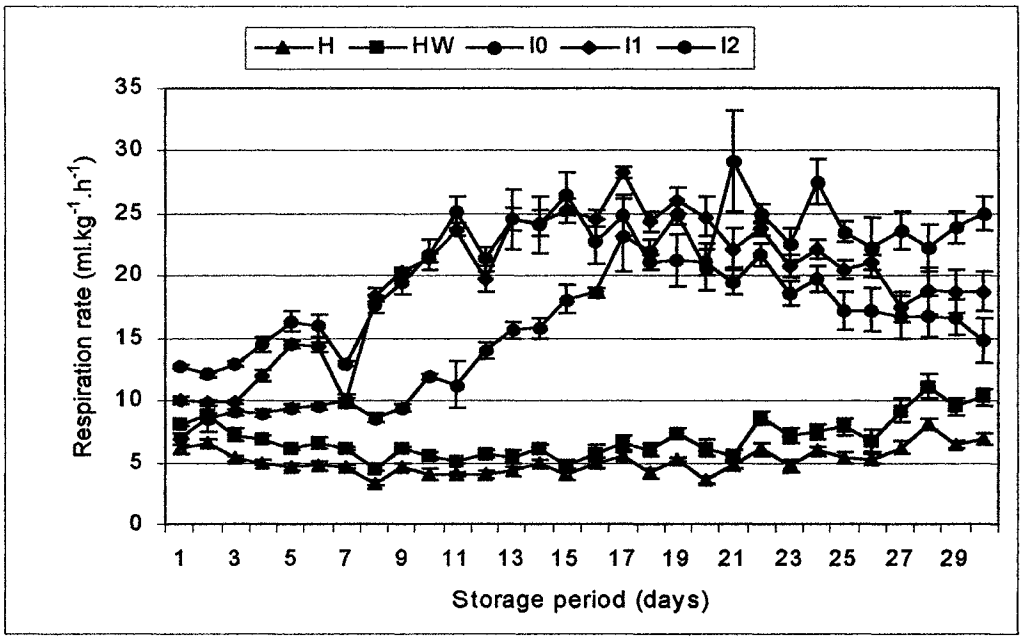


Figure 8.12. Respiration rates as O_2 consumed for the five treatments at 15°C.

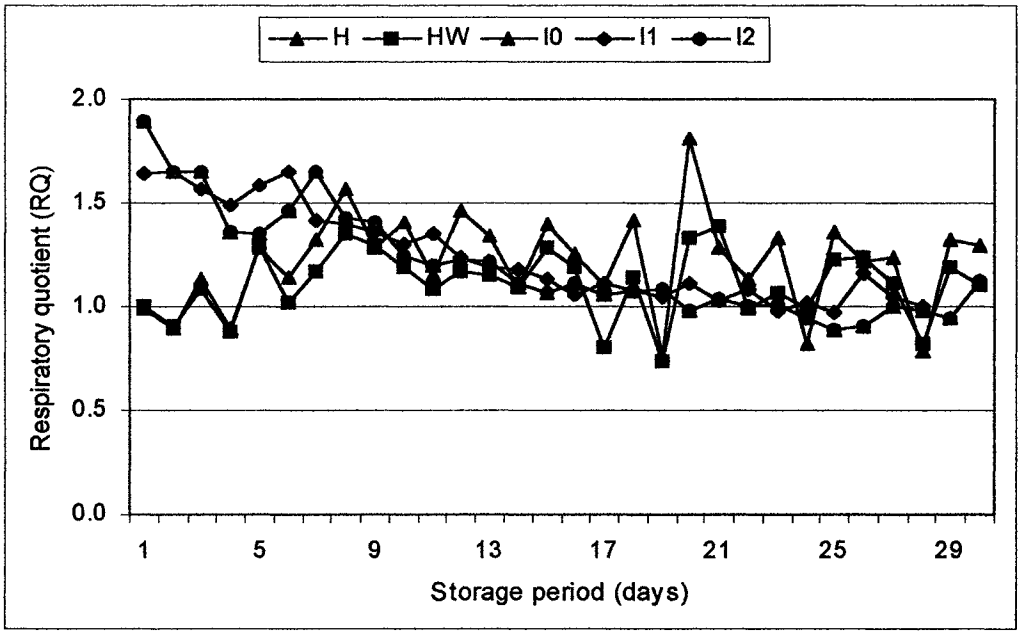


Figure 8.13. Respiration quotient (RQ) for the five treatments at 15°C.

8.6.3.2. Disease progression

Figure 8.14 shows disease progression for the I0, I1 and I2 treatments at 15°C. Unlike with the 5 and 10°C storage temperatures, at 15°C the I0 treatment developed disease at an early stage. For the three treatments, more than 75% of the tuber mass was decomposed after 17 days in storage. At the beginning of the experiment disease progressed at faster rates in the I1 and I2 treatments, while the I0 treatment developed disease at slower rates before day 17 in storage when the disease had infected 75% of the tuber mass, similar to the I1 and I2 treatments.

Comparing the disease progression rates of the I1 and I2 at the three storage temperatures in Figures 8.4, 8.10 and 8.14, one can observe that after 17 days of storage, above 75% of tuber mass was infected at 15°C; while at 10°C, less than 50% of the tuber volume was infected; and at 5°C, less than 25% was infected. This data leads to the conclusion that infection doubled for every 5°C temperature increase.

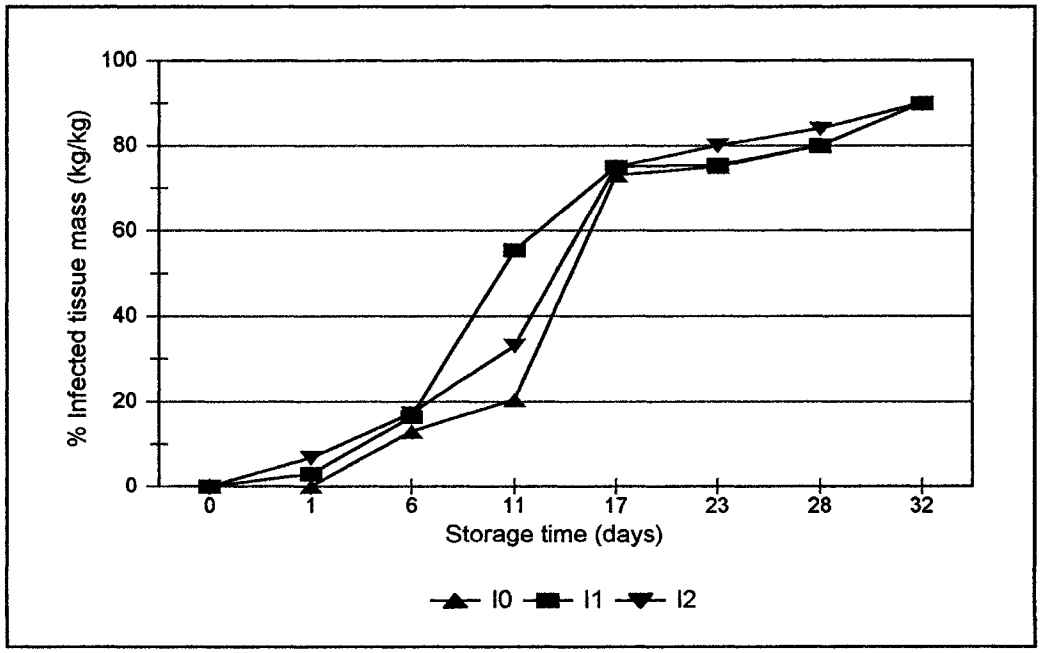


Figure 8.14. Disease progression of the I0, I1 and I2 treatments at15°C

8.7. Summary and Conclusions

The H and HW treatments showed the lowest respiration rates at the three storage temperatures, 5, 10 and 15°C, and wounded tubers (HW) did not show significant differences in respiration rates from the healthy tubers (H). Also inspecting the HW treatment suggested that wound healing can be achieved even for mature stored potatoes. The inoculated tubers with no incubation (I0) treatment showed neither signs of disease development nor respiration rate increase at the 5°C storage temperature, showing that disease development in an infected tuber can be impaired at storage temperatures of 5°C. However, at a 10°C storage temperature, disease appeared to have an effect on respiration rates even when no obvious signs of disease infection were apparent, respiration rates were significantly higher at the beginning of the experiment. At 15°C, disease developed in the I0 treatment, but at lower rates than the I1 and I2 treatments at the beginning of the experiment. After two weeks in storage, the I0 tubers showed similar disease development rates compared to the I1 and I2 treatments.

The I1 and I2 treatments showed significantly higher respiration rates than that of the H and HW at all three storage temperatures, and showed higher respiration rates than the I0 treatments at 5°C and 10°C, but not at 15°C. In general, disease infestation led to roughly four-fold respiration rate increases at each of the three storage temperatures.

The respiratory quotient was affected by both temperature and disease infection. The same treatments showed higher respiration quotients as storage temperature increased; and at the same storage temperature, diseased treatments showed higher respiratory quotients than the healthy treatments.

Disease progression analysis showed similarities between the trends of disease development and respiration rate. Disease development at 5°C exhibited the slowest rate, followed by 10°C, and 15°C which exhibited the fastest disease

development rate. A time-wise comparison showed that disease infestation doubled for every 5°C temperature increase.

CHAPTER IX

CONCLUSIONS, CONTRIBUTIONS TO KNOWLEDGE AND RECOMMENDATIONS FOR FURTHER STUDIES

9.1. Conclusions

The prime objectives of this study were to investigate the applicability of measuring respiration rates of potatoes under real storage conditions and to investigate the effects of postharvest stresses on the respiration rate. The experiments were carried out under real and experimental storage conditions. The study led to the following conclusions:

1. The storage system designed and built for two three ton capacity chambers (bins) performed in accordance to the recommended conditions. Stable temperature and relative humidity were maintained and ventilation air was well conditioned. Potatoes were stored under conditions that were in good agreement with those reported in the literature.

2. A heat and moisture balance was primarily applied on data collected from the two storage bins of the storage facility under specific conditions to ensure system stability; heaters and humidifiers were turned off, air exchange louvers were also closed, and air was circulated between the bins and mixing rooms at low flowrate for a minimum period of 8 hours per day for a two month period. Heat and moisture balance applied on these selected periods resulted in quantifying the amounts of heat rate produced by potatoes with less

variation and accordingly their corresponding respiration rates were generally in agreement with ranges reported in the literature. Respiration rates were also measured using in-store gas analysis and under laboratory conditions using a gas analysis system. Comparing these with rates evaluated by heat and moisture balance, the later respiration rates were higher. But the three measurements were performed under difference conditions that may have attributed to such differences.

3. The moisture balance led to an accurate estimation of moisture losses, as it agreed closely with those determined experimentally and that reported in the literature.

4. Early disease infestation and sprouting exhibited significant increases in respiration rates, up to 3-fold higher than healthy tubers at the 10°C storage temperature. Although no signs of physical disease infection were observed, tubers at an early disease infestation stage exhibited significant increase in their respiration rate. Sprouting was also found to have similar effect to that of disease infestation.

5. Experimental respiration studies, especially those for long term storage crops such as potatoes, require a gas analysis system that is quick, convenient and easy to use. It was found that although using the GC for gas analysis gave accurate results, it was quite time consuming. A faster and accurate gas measurement system was developed and tested. Its performance in terms of accuracy was comparable with that of the GC system. The system developed has

the advantage of being 1 to 18 times faster than the GC system. It was used for a long term respiration study which proved to be convenient and accurate.

6. Three levels of disease infestation by soft rot (*Erwinia carotovora*) were applied to potatoes and their respiration rates were measured for extended periods. The disease development investigations showed that disease infestation led to an increase in respiration rates.

7. At 5°C storage temperature, without pre-storage incubation, disease did not develop during storage a period of 41 days. However, at 10°C the inoculated treatment showed a higher respiration rate than the non-inoculated treatment. At the 15°C storage temperature, disease progressed rapidly for treatments without pre-storage incubation; and respiration rates for the three inoculated treatments were quite similar.

8. Disease infestation led to an increase in respiration rate of more than three fold and disease progression trends were similar to the trends of respiration rate. Both trends progressively increased until the decomposed mass reached 75% of potatoes mass, then both trends stabilized.

9. The respiratory quotient increased as tubers were infected with disease and subjected to higher storage temperatures. The combination of disease and higher temperature led to an even higher respiratory quotient.

Finally, under real storage conditions, the heat and moisture balance showed

that heat rate generated by stored products could be positively quantified. Such measurements can be used to estimate the condition of the stored produce, based on an increase in physiological or pathological activities. Additionally, the moisture balance can be used to quantify mass losses.

The experimental investigation of respiration rate as affected by disease and sprouting combined with the disease progression analysis showed that physiological and pathological stresses are indeed associated with higher respiration rates.

Thus, the findings of the two experimental protocols addressed the feasibility of carrying out a respiration study under real storage conditions that targets postharvest quality and disease detection using respiration rate as an indicator.

9.2. Contributions to Knowledge

This thesis has made original contributions to knowledge by providing new insights on the respiration rate of stored potatoes and its role in relation to disease infestation and the feasibility of its use as an indicator of the status of the stored produce in a postharvest management strategy. The main contributions of this study are as follows:

1. This was the first study aimed at investigating respiration rate of a produce stored under real and experimental conditions being carried out with the goal of using respiration rate as an indicator of produce status. It has proven that physiological and pathological stresses lead to higher respiration rates. Overall, the feasibility of using respiration rate measurements inside a storage facility for intended purpose has been demonstrated.

2. Methodology and experimental procedures presented in this study

introduced a new perception of respiration investigations and its use for postharvest management applications.

3. This study demonstrated the feasibility and accuracy of measuring respiration rates of stored potatoes by quantifying heat rate produced using the heat and moisture balance. It also showed that for accurate results, certain conditions that provide stable conditions inside the facility must be applied.

4. This study led to the development of an alternative methodology to the use of Gas Chromatograph for gas analysis in a respiration study. The system developed was up to 18 folds faster than the GC system without affecting the measurement accuracy.

5. This is the first study that specially quantified the effect of disease infestation on respiration rate and disease progression. It was found that respiration rate increased by up to three folds as tubers were infected with soft rot (*Erwinia carotovora*).

6. The respiration study showed that Respiration quotient (RQ) of potatoes increased as tubers were increasingly affected by disease and/or stored at higher temperatures.

9.3. Recommendation for Further Studies

This study suggests the following recommendations for further investigations:

1. Improving the air humidification and the relative humidity measurements by using a fogging system instead of water sprayers and the use of sturdier humidity sensors. Such installations will allow one to achieve conditions of near saturation and eliminate water accumulation in the ventilation ducts and mixing rooms.

2. Improving the control software to include the heat and moisture balance calculations and present real time heat and moisture balance. Also incorporation of the gas analysis process into the control system and development of a system approach that is specifically designed to assess the overall performance of the storage facility will be excellent additions to management strategy .

3. Applying a combined investigation to include heat and moisture balance, gas analysis for volatile monitoring on potatoes stored in the storage facility. The study should use potatoes with known field history, perform all storage operations in the facility and also initiate laboratory respiration measurements performed simultaneously with the heat balance for the entire storage duration.

4. There is a great need for in-store disease infestation detection that include, the use of deep-in-the-pile diseased pockets and the use of existing and new strategies that targets an early disease detection as the ultimate goal.

5. Expanding the laboratory investigation of respiration rate of infected potatoes to cover several varieties, wider temperature ranges, several storage conditions, and extending the experiments to longer periods.

6. There is a need for investigating the effects of other postharvest diseases and their effects on respiration rates and their detection tools in the laboratory and real storage setups.

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APPENDICES

APPENDIX A *Temperature distribution in ad surrounding the two storage bins*

APPENDIX B *Ventilation air temperature entering and leaving the potato pile for bin 1 and bin 2*

APPENDIX A

Temperature distribution in and surrounding the two storage bins.

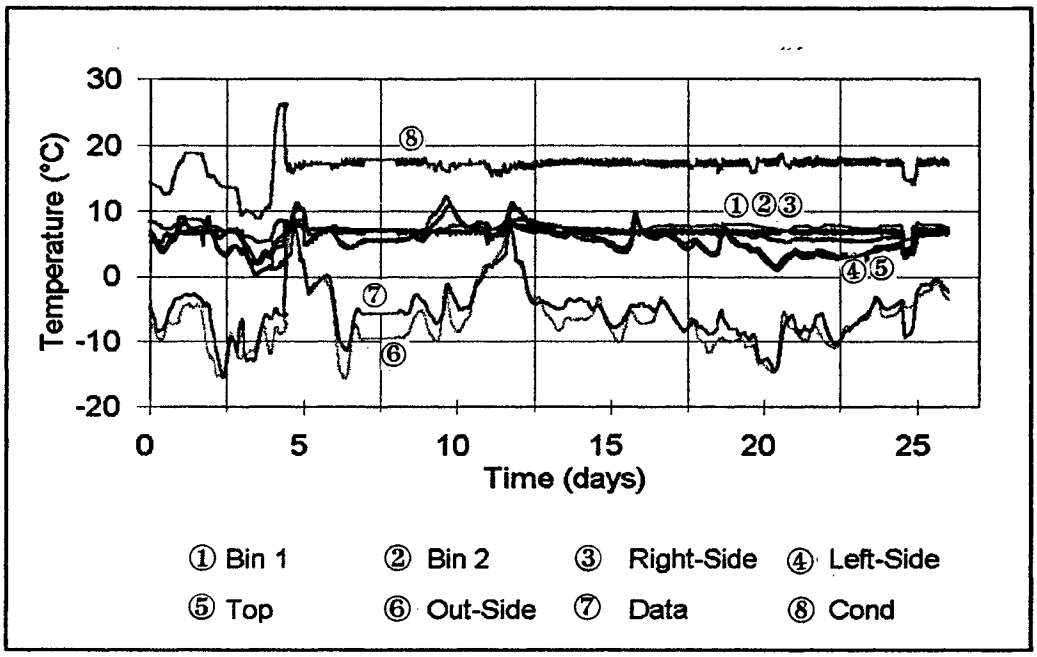

Figure A.1. Pile mean temperatures for the two bins and their surroundings during December, 2000.

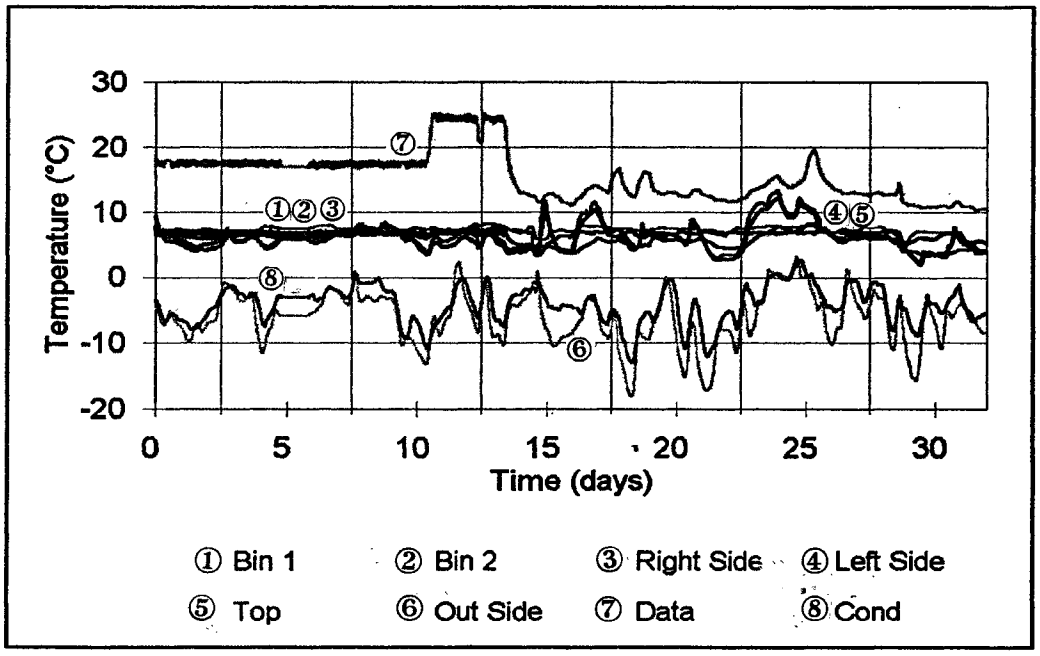

Figure A.2. Pile mean temperatures for the two bins and their surroundings during January, 2001.

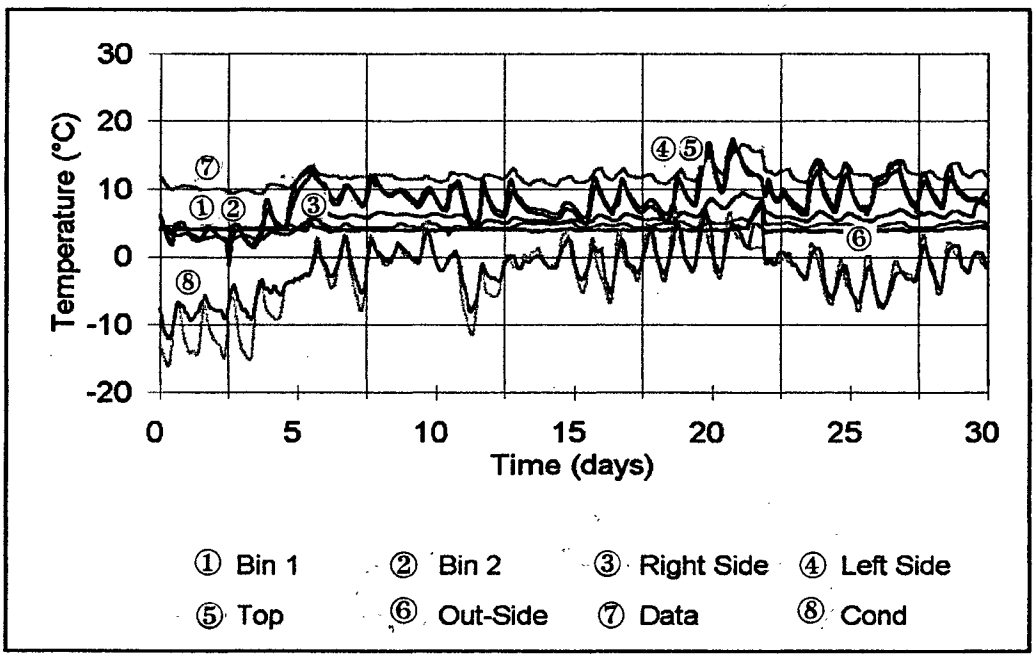

Figure A.3. Pile mean temperatures for the two bins and their surroundings during March, 2001.

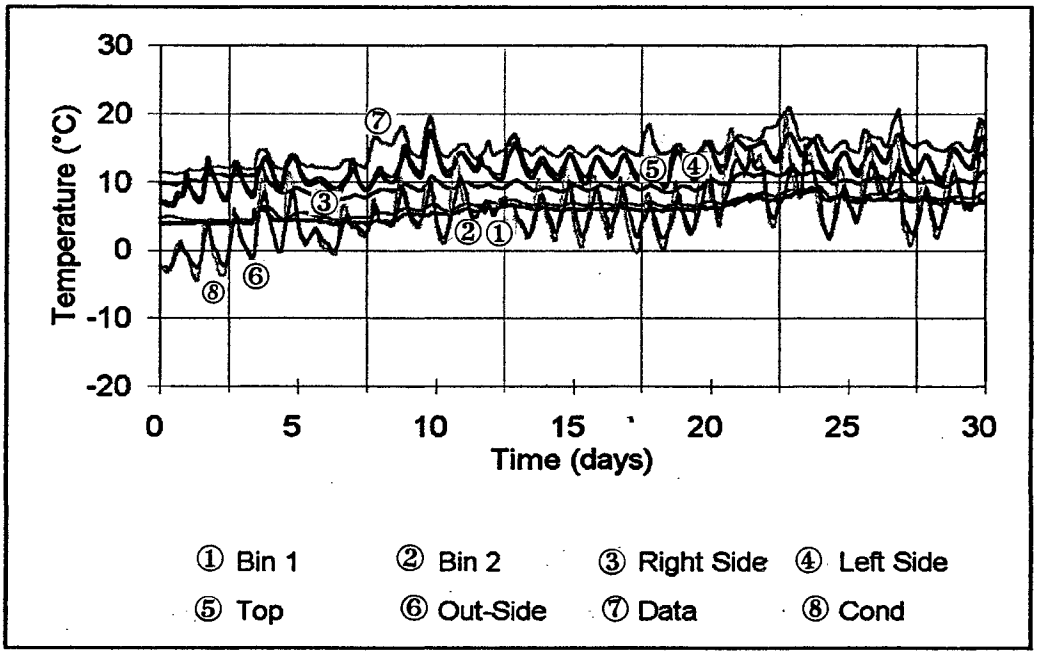

Figure A.4. Pile mean temperatures for the two bins and their surroundings during April, 2001.

APPENDIX B

Temperature of ventilation air entering and leaving the potato pile for bin 1 and bin 2.

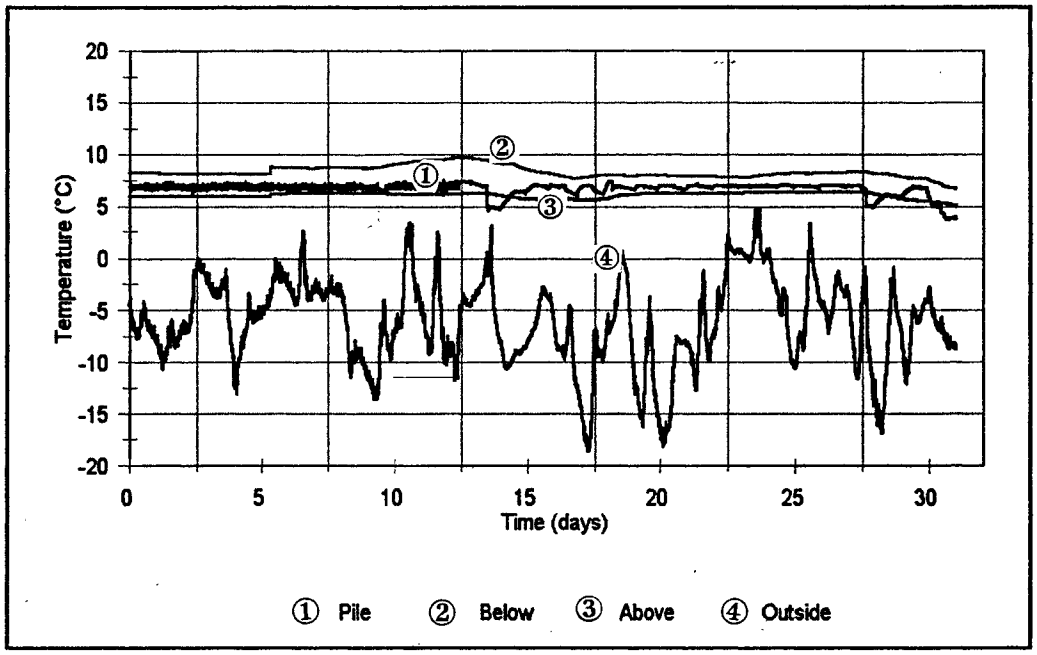

Figure A.5. Air temperature, measured at the ventilation duct (Below the pile), within the pile (Pile), at the head space (Above the pile) and outside air temperatures for Bin1 during January, 2001.

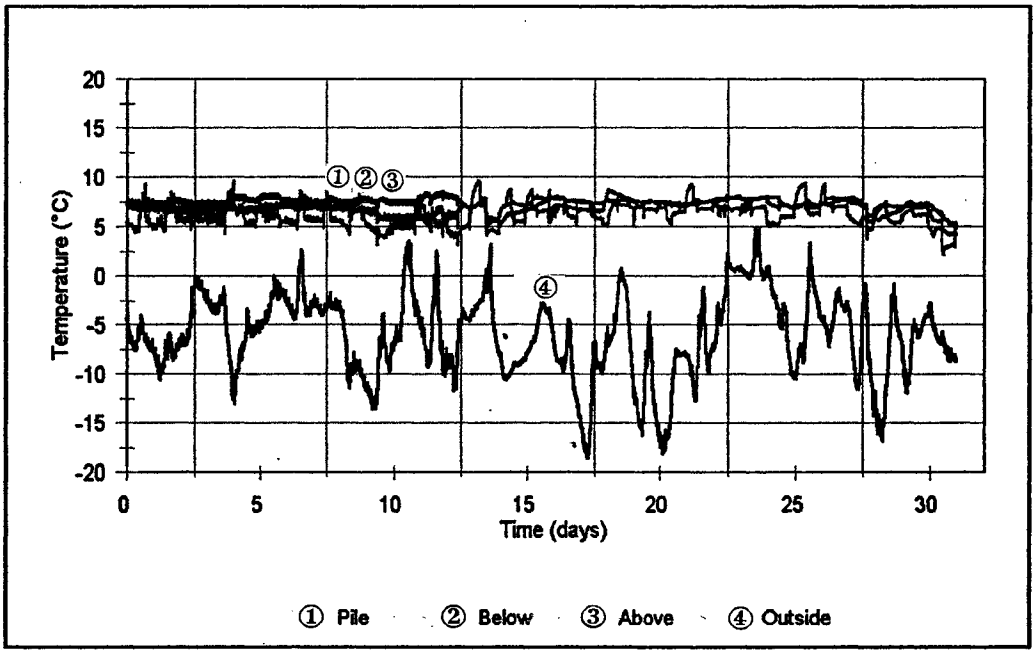

Figure A.6. Air temperature, measured at the ventilation duct (Below the pile), within the pile (Pile), at the head space (Above the pile) and outside air temperatures for Bin 2 during January, 2001.

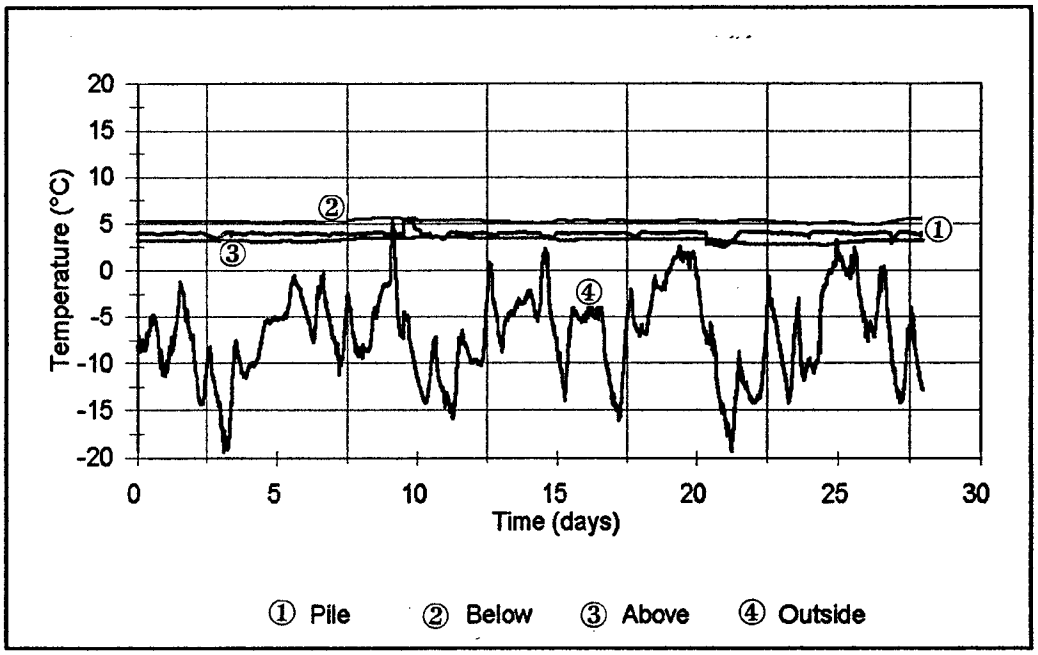

Figure A.7. Air temperature, measured at the ventilation duct (Below the pile), within the pile (Pile), at the head space (Above the pile) and outside air temperatures for Bin1 during February, 2001.

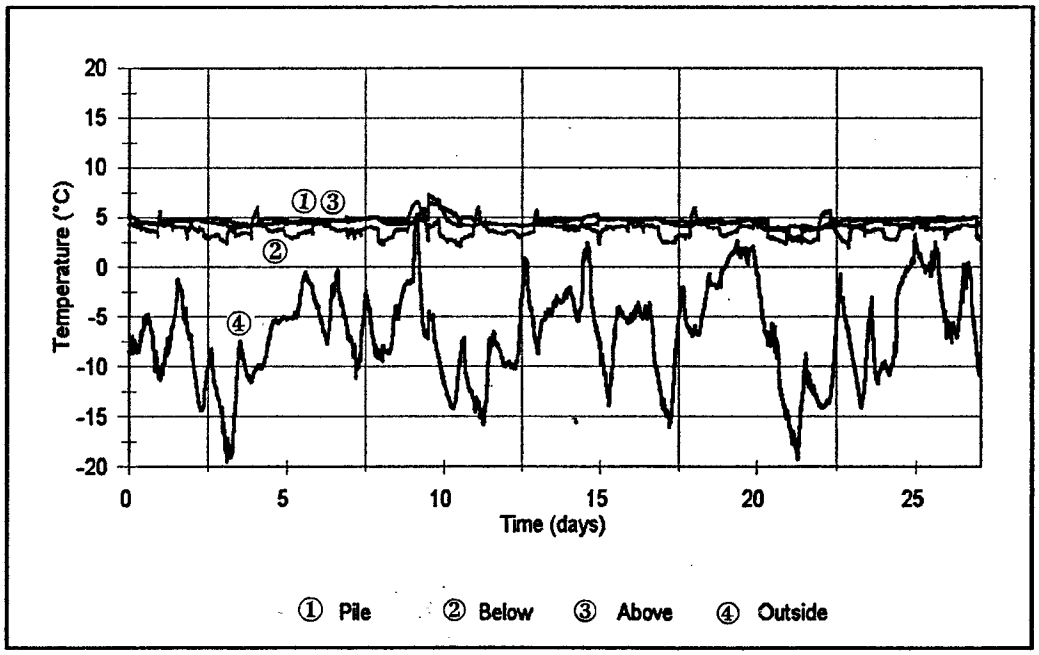

Figure A.8. Air temperature, measured at the ventilation duct (Below the pile), within the pile (Pile), at the head space (Above the pile) and outside air temperatures for Bin2 during February, 2001.

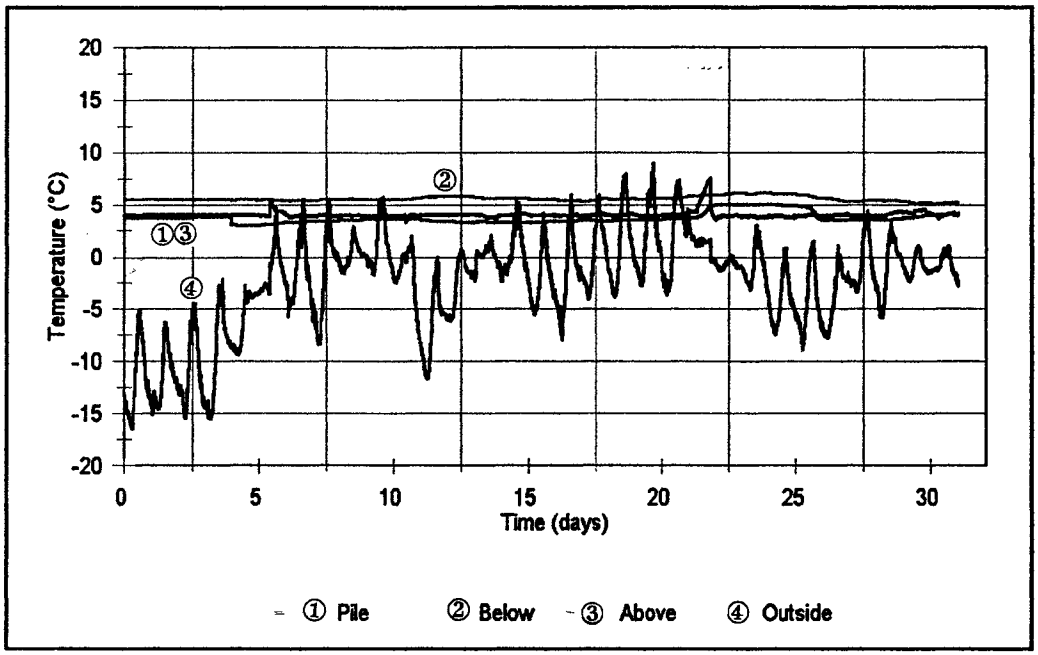

Figure A.9. Air temperature, measured at the ventilation duct (Below the pile), within the pile (Pile), at the head space (Above the pile) and outside air temperatures for Bin1 during March, 2001.

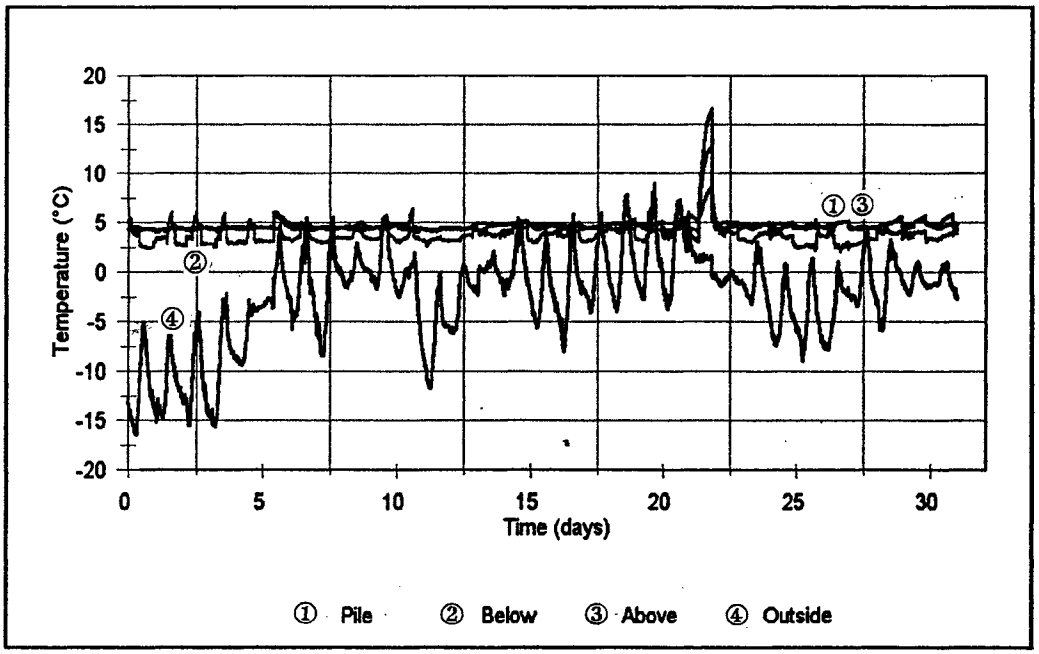

Figure A.10. Air temperature, measured at the ventilation duct (Below the pile), within the pile (Pile), at the head space (Above the pile) and outside air temperatures for Bin2 during March, 2001.

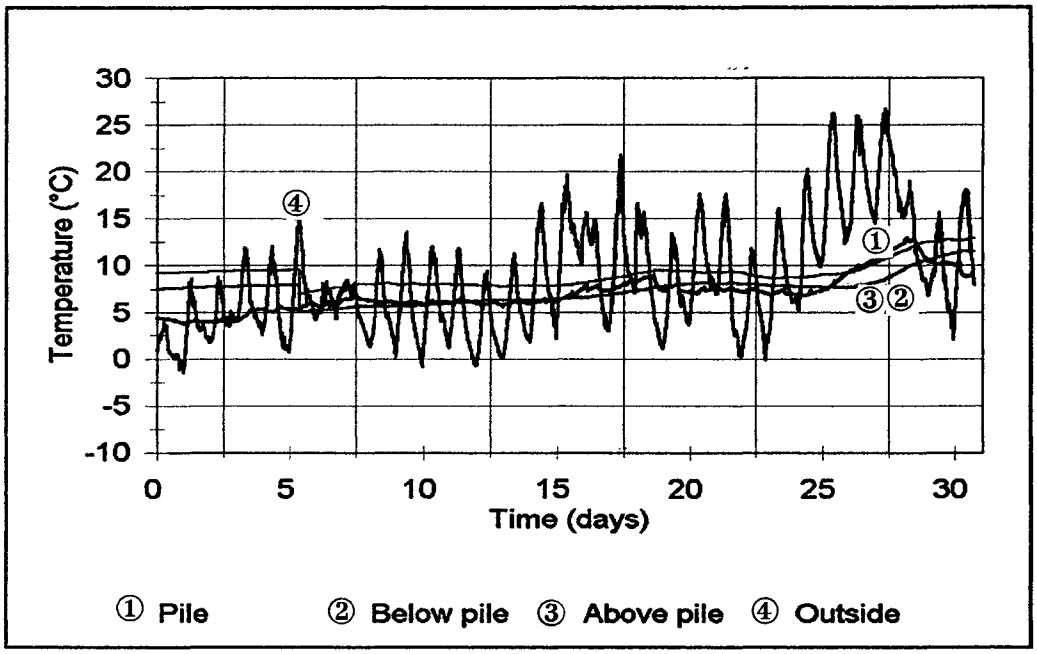

Figure A.11. Air temperature, measured at the ventilation duct (Below the pile), within the pile (Pile), at the head space (Above the pile) and outside air temperatures for Bin1 during April, 2001.

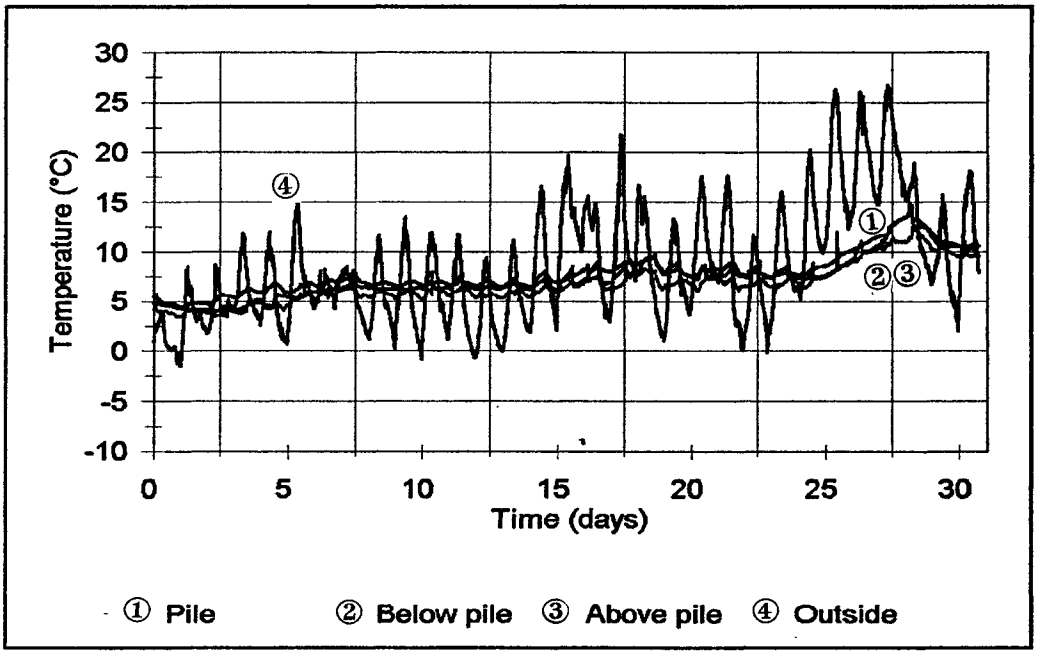

Figure A.12. Air temperature, measured at the ventilation duct (Below the pile), within the pile (Pile), at the head space (Above the pile) and outside air temperatures for Bin 2 during April, 2001.

APPENDIX C

Estimated heat produced by potatoes inside the two storage bins, obtained by applying heat and moisture balance on monthly data.

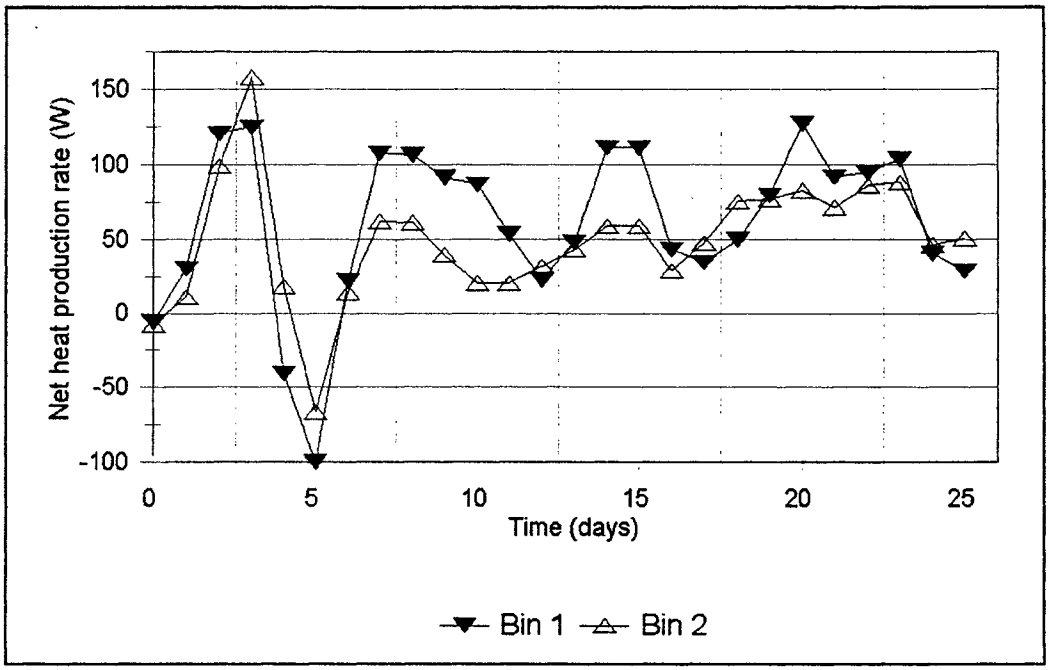

Figure A.13. Net heat produced by potatoes in the two storage bins in December, 2000.

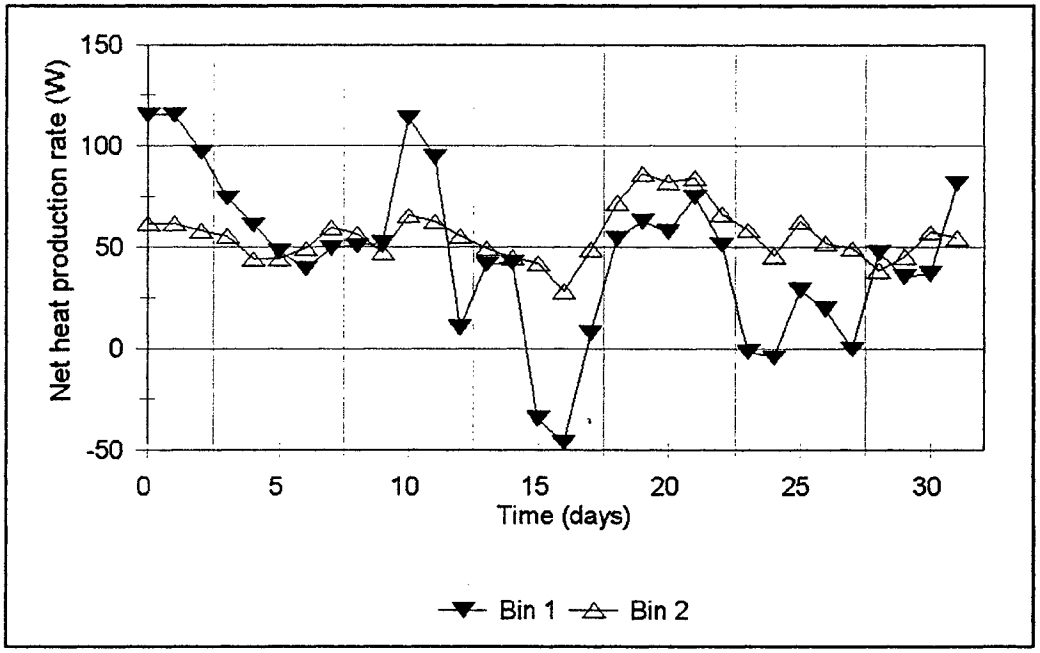

Figure A.14. Net heat produced by potatoes in the two storage bins during January, 2001.

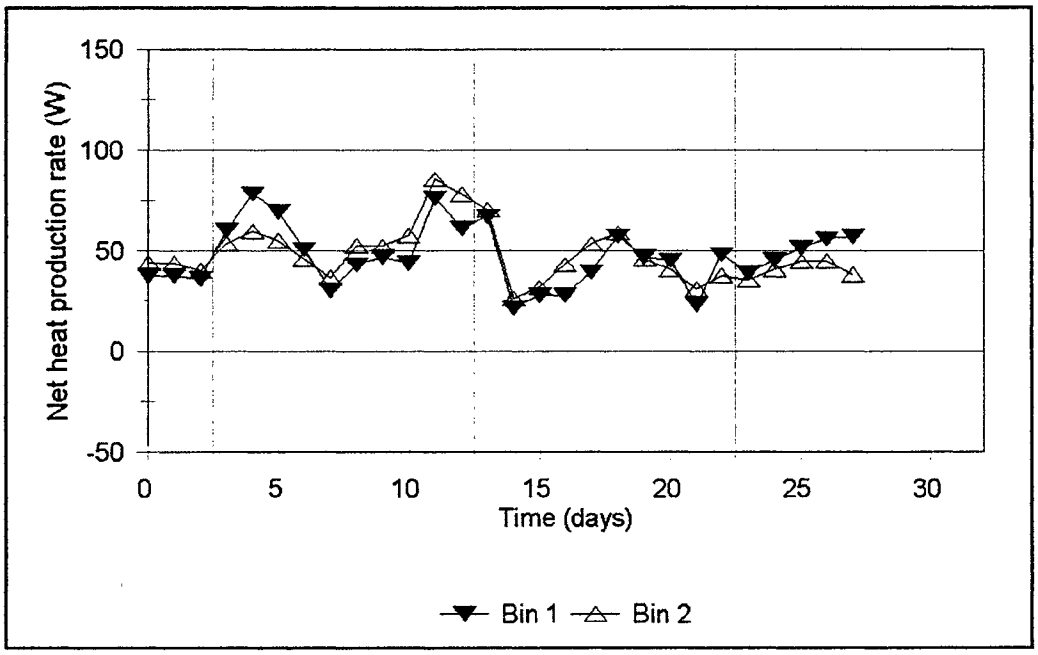

Figure A.15. Net heat rate produced by potatoes in the two storage bins during February, 2001.

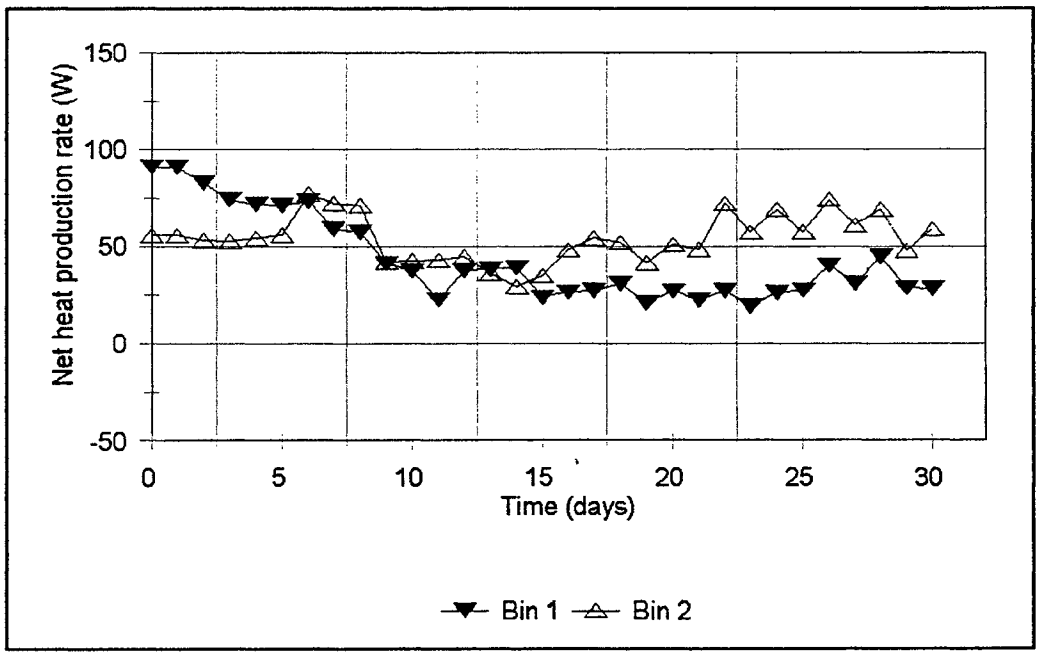

Figure A.16. Net heat rate produced by potatoes in the two storage bins during March, 2001.

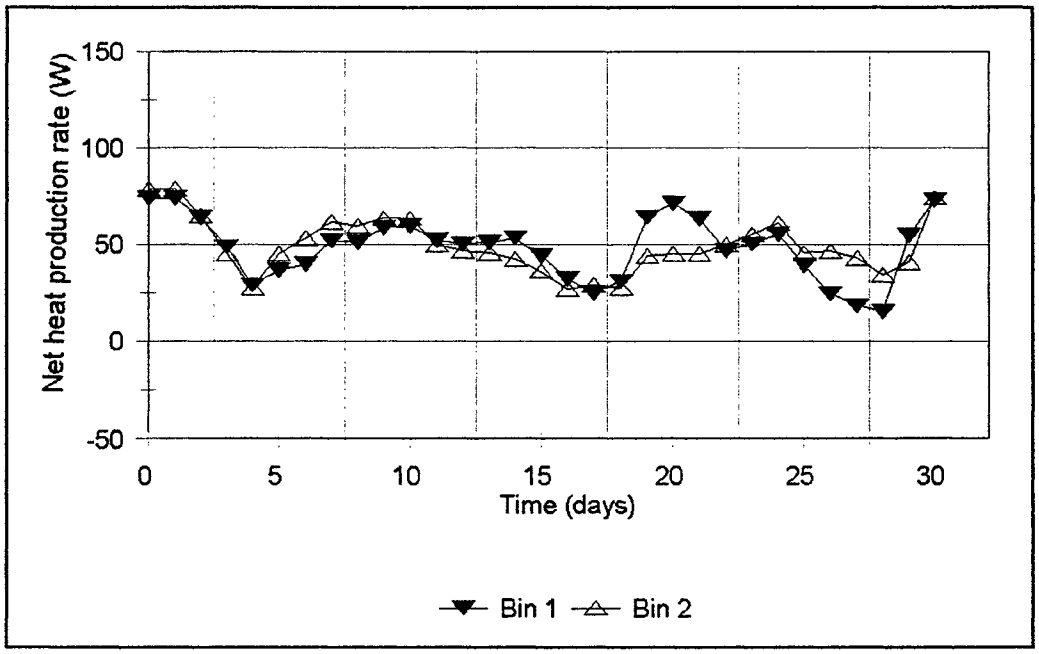

Figure A.17. Net heat rate produced by potatoes in the two storage bins in April, 2001.

APPENDIX D

Relative humidity measured inside the two bins during January, February, and March, 2001

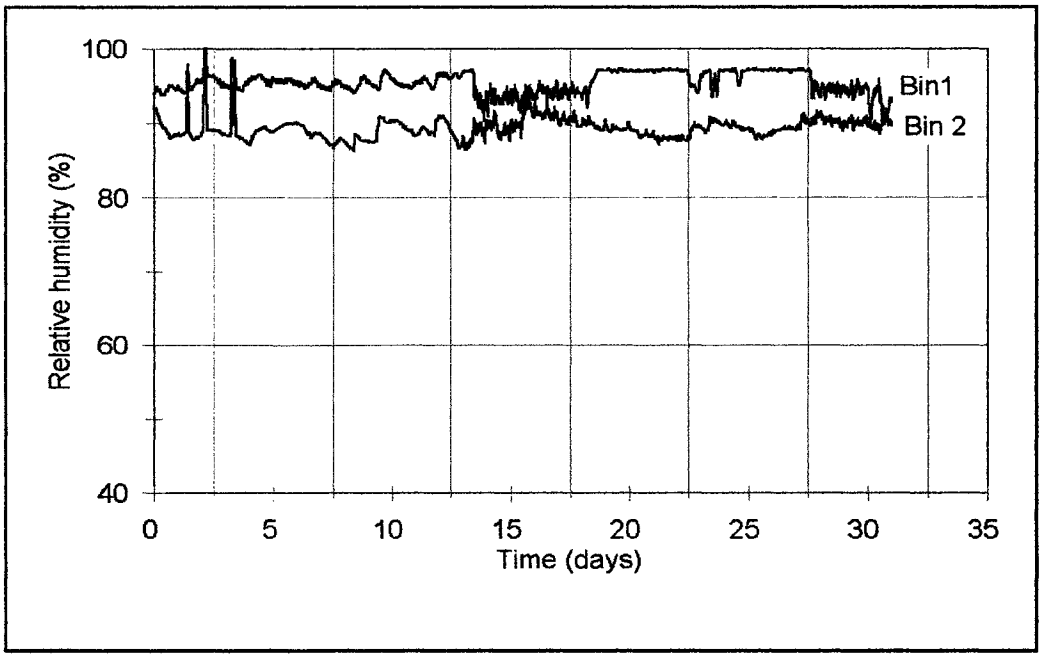

Figure A.18. Relative humidity inside the two bins during January, 2001

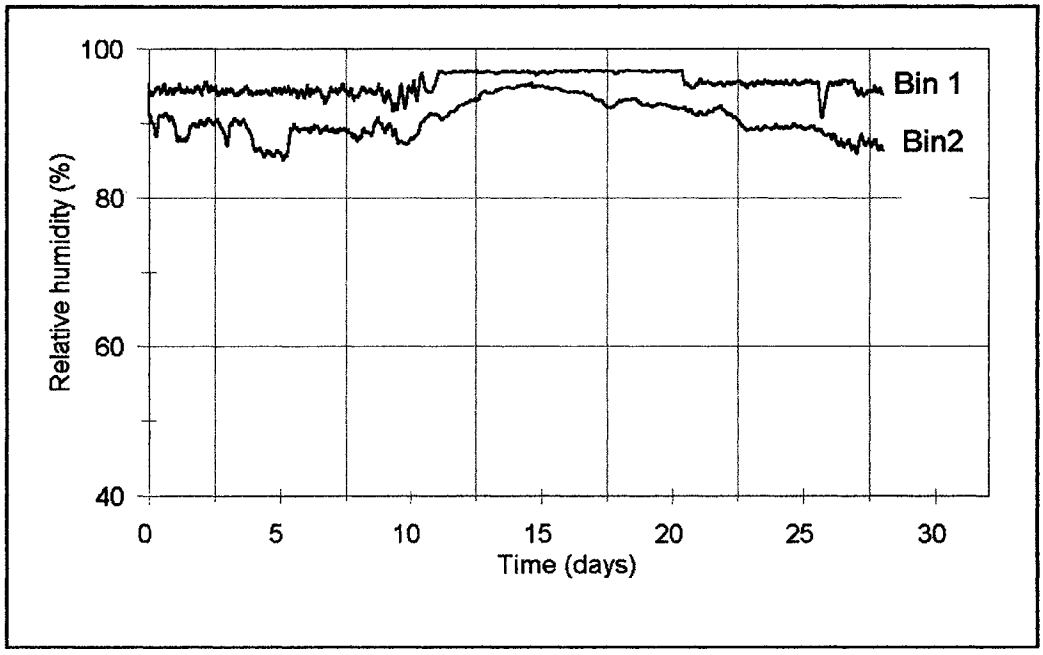

Figure A.19. Relative humidity inside the two bins during February, 2001

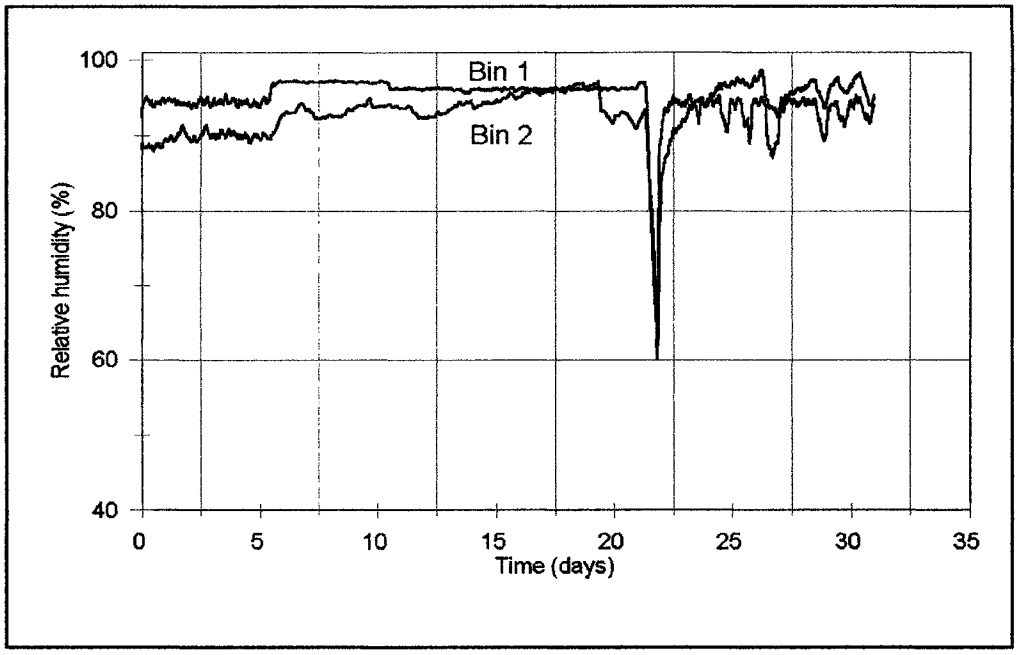

Figure A.20. Relative humidity inside the two bins during March, 2001