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Influence of Ventilation Rate on Potato
Quality Out of Storage

presented by

Todd D. Forbush

has been accepted towards fulfillment
of the requirements for

Master's degree in Ag. Eng.

Major professor

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Influence of Ventilation Rate on Potato Quality Out of Storage

By

Todd David Forbush

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Agricultural Engineering

1989

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ABSTRACT

INFLUENCE OF VENTILATION RATE ON
POTATO QUALITY OUT OF STORAGE

By

Todd D. Forbush

A potato storage research facility was constructed and instrumented to study the effects of varying the ventilation rate through the pile on the quality of stored potatoes. The facility consisted of three storage bins measuring 2.4 m square by 4.9 m deep. The ventilation systems were controlled using a FANCOM 1056 environmental control computer.

The three ventilation rates studied were 56 m^3/tonne-hr, 112 m^3/tonne-hr, and 168 m^3/tonne-hr. The study was conducted for three storage seasons 1986 - 1989. A variable speed fan capable of delivering from 0 - 112 m^3/tonne-hr was substituted for the 168 m^3/tonne-hr rate for the second and third storage seasons.

The results indicate that average weight loss within the bins was not a function of airflow rate. However, weight loss did vary vertically within the potato bins ventilated at the recommended ventilation rate for Michigan. The potatoes stored in the research bins attained an

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acceptable process color following storage durations of 115 to 142 days.

A finite difference temperature generation-weight loss simulation model (Lerew, 1978) was used to evaluate different management strategies for removing moisture from the surface of potato tubers. The simulation studies indicated that ventilating with high airflow rates (112 m^3/tonne-hr) and low inlet relative humidities (65%) will result in acceptable moisture removal with minimal weight loss.

A model was developed to predict the time required for pile temperature changes to be made. The model was used to study the effect of airflow rate and inlet conditions on the time required to cool the potato pile. The results of this study indicated that when cooling a potato pile in 0.5 ^{o}C increments, the cooling is primarily controlled by latent heat energy transfer.

It was concluded that the current ventilation recommendations are acceptable given the state of potato storage monitoring in Michigan. Advances in control and monitoring systems may lead to a reduction in ventilation requirements based on information collected during each storage season.

Dedicated To

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Many thanks also to the members of the guidance committee, Dr. John Gerrish and Dr. Arthur Cameron, for their contributions to this work.

Thanks also to the faculty and staff of the Agricultural Engineering department. Four friends deserve special recognition for their support throughout this project. These include; Dennis Welch, who often sacrificed even his personal vehicle to assure that the spuds were harvested, Dirk Maier, for his many suggestions and willingness to lend a helping hand, Keith Tinsey, who shared many hours on the road in "spud van" in deep discussion, and John Mills for his assistance in completing this work.

I would also like to express my greatest appreciation to my wife Kristen for the support given me, and for putting up with all the hours spent working on this and other projects.

Last, but not least, to my parents Marshall and Margret Forbush for their support and for giving me the perseverance to complete this work.

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1. Introduction

Potatoes were one of the first crops planted as the pioneers moved into the state of Michigan. Potato cultivation has grown from small scale production to its current status as an industry. In 1984, a total of 688,200 tonnes of potatoes were harvested from 23,085 ha of Michigan soil for an average yield of 29.8 tonnes/ha. This placed the state ninth in production among potato producing states in the United States. The production area for the United States was 541,364 ha in 1984, with an average yield of 30.4 tonnes/ha for a total production of 16.44 million tonnes. Potato utilization is outlined in Table 1.1.

Table 1.1 Utilization of the 1983 United States Potato Crop.*

Percent by Volume	Use
82.5 %	Human Consumption (32.6 % Fresh) (49.9 % Processed)
0.9 %	Starch, Flour
1.5 %	Animal Feed
7.6 %	Seed
7.4 %	Shrinkage & Loss

* Taken from National Potato Council's Potato Statistical Yearbook, 1983-84 (Anonymous, 1984).

Potatoes are harvested during all four seasons in the United States, with the majority of the annual crop harvested in the fall. The production distribution among these harvest periods is given in Table 1.2.

Table I

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Table 1.2 Distribution of Annual Potato Harvest by Season in the United States.*

Percent of Production	Harvest Season
0.7 %	Winter
5.9 %	Spring
5.8 %	Summer
87.6 %	Fall

* Taken from National Potato Council's Potato Statistical Yearbook, 1983-84 (Anonymous, 1984).

Table 1.2 indicates the importance of the storage of potatoes in the United States to maintain a uniform supply of potatoes for use throughout the year. It is estimated that 8.73 million tonnes or 53 % of the United States potato crop is held in storages across 15 states from October through the month of December, with 2.29 million tonnes or 13.9 % of the crop remaining in storage through May 1 (Anonymous, 1984). The necessity of maintaining high quality potatoes through a storage period of nine months is evident.

1.1 The Potato in Storage

The goal of potato storage is to maintain a near harvest-quality potato throughout the storage season. The potato storage is not a hospital; there can be no recovery for poor quality potatoes in going into the storage. The quality of potatoes from storage is directly proportional to the quality of the potato going into the storage. Factors such as potato maturity, bruising, disease, stress during the growing season, and foreign material content in the storage (dirt, vines, stones, etc.), all play a major role in determining the potato quality out of storage.

The definition of "quality" is based on the market for which the potato is destined. For table stock potatoes, it is critical that the potato maintain a smooth unscarred surface and a high percentage of its original internal moisture. These quality indices can be controlled by maintaining a storage environment that limits the water loss of the potato due to evaporation and respiration. For potato processors, a low reducing sugar content is necessary for acceptable process color. The reducing sugar content of the potato is a function of the variety, growing conditions, maturity at harvest, the storage environment and other factors which are not clearly understood. To avoid the build up of reducing sugars, a storage environment must be maintained that will inhibit the low temperature conversion of starch to sugar (Rastovski et. al., 1987), while enhancing the progression of tuber respiration to remove existing reducing sugars.

Adequate environmental control is important to maintain an acceptable level of potato quality throughout storage. Ventilation air is the means of controlling the potato storage environment. The adequacy of the environmental control is directly dependent on the performance of the ventilation system.

1.2 Potato Storage Ventilation Systems

Systems used for the ventilation of potato storages have evolved regionally throughout the world since the introduction of through-the-pile ventilation. At the International Potato Storage Symposium held at Michigan State University in 1985, ventilation recommendations ranged from 22 m^3/hr-tonne for the Eastern Oregon and Idaho regions of the United States (Waelti, 1989) to 150 m^3/hr-tonne for several Western European countries including The Netherlands (Hesen et. al. , 1989), Hungary (Horvath, 1989), and West Germany (Leppack, 1989). The reasons for these variations include local climate, market requirements, and condition of potatoes going into the storage. Hesen (1989) states that 'the shorter the duration of favorable outside air temperature, the higher the ventilation rate required'. He argued that the high ventilation rates 'make it possible to keep potatoes at the mean minimum temperature of (the) outside ambient (temperature)'. But he also stated that 'in modern storages, lower ventilation rates could be used, but the storage managers are reluctant to change .. '. Horvath (1989) agreed with Hesen stating that 'just after harvesting, highly humid cool air, suitable for the uniform drying and cooling of potatoes, is available during limited periods .... therefore the ventilation systems are designed with the highest reasonable ventilation performance.'

In response to the many questions that were raised during International Symposium, this study has evolved as an attempt to justify or verify the current recommendations and practices in ventilation system design in Michigan.

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2.0 Objectives

The goal of this study is to determine the effect of different rates of through-the-pile ventilation on potato quality from potato storages in Michigan, justify the current ventilation recommendations for Michigan, and determine a probable cause for the differing ventilation recommendations found elsewhere. The following set of individual objectives were established to attain the goal of this study:

1) Construct an on-farm storage research facility which would accurately control and monitor the potato storage environment with different air flow rates.

2) Modify an existing potato storage temperature and weight loss model (Lerew, 1978) and compare its predicted results with the experimental results.

3) Evaluate management strategies for removing moisture from and cooling potatoes stored in bulk piles with the simulation models.

3. Literature Review

3.1 Managing The Potato Storage Environment

The storage environment is the key to the success of potato storage as it directly affects the market quality of stored potatoes. Three aspects of the storage environment that are important to the quality of potatoes are the storage temperature, ventilation air relative humidity, and oxygen/carbon dioxide levels within the storage. The management of the potato storage depends on the quality of the crop that will be placed into the storage bin. The following sections outline storage management for mature potatoes grown and harvested under ideal conditions, these procedures are based on conversations with potato growers in Michigan. Three terms require definition:

1) Mature potatoes - Potatoes with good skin set harvested from potato plants with dead vines.
2) Ideal growing conditions - No excessive stress on the tubers, ie. moisture, nutrient, heat, or mechanical.
3) Ideal harvest conditions - soil temperatures between 10 and 18 ^{o}C with moisture content below field capacity.

3.1.1 Equalization and Drying Phase

The pulp temperature of potatoes harvested under ideal conditions should be between 10 and 18 ^{o}C. The tuber pulp temperature often ranges 5 C^{o} or more throughout a bin of freshly harvested potatoes due to time of harvest ar

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and soil temperatures. The equalization and drying phase takes place immediately after placing the potatoes in storage to allow pile temperature to equalize. The equalization and drying phase is also required to dry any surface moisture from the potatoes. Traditional management schemes would suggest that the main ventilation fan should run continuously during this phase. The average potato pile temperature should equalize within 2 ^{o}C of the potato pulp temperature upon entry into storage. The completion of the equalization and drying phase is indicated by a dry pile of potatoes with a uniform pile temperature. The equalization and drying phase may take up to one week or may not be required at all if the potatoes are harvested from uniform soil under ideal harvest conditions.

3.1.2 Wound Healing Phase

The wound healing phase is initiated upon the completion of the equalization phase. The purpose of wound healing is to allow the tubers to heal wounds from harvesting and handling that occurred prior to storage. Pisarczyk (1982) reported that suberization or wound healing is vitally important to the success of extended storage. The potato pile temperature is generally allowed to seek its own level in the range of 15 to 18 ^{o}C as long as temperatures of 21 ^{o}C are not exceeded (Schaper et. al. 1989; Cargill et. al. 1989). The relative humidity should be in the 95 to 100% range, with some producers advocating that condensation must form on the surfaces within the po

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potato storage, or the potato bin must "sweat" for good suberization.

Varns et. al. (1986) reported that the process of allowing the potatoes to "go through a sweat" was conducive to high carbon dioxide build up within the potato pile. Carbon dioxide levels in excess of 6% were measured in a commercial potato storage facility in North Dakota. It has also been noted that high levels of carbon dioxide, above 1% for some varieties (Cameron, 1988), inhibit the formation of the wax or suberin layer in potatoes. Wax (suberin) layers prohibit the entry of pathogens which will damage and limit the storage potential of potatoes.

Fan operation recommendations vary during suberization from continuous ventilation at low rates (Sparks et. al., 1968) to fan operation in the evenings only to assure no CO_2 build up occurs (Schaper et. al., 1989). Cargill et. al. (1989) recommended that ventilation fans should be run at least eight hours a day in two four hour intervals to maintain acceptable temperatures and reduce the concentration of carbon dioxide generated by potato respiration. The common industry practice in Michigan is to run ventilation fans continuously at a rate of 56 m^3/tonne-hr to minimize carbon dioxide accumulation, while maintaining a uniform pile temperature.

3.1.3 Pre-Conditioning Phase

The pre-conditioning phase of storage has been commercially adapted due mostly to the unpredictable nature of reconditioning process varieties that have been stored at temperatures in the 8 to 10 C range following suberization. Schaper et. al. (1989) indicated that inadequacies exist in reconditioning with the statement that "certain lots of potatoes do not recondition to the desired color, while those that do will not stay in the desired condition for an indefinite period of time."

The concept of pre-conditioning was defined by Singh (1974) as the holding of potatoes at 18 ^{o}C for six weeks prior to long term storage at low temperatures. The purpose of pre-conditioning is to eliminate pools of reducing sugars prior to low temperature storage. The current industry practice for pre-conditioning is to maintain the storage environment similar to the suberization phase. The main difference being that the potato pile temperature is actively controlled around the 16 ^{o}C level. At this temperature, the respiration rate of potatoes is sufficient to respire or "burn" away existing reducing and non-reducing sugar accumulated within tubers.

The duration of the pre-conditioning phase is dependent on the process color of the potatoes, as determined by sugar content. Potatoes harvested in an immature state may take months to condition, and may never process adequately. Preco

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conditioning is complete when desirable process color is attained.

3.1.4 Cooling Phase

The rate of cooling is dictated by the ambient conditions if refrigeration is not available. Time periods when cooling air is available generally exist only in the night in many potato producing regions; a time when manual control is difficult (Hesen et. al., 1989; Thornton, 1989). For this reason, it is critical to have a control system that is capable of introducing cool fresh air into the storage any time that it is available.

The nature of the cooling process is dependent on the desired market for the potato. A table stock or seed potato producer is interested in reducing weight loss and soft rot, which may dictate a quick cooling phase to the temperature range of 5 ^{o}C. Process potato producers must be concerned with the reducing sugar content of the potatoes, which may be controlled by slower cooling practices. A maximum cooling rate of 3 ^{o}C per week for a processing potato storage is recommended by Cargill et. al. (1989) to reduce temperature stress and avoid reducing sugar build up. Other process storage recommendations (Tolsma, 1988) suggest cooling at a rate as fast as possible to 10 ^{o}C, then slow cooling if desired below this temperature.

3.1.5 Holding Phase

Once the potatoes are cooled to the proper holding temperature, the amount of ventilation is reduced to a minimum level capable of maintain a uniform pile temperature within 0.5 ^{O}C (Cargill et. al., 1989) of the desired level. A fine level of temperature control is necessary to maintain the required process color as storage managers lower the average pile temperature near the critical level for the variety being stored. A uniform pile temperature also helps maintain a uniform product throughout the storage season, which increases the value of the crop at the market place.

3.1.6 Reconditioning Phase

Reconditioning is the practice of warming the potatoes from the holding temperature to obtain desirable process color and reduce the handling damage that occurs while unloading the storage. During reconditioning, the potatoes are slowly warmed by either allowing generated heat to remain within the storage, or through the use of heaters. Ventilation air with a low relative humidity is generally recommended to reduce the possibility of moisture condensing on the cool tubers as warming occurs (Schaper et. al., 1989). The unpredictable nature of the reconditioning of process potatoes was previously stated.

3.2 Weight Loss During Storage

The potato industry suffers large losses each year due to weight loss throughout the storage season. It is estimated that shrinkage and loss figures for the potato crop in the United States has ranged from 6 to 10% annually over the past decade (Anonymous, 1984).

Yeager (1977) studied the effect of potato pile pressure and storage environment relative humidity on weight loss of potatoes stored for a six month period. The work was done with small lots of potatoes stored in boxes measuring 0.03 m^3. A spring system was developed which placed pressure on the potatoes similar to the pressure experienced within a pile of potatoes. Yeager concluded that the relative humidity of the storage environment was the most important parameter studied. He also reported that pile pressure may affect weight loss.

Villa (1973) developed a semi-theoretical mathematical model for predicting moisture losses from horticultural products in storage. The model included an estimate of the skin permeability and surface area of potatoes (cv. Monona). Villa concluded that there was a correlation between the velocity of the ventilation air and the moisture lost, but the effect was slight; doubling the airflow rate resulted in an increase in predicted moisture loss of only 15%.

A comprehensive study of weight loss and respiration rates of small lots of potato tubers was conducted by Hunter (1985). The conclusion of Hunter's work was that the weight lo

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loss is a function of potato variety, preharvest treatment, curing regimen, storage temperature and vapor pressure deficit. Hunter also concluded that if ventilation is performed with high relative humidity air, weight loss may be correlated to tuber respiration rate.

3.3 Potato Quality Requirements

The definition of the potato quality from storage is determined by the end user of the product. Gould (1988) defined a series of quality parameters which are of importance to the processing industry. These include the shape of the tubers, external defects such as bruises or sprouts present, specific gravity of the tubers, and the process color as evaluated with color charts or an Agtron colorimeter.

The color of the finished product is affected by the concentration of reducing sugars (glucose and fructose) present in the tuber upon processing. The potato tuber is a living organism which has a solids content primarily made up of starches (Rostovski, 1987). Starch within the potato is converted to sucrose, a twelve carbon disaccharide which is broken down enzymatically into the reducing sugars glucose and fructose. These reducing sugars are then consumed in the respiration process of the tuber throughout the storage season for the generation of energy.

The size of the free sugar pools within the tuber is determined by the cultivar, maturity at harvest, and temperature of storage. Sowokinos (1987) proposed a

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Chemical Maturity Monitoring (CMM) technique to determine the chemical maturity of the tubers upon harvest. CMM utilizes sugar analysis methodology to evaluate the tuber flesh and determine the potential of the tuber to obtain acceptable sugar levels after harvest. Sowokinos found that if potatoes (cv. Norchip) had a Sucrose Rating below 1.0, and a glucose percentage below 0.035 %, then the potatoes could survive long term storage and still produce potato chips with acceptable process color upon removal from long term storage.

3.4 Potato Storage Ventilation Recommendations

An international meeting of potato storage researchers took place at Michigan State University in 1985 to discuss the practices and recommendations employed for the storage of potatoes throughout the world. Table 3.1 lists the ventilation rate recommendations for the different potato production regions represented.

The rationale given for the recommendations in Table 3.1 centered around the drying and cooling process which take place during the initial phases of storage.

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Table 3.1. Ventilation Rate Recommendations for Different Potato Production Regions throughout the World.

Ventilation Rate m^3/tonne-hr	Production Region	Reference	
72-108	Great Britain	Statham	(1989)
100-150	West Germany	Leppack	(1989)
64- 92	Belgium	Hesen	(1989)
100-150	The Netherlands	Hesen	(1989)
120-150	Hungary	Horvath	(1989)
69- 83	Poland	Karwowski	(1989)
50-100	Denmark,Norway Finland	Rasmussen	(1989)
24- 72	Japan	Wada	(1989)
	United States		
19- 32	Northwest	Thornton	(1989)
26- 56	Red River Valley	Schaper	(1989)
38- 56	Michigan	Cargill	(1989)
22- 50	Northeast	Hunter	(1989)

3.5 Potato Storage Ventilation Modeling

The evolution of the digital computer has advanced the area of mathematical modeling and simulation of physical events. Prior to the computer age, the determination of cause-and-effect relationships was limited to time consuming experimental procedures. In the field of agriculture, where experimentation is restricted to a seasonal exercise, the practices of mathematical modeling and simulation are especially valuable tools. Models allow researchers to evaluate theories throughout the year, thus minimizing the amount of experimentation required.

Misner (1973) developed a simulation routine to model the cooling of potatoes. The model used the set of differential equations for simultaneous heat and mass transfer developed by Bakker-Arkema et. al. (1967). A finite difference approach to computing the potato and ventilation air parameters during cooling was applied. An attempt was made to determine the optimum ventilation rate based on a cost analysis which included the cost of the fan, the cost of fan operation, and economic losses due to product moisture loss. Misner concluded that an economically feasible range for the ventilation rate would be from 69 to 97 m^3/tonne-hr, based on a bulk density of 1085 kg/m^3 of potatoes, and a pile depth of 4 m.

Lerew (1978) investigated different ventilation management practices and control procedures utilizing much the same approach as Misner. Lerew that control of the ventilation system designed to ventilate only when excessive temperature build-up had occurred, resulted in a lower weight loss than did other ventilation control strategies.

Ofoli (1984) approached the problem of optimizing potato storage ventilation rates by attempting to minimize entropy production during ventilation. The conclusion of this work was that the dominant parameter in entropy production in the ventilation of potato storages is the velocity of airflow over the tubers. The optimum ventilation rate with respect to entropy production arrived at by Ofoli was in the range of 35 to 40 m^3/tonne-hr, based on a pile depth of 4 m and a bulk density of 1085 kg/m^3.

4.0 Methods and Materials

4.1 Storage Research Facility Construction

The criteria proposed for the storage research facility was to allow the study of potato storage utilizing various ventilation rates under simulated commercial storage conditions. Three bins were constructed each measuring 2.4 X 2.4 X 5.5 m high. This allowed medium scale research on 16 to 18 tonnes of potatoes, which is the approximate yield from 0.4 ha of land. The bins utilized panel construction methods to facilitate the complete removal from the commercial bin in which they were located after completion of the storage season. The Simulated Storage research facility was located within a commercial storage bin at Sandyland Farms, Howard City, MI. Figure 4.1 gives an overview of the Simulated Storage research facility.

4.2 Ventilation System Design

The ventilation systems of the simulated storages were designed with independent fans, intakes, and distribution duct systems. Half-round ducts were used to distribute air under the pile, as is done in commercial potato storages. Proportionally controlled louvers were used to mix fresh air with recirculated air for temperature control. Each system was supplied with a humidifier to maintain adequate inlet relative humidity. Figure 4.2 illustrates the ventilation systems of the simulated storage research bins.

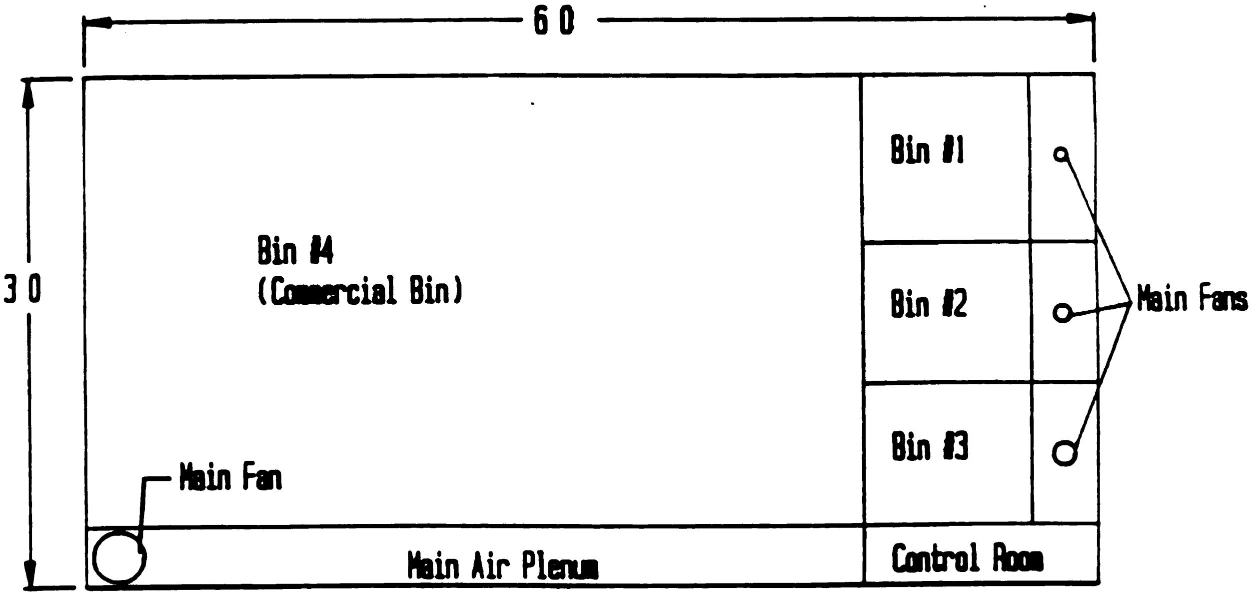

Figure 4.1 Overview of the Simulated Storage Facility.

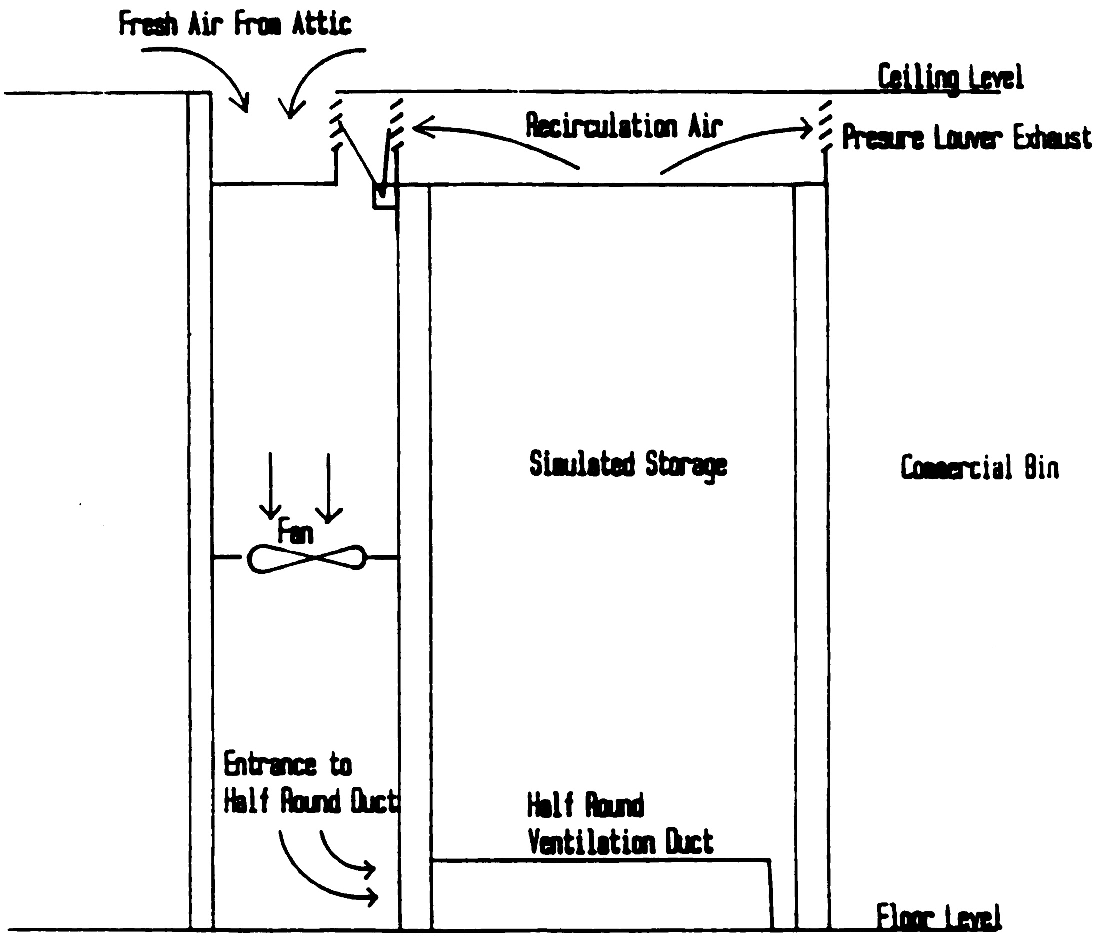

Figure 4.2 Detail of Ventilation System for the Simulated Storage Bins.

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Ventilation rates of 56, 112 and 168 m^3/hr-tonne were selected as 1 X, 2 X, and 3 X the recommend ventilation rate for the state of Michigan. The ventilation systems were designed using the criteria outlined by Cargill et. al. (1986). The mean air velocities within the system were maintained below 2.5 m/s with a slot velocity of 4.7 m/s. The slot velocity of all three ventilation systems were approximately equal to assure similarity in the flow of air through the pile.

The ventilation system delivering 168 m^3/hr-tonne was modified after the first storage season by the substitution of a variable-speed-fan. This system was designed to deliver ventilation air at a rate that varied from 0 - 112 m^3/hr/tonne, depending on the required ventilation demanded by the control system. The slot was designed to deliver air at 4.7 m/s at a ventilation rate of 56.1 m^3/tonne-hr.

4.3 Research Potato Samples

The Simulated Storage facility was first filled with potatoes in 1986 with commercially grown potatoes (cv. Atlantic). Atlantic is a round white variety that was developed as a high specific gravity variety suited for the potato chip industry. Ten tubers were collected from a randomly selected potato hill within each of five regions in the field each week beginning prior to vine kill and continuing through harvest. Four sample bags (approx. 11 kg) were placed with the potato pile at each of three levels

1.2, 2.4, and 3.6 m from the floor within the simulated storages.

In 1987, sampling tubes constructed of 20 cm diameter PVC pipe were inserted through the side wall of each Simulated Storage at levels of 0.9, 1.8, and 2.7 m from the floor. These tubes extended 0.6 m into the pile, and allowed for the collection of samples to evaluate potato conditions within the potato pile throughout the storage season.

4.4 Environmental Control

The ventilation system was controlled using a FANCOM 1056 environmental control computer developed in The Netherlands by FANCOM B.V. (commercially available at Techmark Inc., Lansing, MI).[1] The 1056 is a micro-processor based controller capable of controlling the ventilation rate (variable and fixed speed fan), the fresh and recirculation air volume, and the heating, cooling, and humidifying devices. The Fancom 1056 uses a decentralized control theory, which required that each storage bin be controlled independently. The advantage of decentralized control is the reduced risk of loss in the event of controller failure.

The Fancom controller uses a multiple input, single output control procedure to operate the fan, louvers, heater, and humidifier. This control allows the user to specify the "influence" different storage parameters have on

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[1]The mention of commercial products is for clarification and does not constitute endorsement of such products by Michigan State University or The United States Government.

the control of the ventilation devices. For example, the air circulation is determined by the pile temperature differential and the amount of fresh air required. The amount of fresh air required is determined by the pile temperature, main air temperature, outside air temperature, and the CO_2 content of the air in the storage. Thus, the fan operation is influenced either directly or indirectly by five environmental parameters measured by the computer. The computer determines the amount of air circulation required for each of the influences, then controls the fan to supply the largest requirement for air circulation. Adjustments are made with other ventilation equipment to accommodate further requirements.

The performance of the 1056 was evaluated after the 1986-87 storage season, and program modifications were made by the programmers at FANCOM B.V. The following changes were made for the 1987-88 storage season: 1) an increase in pile temperature sensor resolution from 0.5 ^{o}C to 0.1 ^{o}C; 2) additional aspirated psychrometers were placed above the potato pile to measure the air conditions; 3) three additional gas sampling tubes were placed within the potato pile; and 4) air volume sensors were added to determine the amount of fresh and recirculation air used. The air volume sensors consisted of 30 cm diameter fans mounted in the fresh and recirculation air inlets. The fan rotated at a speed proportional to the volume of air that was drawn through it. A hot wire anemometer (Solomat model 556C) was

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used to measure the velocity of the air through the opening, which was converted to a volume reading for the calibration of the air volume sensors.

4.4.1 Sensor Placement

The control computer allowed sampling of 16 analog and 8 digital inputs, while utilizing 16 relay and 2 analog outputs for control purposes. Information on the condition of the air within the potato pile was collected from four pile temperature sensors and four sampling tubes (1987 modification) for carbon dioxide and oxygen analysis. Both the temperature sensors and the gas sampling tubes were placed at 0.9, 1.8, 2.7, and 3.6 m from the floor of the storage in the center of each simulated storage. Wet bulb and dry bulb air temperatures were collected before the air entered the potato pile, and as the air exited the pile (1987 modification). The computer used this information to calculate and report the absolute and relative humidity of the air. Temperature sensors were also placed at the fresh air intake and in the mixing chamber to report air conditions. Figure 4.3 is a detailed illustration of the sensor placement in each simulated storage.

The temperatures were measured using Nickel-100 sensors calibrated to have a resolution of either 0.5 or 0.1 ^{o}C depending on the temperature measured. Aspirated psychrometers using Nickel-100 temperature sensors were used

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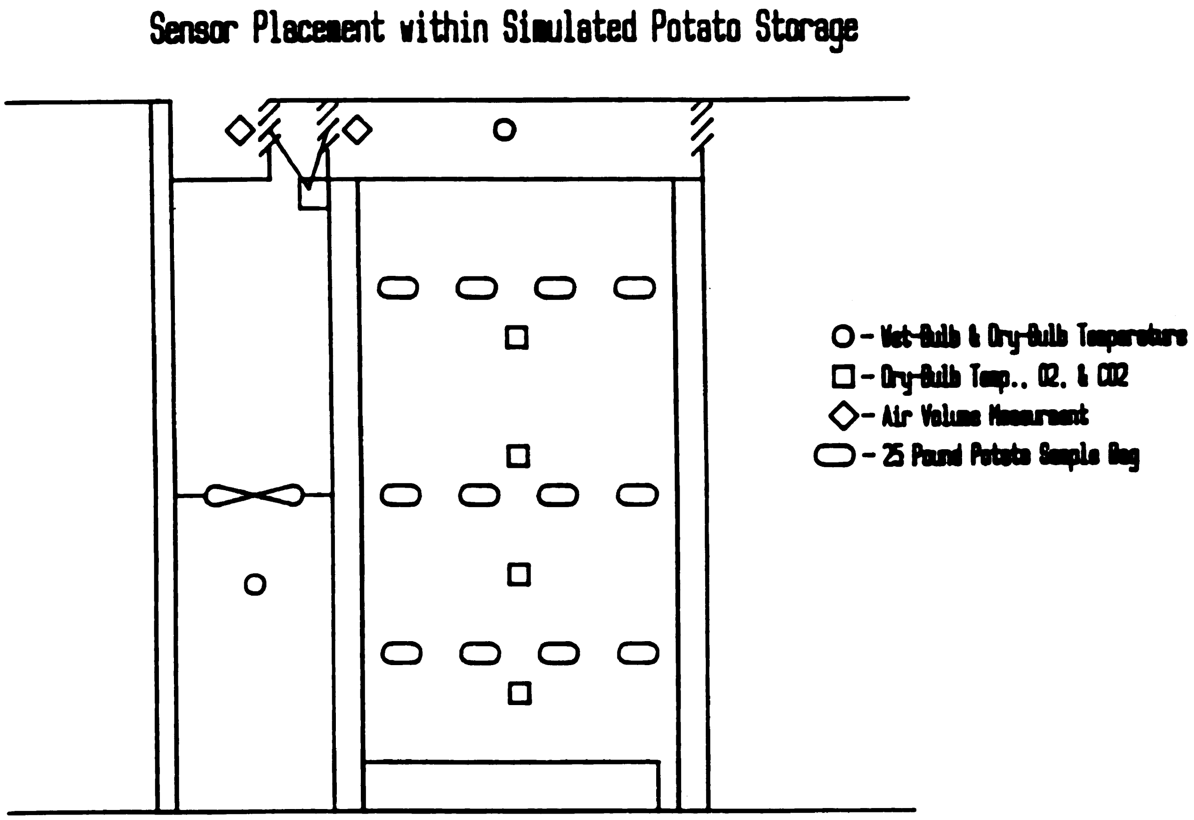

Figure 4.3 Detail of Sensor Placement within the Simulated Storage Research Bins.

for humidity measurement. A software multiplexing system within the control computer routed the gas samples from the potato pile through the analysis equipment. The carbon dioxide analysis was performed with a Siemens model ZFPCS infrared gas analyzer. The oxygen sensing unit was a Phillips model PW9612 analyzer.

4.4.2 Ventilation Fan Control

As previously stated the operation of the main ventilation fan may be influenced by up to five different environmental factors. The factors that influenced fan control in this research project were the pile temperature differential and fresh air requirement. The air circulation was adjusted by the computer when the largest differential between any two pile temperature sensors exceeded 0.5 ^{o}C to assure that a uniform pile temperature was maintained. The amount of ventilation due to a pile temperature differential in excess of 0.5 ^{o}C was based on the "influence" of a pile temperature differential on air circulation. An example of the required air circulation calculation is given below:

Highest Pile Temperature	11.5 ^{o}C
Lowest Pile Temperature	10.0 ^{o}C
Allowable Difference	0.5 ^{o}C
Pile Differential Influence	100.0 %

Air Circulation = ((11.5 - 10 - 0.5) * 1.0) * 10 = 10 %

The computer adjusts the circulation to 10 % of maximum if a variable speed is in use, or turns on a single speed fan.

4.4.3 Fresh Air and Relative Humidity Control

The amount of fresh and recirculation air was proportionally controlled by the FANCOM computer through a single Honeywell model M945B1057 actuator motor in each storage. In the 1986-87 storage season a potentiometer feedback was used to report the actual louver position to the computer. This feedback system was replaced with an air volume measurement system in the 1987-88 storage season to assure that the correct mixture of fresh and recirculation air was used.

Fresh air and a heater were used by the computer to maintain the main air plenum temperature within a specified range. If the temperature of the plenum varied from this range, the ventilation fan was turned on and the fresh air louver was adjusted by sending a low voltage pulse to the actuator motor for a set pulse time. After a pulse repeat time had elapsed, the temperature requirements were re-evaluated, and additional control commands were made by the computer. The minimum pulse and pulse repeat times used for this research were 0.2 and 16 seconds respectively. The pulse time was automatically adjusted above the minimum pulse time by the computer based on the differential between the desired and measured air volume position.

A relative humidity measurement of the air as it entered the potato pile was used for relative humidity control. A wheel type humidifier capable of applying three gallons of water in 24 hours was used to increase the relativ

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relative humidity of the inlet air to the desired range. If the humidity was below the desired level, a relay energized the humidifier. The setpoint for the relative humidity for this research was 92% for the 1986-87 season, and 95% for the 1987-88 and 1988-89 seasons.

4.4.4 Computer Influences and Setpoints

The 1056 is a flexible control computer. The influences and setpoints used in this research are listed in Table 4.1. This information was determined through the advice of control experts from Fancom B.V., and is intended for use with the 1056 only.

4.4.5 Data Logging

The 1056 control computers were networked with a dedicated Zenith personal computer for data logging and remote operation. Information was collected from the storage computers at the desired sampling rate, 10 - 30 minute intervals for this study, and stored on the PC's hard drive for future reference. A partial list of the data values stored on the PC is given in Table 4.2.

A phone modem and a commercially available communication software package (Carbon Copy, Meridian Technology) was used to access the PC remotely. The software and modem allowed a remote PC to view the measured storage conditions and make control parameter changes.

Table

Code
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Table 4.1 Influences and Setpoints used for the FANCOM 1056 Computer for the Control of a Potato Storage Environment.

Code Number	Description	Setting
100	Desired Room Temperature	10 - 15 C
103	Heat Up Time	0.1 min
104	Cool Down Time	0.1 min
105	Range Room Temp. Control	1.1 C
107	Influence of Pile Temp. on Room Temp.	2.0 C/C
114	Maximum Fresh Air	(60% of total airflow)
115	Influence of Pile Temp. on Fresh Air	0.0 %
116	Influence of Room Temp. on Fresh Air	0.3 %/C
117	Influence of Relative Hum. on Fresh Air	0.0 %/%
118	Influence of Carbon Dioxide on Fresh Air	0.0 %/%
119	Minimum Circulation	0.0 m^3/s
120	Maximum Circulation	(vary by bin)
123	Influence Differential Pile Temp. on Circulation	1.0 %/C
124	Allowable Pile Differential	0.5 C
135	Delay of Room Temp. Influence on Fresh Air	0.2 min
137	Graphics Sample Time	15.0 min
166	Zero If Air Volume Measured	0
167	Influence of Low Outside Temp. on Fresh Air Volume	2 %/C
168	Influence of High Outside Temp. on Fresh Air Volume	2 %/C
171	One If RH controlled by a humidifier	1
175	Minimum Pulse Fresh Air	0.2 sec
176	Pulse Repeat Time Fresh Air	0.2 min
177	Diff. Switch Fresh Air	0.0
178	Minimum Pulse Circulation	0.5 sec
179	Pulse Repeat Time Circulation	0.1 min

Table 4

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Table 4.2 List of Parameters Stored on the Personal Computer by the FANCOM Control System.

1) Bin Number
2) Date
3) Time
4) Main Plenum Temperature
5) Outside Temperature
6) Relative and Absolute Humidity (Above Pile, and Inlet)
7) Carbon Dioxide (Four levels in Pile and Outside)
8) Pile Temperatures 1 - 4
9) Measured Fresh and Recirculation Air Volumes
10) Lowest Measured Pile Sensor
11) Highest Measured Pile Sensor
12) Desired Main Plenum Temperature
13) Desired Pile Temperature
14) Desired Relative Humidity

A complete listing of the values stored is given in the FANCOM user manual for the 1056 (Fancom, 1986, 1987).

4.5 Storage Management Procedures

The condition of the potatoes taken from the field varied for each storage season studied. In September of 1986, Michigan experienced one of the worst floods in recorded history, while the drought of 1988 caused many to speculate on the storability of the potato crop. The procedure used for storage management was based on information gathered from commercial potato storage managers. The management decisions were based on observations and are explained below.

4.5.1 Suberization

The potatoes were harvested in October with an average pulp temperature of 10 ^{O}C over the three years of the study. Upon placement into storage, the potatoes were subjected to a period of continuous ventilation with total air recirculation to allow the uniform build up of temperatures into the 15 ^{O}C range for suberization. The ventilation was continued with the controllers set to maintain the temperature of 15 ^{O}C and a relative humidity setpoint of 92 - 95% throughout the 2 to 3 week suberization period. The controllers were switched into the automatic mode for fan control after suberization was complete.

4.5.2 Pre-Conditioning

The pre-conditioning phase was initiated after the completion of the suberization phase. The storage environment was controlled by the computers throughout the remainder of the storage season. The environment was controlled in the 15 ^{O}C temperature range with a relative humidity setpoint of 92 - 95%. The purpose of this phase of storage is to allow the potatoes to "burn" or respire off excess internal sugar pools. Potato samples were tested once a week for process color and sugar content during the pre-conditioning phase. As the sugar content was reduced, the process color improved. The pre-conditioning phase was terminated when the potatoes maintained a desirable process color and sugar content for two weeks in a row. This phase of storage took from 3 to 8 weeks to complete.

4.5.3 Cool Down

The potatoes were slowly cooled from the pre-conditioning temperature of 15 °C toward the desired temperature of 10 °C. The rate of cooling was 0.5 °C per week in the 1986-87 and 1987-88 storage seasons, while a cooling rate of 1 °C per week was used for the 1988-89 season. At the slower cooling rate, the potatoes were marketed during the cool down phase in late February at temperatures in the 11.5 to 12 °C range. In the 1988-89 season, the potatoes were cooled to 10 °C by the first week of January, then placed in a holding phase. Potato samples were analyzed during cooling to assess the process color and sugar content.

4.5.4 Holding

The holding phase was the final phase for the 1988-89 season. The environment was maintained at the desired conditions with the fans running only when required by temperature changes within the potato pile. The relative humidity was controlled at the 95% level. Samples were taken for process color and tuber sugar content throughout the holding phase. The potatoes were marketed from storage at a temperature of 10 °C in early March, 1989.

4.6 Evaluation Procedures

Several evaluation procedures were used to quantify the physiological response of the potatoes during the storage season. These evaluations were also used to help make management decisions on the operation of the storage and equipment. The 1056 environmental control computers were evaluated for temperature and relative humidity control efficiency.

4.6.1 Potato Quality

Potato quality was monitored from the initiation of tubers in the field throughout the storage season. The potatoes stored in this study were of the cultivar Atlantic, which is a high gravity potato developed specifically for the potato chip industry. The most critical quality factor is the color of the potato chip. Other important factors include the percent solids and internal and external defects such as bruises, sprouts or discoloration. The processor retains the right to reject loads which have an unacceptable appearance, placing the burden of delivering an acceptable product to the market on the storage manager. For this reason, a chemical sprout inhibitor (CIPC) was applied after suberization and the internal sugar content and process color were monitored throughout all phases of potato development.

The procedure for internal sugar content analysis was outlined by Sowokinos (1988). A Yellow Springs Instrument (YSI model 27) industrial analyzer was used to determine the content of internal reducing (glucose and fructose) and non-reducing (sucrose) sugars. A sample of 10 tubers were randomly selected, and a center core of each was obtained by block peeling. These cores were mixed together, and 200 grams of potato tissue selected. An extract taken by juicerating the tissue was diluted and analyzed for glucose content. This extract was then subjected to invertase enzymatic action which breaks the existing sucrose molecules into six carbon sugars (glucose and fructose). The extract was again tested for glucose content, and the percent glucose and sucrose rating calculated.

Weight loss analysis was performed using the twelve 11.4 kg sample bags placed at three levels within the storage. The bags were weighed upon placement into and removal from storage. The results were calculated in terms of weight loss as a percentage of the original weight.

$$\text{Wt. Loss \%} = \frac{\text{Original Wt.} - \text{Final Wt.}}{\text{Original Wt.}} \qquad (4.1)$$

This information was compiled for all levels within each potato pile. A two way analysis of variance (ventilation rate X pile depth) with four replications was performed to determine the weight loss variation between different levels under the same ventilation rate, and between different ventilation rates.

4.6.2 Environmental Control Analysis

The computerized environmental control and monitoring system generated 5 megabytes of data to be analyzed for each storage season. A series of Pascal computer programs were developed to evaluate the controller performance and storage environment.

One set of programs was designed to evaluate the performance of the controller by calculating the difference between measured and desired temperature and relative humidity values. The programs calculated the mean and standard deviation of the difference. Time periods when the controller was making temperature changes were evaluated separately. The temperature change information was not used to determine the uniformity of temperature and relative humidity control.

Step changes of -0.5 ^{o}C were performed throughout the storage season to lower the temperature of the potato pile. Temperature change time periods were separated from the information base and analyzed individually. The information consisted of the temperature at four points in the potato pile, ventilation rate, and ventilation air temperature and humidity levels. The temperature change characteristics in terms of the time required for the temperature change and the average temperature and humidity driving potentials throughout the temperature change were calculated from this data. The information was then subjected to a statistical analysis using the students t-test with 10 temperature change time periods to determine the temperature change characteristics at each ventilation rate and between ventilation rates.

As previously stated, the main ventilation fan was activated to correct out of range pile temperatures and non-uniform pile temperatures. Another set of programs extracted information on the duration and frequency of ventilation. The fan operation was separated into two categories based on the reason for ventilation. If the fan operated to cool the potato pile, the fan operation period was attributed to temperature control. Otherwise, the fan operation was attributed to the control of potato pile uniformity.

4.7 Computer Modeling and Simulation

An existing computer model (Lerew, 1978) was modified to include a ventilation control routine similar to that used in the Fancom 1056 control computer. A heat generation rate was used which was similar to measured in the simulated storages. The computer model used finite difference techniques to estimate vertical temperature profiles and weight loss characteristics of bulk stored potatoes. The modified simulation model was verified against the data collected from the control computers.

4.7.1 Condensation Control Simulation

Burton and Wigginton (1970) found that a film thickness-time product of 7.5×10^{-5} h-m at 10 ^{o}C will result in the initiate tuber decay. Hylmo et. al. (1976) stated that free water on the surface of tubers helps the growth of fungi and bacteria, which will cause losses.

Condensation on the tuber surfaces may occur at the interface between successive days of harvest while filling a potato storage bin. At this interface, potatoes that were harvested one day (pulp temperature 21 ^{o}C) could come into direct contact with potatoes harvested the next day (pulp temperature 10 ^{o}C). A diagonal region, determined by the angle of repose, corresponding to the face of the pile is affected by this temperature differential. Condensation may occur on the cooler potatoes, and must be controlled with minimum loss.

The computer simulation model developed by Lerew (1978) and modified for this research was used to evaluate ventilation strategies to remove this condensation. The condensation problem studied was that of having a 4 m deep pile of potatoes with 2 m of 21 ^{o}C pulp temperature potatoes in the lower portion of the pile, and 2 m of 10 ^{o}C potatoes in the upper half of the pile.

The ventilation strategies studied were as follows:

1) No Ventilation
2) Recirculation with 56 m^3/tonne-hr ventilation
3) Fixed Inlet Conditions of:
   a) 15.6 C, 65 % RH, with 28 m^3/tonne-hr ventilation
   b) 15.6 C, 65 % RH, with 56 m^3/tonne-hr ventilation
   c) 15.6 C, 65 % RH, with 112 m^3/tonne-hr ventilation
   d) 15.6 C, 85 % RH, with 28 m^3/tonne-hr ventilation
   e) 15.6 C, 85 % RH, with 56 m^3/tonne-hr ventilation
   f) 15.6 C, 85 % RH, with 112 m^3/tonne-hr ventilation

These conditions are representative of the typical fall weather conditions in Michigan.

The water film thickness on the tuber surface was calculated by taking the total amount of moisture condensed, based on psychrometric data. This amount of water was then distributed evenly over the surface area of the potatoes where condensation occurred. The temperature rise of the pile, or heat generation was calculated using a temperature-dependent respiration equation obtained from Misener and Shove (1976):

$$Q = 6.99 * T - 17.7 \qquad (4.2)$$

The equation is valid for a tuber temperature range of 4.5 to 21.0 ^{o}C, and was obtained by linear regression. Weight loss was calculated based on skin permeability and air velocity (Villa and Bakker-Arkema, 1974). It was assumed in this work that the velocity of the air has an effect on convective moisture transfer until a critical ventilation rate is obtained (Burton, 1963). Above the critical ventilation rates of 42 and 12 m^3/tonne-hr for freshly harvested and well suberized unsprouted potatoes respectively, the permeability of the tuber skin limits the amount of moisture loss.

4.7.2 Temperature Change Simulation

The characteristic response to the step temperature changes were observed throughout the storage experiment. A simple model (See Figure 4) was developed to obtain an approximation of the potato pile's response to the step cooling process. Energy transfer was modeled using heat and

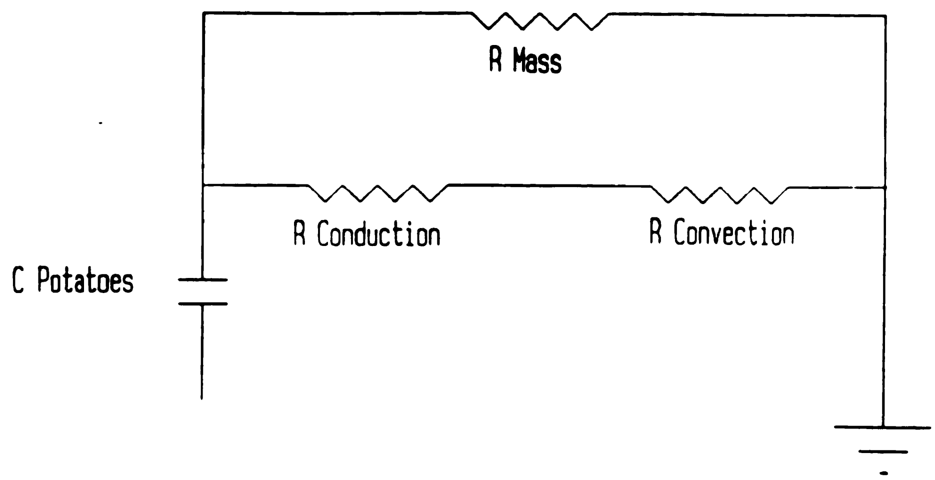


Figure 4.4 Electrical Analogy used to Model the Heat and Mass Transfer System Involved while Cooling Potatoes.

mass transfer theories.

The model assumed parallel paths of heat and mass transfer from the potato into the ventilation air stream. The heat transfer path included the series combination of the resistance to energy flow from conduction and convection.

The ventilation air temperature was assumed to be constant and cooler then the center temperature of the potato. The thermal conductivity (Kc) was taken from Lerew (1978) as 2450 J/hr-m-^{o}C. The convective heat transfer coefficient was calculated using equation 4.3 as described in Lerew (1978):

$$h = V*e*952.1*Re^{-0.41} \qquad (4.3)$$

$$Re = \frac{rho*V*e}{mu*a} \qquad (4.4)$$

Equation 4.3 is valid for Reynolds numbers above 50, which was the case for all ventilation rates studied with this model. Equation 4.5 and 4.6 were used to estimate energy transfer through conduction and convection, respectively:

$$\dot{q}_{cond.} = Kc*x*(T_{internal} - T_{surface}) \qquad (4.5)$$

$$\dot{q}_{conv.} = h*A*(T_{surface} - T_{air}) \qquad (4.6)$$

The temperature at the center of the potato was assumed constant. The potato surface temperature was calculated by varying the conduction driving potential.

The Biot modulus, a measure of the ratio of convective to conductive heat transfer, was calculated using equation 4.7 at a ventilation rate of 56 m^3/tonne-hr with air conditions of 10 ^oC and 95% relative humidity. A Biot modulus > 0.1 indicates that the conduction of heat through the product is significant as compared to the convection of heat from the surface of the product (Holman, 1976):

$$Biot = \frac{h * d}{Kc} \qquad (4.7)$$

The convective heat transfer coefficient calculated as previously stated was 21834 J/hr-m^2-^{o}C with a thermal conductivity of 2450 J/hr-m-^{o}C, and a tuber diameter of 0.045 m. The resultant Biot number of 0.4 indicates that the conduction of heat through the potato has a significant influence on the cooling process. The calculation at the minimum ventilation rate used in this study resulted in the lowest Biot modulus. At higher ventilation rates, the convective heat transfer coefficient increases, thus increasing the Biot number. The mass transfer process was modeled as the resistance to moisture flow through the tuber skin in series with moisture convection from the tuber surface. Due to the high internal moisture content of the potato, the vapor pressure at the surface of the potato was calculated as the saturated vapor pressure at the potato surface temperature. The surface temperature of the potato was calculated as stated previously.

The equation used to predict mass transfer rate was derived by Lerew (1978) and is stated by equations 4.8 - 4.10. Equation 4.9 is derived using the Colburn J factor relationship between the convective heat and moisture transfer coefficients at 10 ^{o}C. The relationship of the skin permeability is the product of the membrane thickness and the resistance to moisture flow. Villa and Bakker (1974) found that this was a function of the Vapor Pressure

Deficit, which is expressed by equation 4.10:

$$\dot{M} = \frac{(b1*hd\ /\ T(abs))*b2}{Rdel*hd\ +\ b2} *gamma*a*(VPD) \qquad (4.8)$$

$$hd = 8.96 * 10^{-4} * h \qquad (4.9)$$

$$Rdel = 4.94 * 10^{-4} + 3.31 * 10^{-6} * VPD \qquad (4.10)$$

The amount of energy removed while cooling a square meter column of potatoes, 4 meters deep, 0.5 ^{o}C was calculated using equation 4.11:

$$\text{Energy Transfer} = M*cp*(T_{orginal} - T_{final}) \qquad (4.11)$$

The model was then used to demonstrate the effects of varying the temperature gradient within the potato, the inlet relative humidity and the air flow rate on the time required for energy transfer determined by eqn. 4.11. The mass lost during the cooling process was investigated by multiplying the moisture loss rate by the time required for the energy transfer.

5. Results and Discussion

5.1 Weight Loss Results

The weight loss (expressed in percentage of original weight) for the 1986-87, 1987-88 and 1988-89 storage seasons of the Simulated Storage Research facility are presented in Tables 5.1, 5.2 and 5.3, respectively. The information is reported by level within the potato pile, and as an average for each simulated storage.

Table 5.1 Weight Loss Percent of the Potatoes Stored in the Simulated Storage Facility for the 1986-87 Storage Season.

	Bin #1	Bin #2	Bin #3
Ventilation Rate m^3/tonne-hr	56	112	168
	Weight Loss Percent (Std. Deviation)		
Above Floor			
1.22 m*	18 (3.2)	15 (2.9)	15 (1.7)
2.44 m	10 (1.3)	12 (2.0)	15 (1.1)
3.66 m	11 (1.9)	11 (1.7)	15 (2.9)
Average	13 (4.4)	13 (2.6)	15 (2.8)

*Each level represents four samples.

Table 5.2 Weight Loss Percent of the Potatoes Stored in the Simulated Storage Facility for the 1987-88 Storage Season.

	Bin #1	Bin #2	Bin #3
Ventilation Rate m^3/tonne-hr	56	112	52*
	Weight Loss Percent (Std. Deviation)		
Above Floor			
1.22 m **	4.4 (1.4)	7.8 (0.9)	9.2 (0.9)
2.44 m	5.3 (0.9)	7.9 (0.9)	7.9 (1.1)
3.66 m	6.2 (3.5)	8.0 (1.1)	8.0 (0.6)
Average	5.3 (2.3)	7.9 (1.0)	8.3 (1.3)

* Average of variable rate for entire storage season.

** Each level represents four samples.

Table 5.3 Weight Loss Percent of the Potatoes Stored in the Simulated Storage Facility for the 1988-89 Storage Season.

	Bin #1	Bin #2	Bin #3
Ventilation Rate m^3/tonne-hr	56	112	37*
	Weight Loss Percent (Std. Deviation)		
Above Floor			
1.22 m **	8.8 (0.5)	10.0 (0.5)	9.3 (1.0)
2.44 m	7.0 (1.1)	7.9 (0.6)	5.6 (0.7)
3.66 m	6.1 (1.1)	6.2 (0.4)	5.6 (1.2)
Average	7.3 (1.5)	9.2 (1.3)	6.8 (2.0)

* Average of variable rate for entire storage season.

** Each level represents four samples.

A statistical analysis was performed using a two way analysis of variance (ventilation rate X storage depth) using four replications to determine differences in weight loss between the storage bins and between levels within each storage (levels 1, 2 and 3 relate to samples stored at 1.22, 2.44 and 3.66 m from the floor respectively). The significant differences (95% confidence level) are presented below:

1) bin #2 and bin #3 for the 1986-87 storage season.
2) bin #1 and bin #2 for the 1987-88 storage season.
3) bin #1 and bin #3 for the 1987-88 storage season.
4) 1.22 and 2.44 m from the floor in bin #1 for the 1986-87 and 1988-89 storage seasons.
5) 1.22 and 3.66 m from the floor in bin #1 for the 1986-87 and 1988-89 storage seasons.
6) 1.22 and 2.44 m from the floor in bin #2 for the 1988-89 storage season.
7) 1.22 and 3.66 m from the floor in bin #2 for the 1988-89 storage season.
8) 2.44 and 3.66 m from the floor in bin #2 for the 1988-89 storage season.
9) 1.22 and 2.44 in bin #3 for the 1988-89 storage season.

5.2 Weight Loss Discussion

5.2.1 Differences Between Bins

In the 1986-87 storage season, a weight loss difference of 2.0 % occurred between bin #2 and bin #3. Weight loss differences of 2.6% and 3.0 % were recorded between bin #1 and bins #2 and #3 respectively for the 1987-88 season. No significant differences were recorded between bins for the 1988-89 storage season.

The bins of the simulated storage facility differ only in air flow rates as listed in Tables 5.1 - 5.3. Burton (1963) found that above the critical ventilation rate of 12 m^3/tonne-hr for well suberized tubers, moisture loss was not a function of air velocity (ventilation rate), due to limitation of moisture transfer through the tuber skin. Villa (1973) modeled this phenomenon as a function of skin permeability and vapor pressure deficit and obtained correlations between weight loss of potatoes (cv. Monona) and intersticial air velocity. He concluded that the environmental air velocity has little effect on moisture losses from Monona potato tubers. Consistent significant differences did not exist between simulated storages throughout the three years of experimental data collected. The results obtained in this study indicate an agreement with the information collected by Burton (1963), and Villa (1973).

5.2.2 Weight Loss Within Each Bin

The driving potential for moisture transfer from the tuber surface into the ventilation air is the vapor pressure deficit. This is determined by the temperature and humidity of the ventilation air and tuber surface temperature. As the air passes through the potato pile, the amount of water in the air is increased as moisture is taken up from the potatoes. The point at which the ventilation air becomes saturated moves up in the column of potatoes as the ventilation rate is increased. Grahs et. al. (1978) defined a critical ventilation rate at which the ventilation air would become saturated at the top of the pile. At an inlet relative humidity of 95 %, the critical ventilation rate was calculated by Grahs as 72 m^3/tonne-hr.

The weight loss uniformity from the top to the bottom of a potato pile should increase as the ventilation rate increased above the critical ventilation level, due to a more uniform vapor pressure deficit throughout the pile. This was noted in the weight loss results from Bin #3 in the 1986-87 storage season, and Bin #2 throughout the three storage seasons. The potatoes stored in these bins consistently had a lower standard deviation in weight loss within the bin then did the storage bins ventilated at lower rates in the same season.

Ventilation at a rate lower than the critical level would lead to greater vapor pressure deficits in the lower regions of the potato pile than in the regions where the ventilation air is saturated. This hypothesis would suggest that the moisture lost in the lower regions of the potato pile ventilated below the critical rate should be greater then moisture lost in the upper regions of the pile. This was the case in bin #1 for the 1986-87 and 1988-89 storage seasons. Increased weight loss in the lower regions of the pile was also noted in bins #2 and #3 for the 1988-89 storage season. The inlet air relative humidity was controlled to 92 % for the 1986-87 storage season, and 95 % for the 1987-88 and 1988-89 storage seasons.

5.3 Pre-Harvest Internal Sugar Analysis Results

Tuber sugar analyses were performed throughout all stages of tuber development for the 1987-88 and 1988-89 seasons, and this information is presented in Tables 5.4 and 5.5 respectively. Figures 5.1 and 5.2 present this data in graphical format.

Table 5.4 Internal Sugar Content of Potato Tubers Before Harvest 1987-88.

Date or Location Pre-Harvest Samples	Glucose (%)	Sucrose Rating
8-15-87	0.04	0.52
8-25-87	0.05	0.22
8-29-87	0.05	0.15
9-08-87	0.05	0.45
9-16-87*	0.04	0.40
9-18-87	0.05	0.39
10-02-87	0.05	0.47
10-07-87	0.06	0.79

*Chemical Vine Kill Applied.

Table 5.5 Internal Sugar Content of Potato Tubers Throughout Development 1988-89.

Date or Location Pre-Harvest Samples	Glucose (%)	Sucrose Rating
8-02-88	0.086	0.21
9-06-88	0.108	0.39
9-12-88	0.086	0.52
9-20-88*	0.043	0.52
10-04-88	0.065	0.90
10-11-88	0.065	0.54

*Chemical Vine Kill Applied.

5.4 Pre-Harvest Sugar Content Discussion

The data presented in Table 5.4 for the 1987 growing season indicated a constant to decreasing sugar content (both sucrose rating and percent glucose) until vine killing. The data presented in Table 5.5 for the 1988 growing season, indicate that a gradual decrease in glucose content occurred throughout the growing season, while the sucrose rating remained relatively constant.

In both the 1987-88 and 1988-89 growing season, the potatoes were harvested with the sucrose ratings less than 1.0 which is acceptable by criteria defined by Sowokinos (1988). The percent glucose readings, however, were greater than the 0.035 % level which is defined as the acceptable range for this value in Norchip potatoes.

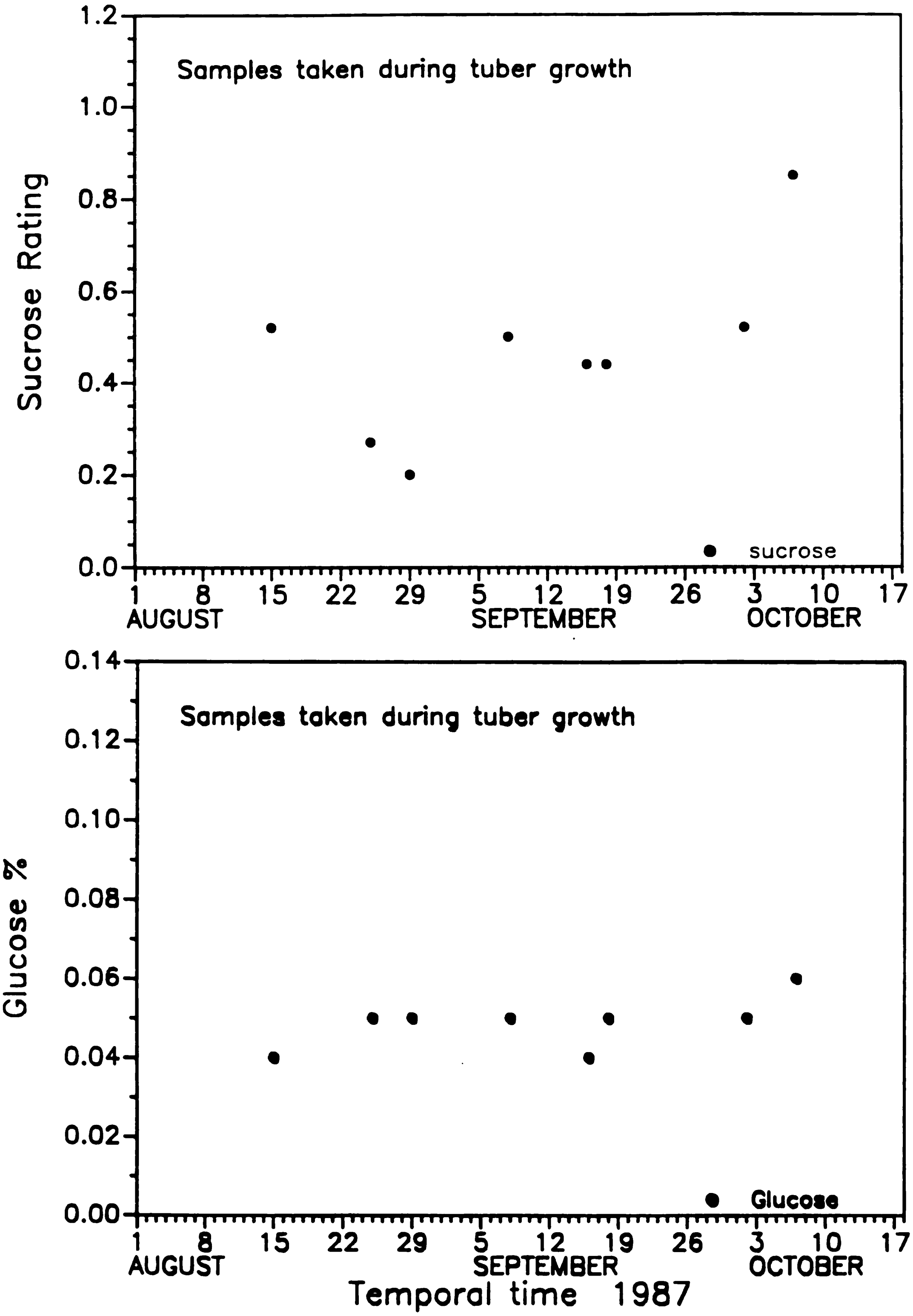


Figure 5.1 Sucrose Rating and Percent Glucose Readings of Tubers throughout the 1987 Growing Season.

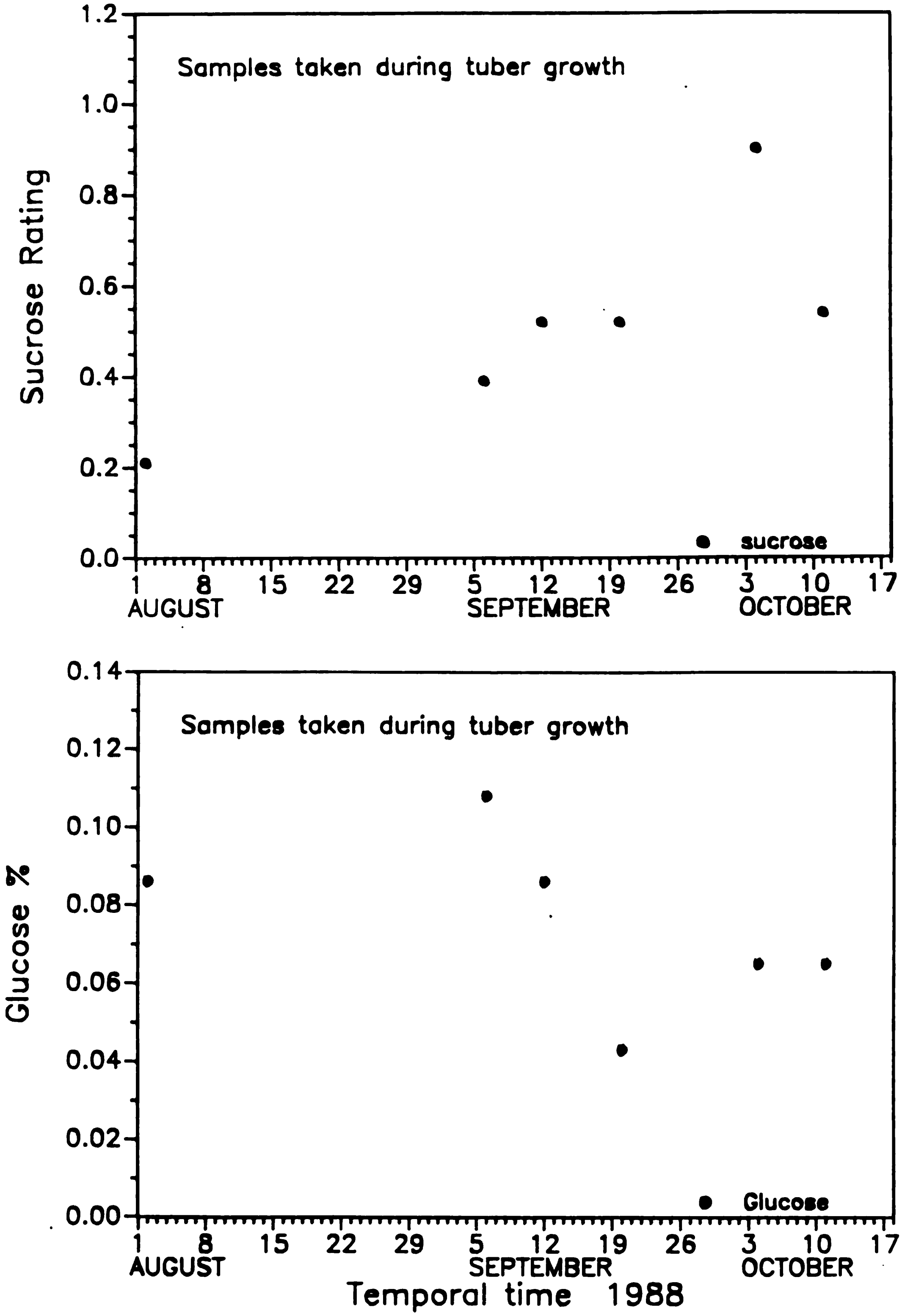


Figure 5.2 Sucrose Rating and Percent Glucose Readings of Tubers throughout the 1988 Growing Season.

5.5 Process Quality Results

The potatoes stored in the simulated storage facility were marketed through Frito-Lay Inc. each year. Results of the standard Frito-Lay cook test are presented in Tables 5.6, 5.7 and 5.8 for the three storage seasons. Results are presented by vertical location only for the 1987-88 and 1988-89 seasons. Upon removal from storage in the 1987-88 and 1988-89 season, tuber sugar analyses were performed and are presented in Tables 5.7 and 5.8.

Table 5.6 Frito-Lay Cook Test Results for the Potatoes Stored in the Simulated Storage Research Facility for the 1986-87 Storage Season.

	Bin #1	Bin #2	Bin #3
Ventilation Rate m^3/tonne-hr	56	112	168
Color*	61	57	56
Appearance**	14	25	12

*Agtron Scale calibrated at 0 (M-00) and 90 (M-90) on red mode.

**Frito-Lay Quality criteria, 0 = excellent, 15 = not acceptable.

Table 5.7 Frito-Lay Cook Test Results for the Potatoes Stored in the Simulated Storage Research Facility for the 1987-88 Storage Season.

	Bin #1	Bin #2	Bin #3
Ventilation Rate m^3/tonne-hr	56	112	52 *
1.22 m Level			
Color**	62	63	63
Appearance***	0	3	2
Percent Glucose	0.010	0.010	0.022
Sucrose Rating	0.08	0.15	0.56
2.44 m Level			
Color	63	63	60
Appearance	0	0	0
Percent Glucose	0.006	0.006	0.027
Sucrose Rating	0.06	0.10	0.61
3.66 m Level			
Color	63	62	63
Appearance	0	1	0
Percent Glucose	0.016	0.006	0.027
Sucrose Rating	0.08	0.09	0.41

*Average of variable rate for entire storage season.

**Agtron Scale calibrated at 0 (M-00) and 90 (M-90) on red mode.

***Frito-Lay Quality criteria, 0 = excellent,
15 = not acceptable.

Table 5.8 Frito-Lay Cook Test Results for the Potatoes Stored in the Simulated Storage Research Facility for the 1988-89 Storage Season.

	Bin #1	Bin #2	Bin #3
Ventilation Rate m^3/tonne-hr	56	112	37 *
<u>1.22 m Level</u>			
Color**	67	62	65
Appearance***	0	8	0
Percent Glucose	0.028	0.023	0.032
Sucrose Rating	0.736	1.10	0.490
<u>2.44 m Level</u>			
Color	61	68	64
Appearance	2	3	3
Percent Glucose	0.011	0.023	0.017
Sucrose Rating	0.45	0.90	0.409
<u>3.66 m Level</u>			
Color	61	63	58
Appearance	0	0	1
Percent Glucose	0.039	0.028	0.032
Sucrose Rating	0.695	0.653	0.695

*Average of variable rate for entire storage season.

**Agtron Scale calibrated at 0 (M-00) and 90 (M-90) on red mode.

***Frito-Lay Quality criteria, 0 = excellent, 15 = not acceptable.

The following observations are noted from the data presented in Tables 5.6, 5.7 and 5.8:

1) All potatoes stored in the simulated facility during the 1987-88 and 1988-89 maintained acceptable process quality throughout the storage season, and were acceptable for market.

2) The potatoes stored in Bin #2 during the 1986-87 season were rejected by the processor, due to defects.

3) The potatoes stored in Bin #3 during the 1986-87 season were accepted as marginal quality product due to defects.

4) Samples tested throughout all three years of this study attained an acceptable process color reading (above 55 Agtron) upon removal from storage.

5) All samples tested for tuber sugar content upon removal from storage had acceptable levels of percent glucose and sucrose rating.

The tuber sugar content and process color of the potatoes were monitored throughout the 1988-89 storage season by the Frito-Lay field lab in Sidney, MI. Samples were taken from the surface of the potato pile of each simulated storage bin on approximately two week intervals. These readings, presented in Tables 5.9, 5.10, and 5.11 and Figures 5.3, 5.4, and 5.5, were used as management tools to determine the state of the potato pile, and the environmental requirements to maintain potato quality throughout the storage season.

Table 5.9 Process Color of Potatoes Taken from the Potato Pile Surface within the Simulated Storages throughout the 1988-89 Storage Season.

	Bin #1	Bin #2	Bin #3
Ventilation Rate m^3/tonne-hr	56	112	52*
11-04-88	60**	62**	62**
11-18-88	60**	60**	60**
12-02-88	62	66	60
12-16-88	61	61	61
01-04-89	63	62	64
01-27-89	66	67	64
02-06-88	61	63	61
02-16-89	65	62	63

* Average of variable rate for entire storage season.

** Dark internal coloration noted.

Table 5.10 Percent Internal Glucose of Potatoes Taken from the Potato Pile Surface within the Simulated Storages throughout the 1988-89 Storage Season.

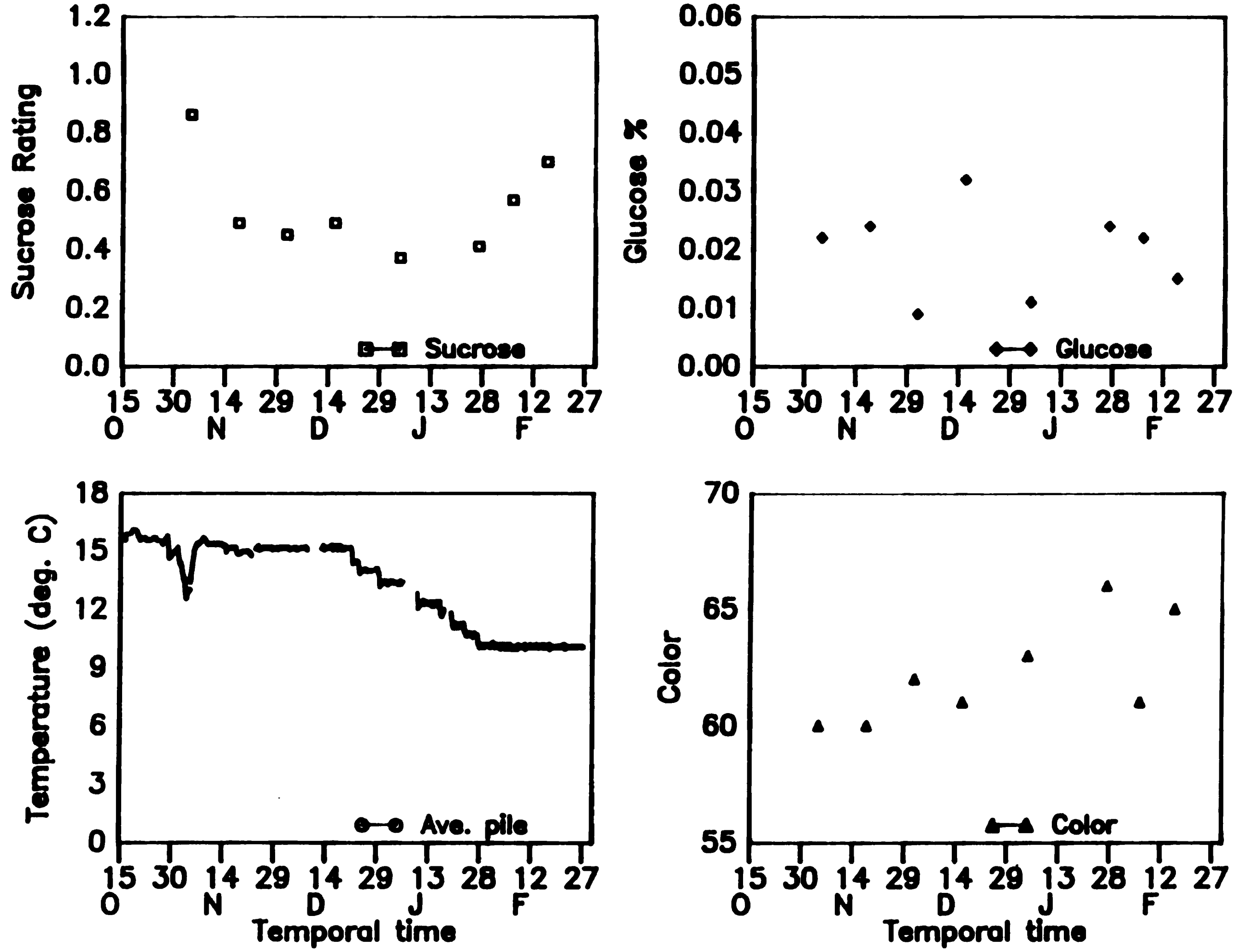
	Bin #1	Bin #2	Bin #3
Ventilation Rate m^3/tonne-hr	56	112	37*
11-04-88	0.022	0.024	0.019
11-18-88	0.024	0.015	0.022
12-02-88	0.009	0.026	0.032
12-16-88	0.032	0.030	0.017
01-04-89	0.011	0.015	0.013
01-27-89	0.024	0.026	0.015
02-06-89	0.022	0.032	0.013
02-16-89	0.015	0.054	0.024

* Average of variable rate for entire storage season.

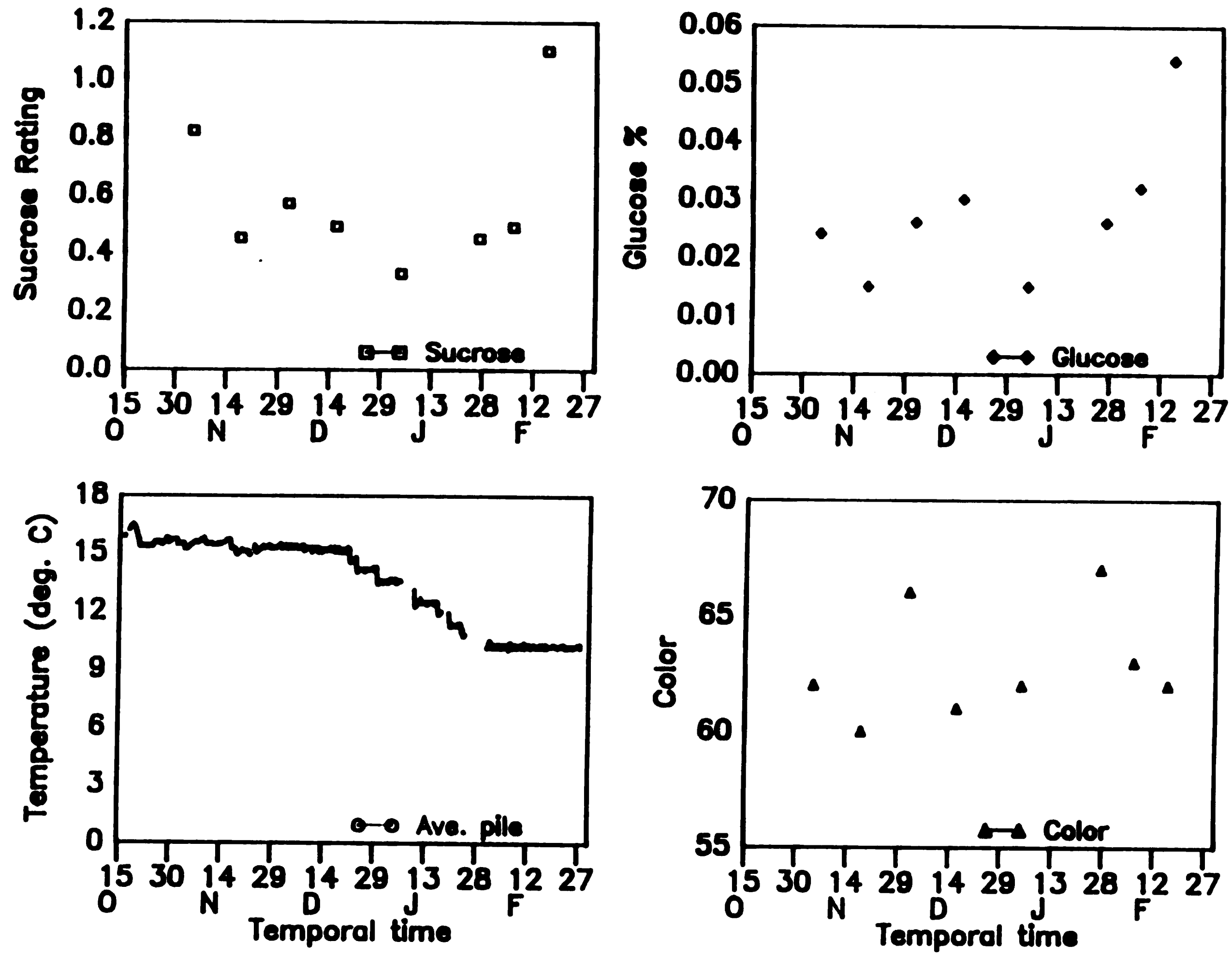
Table 5.11. Sucrose Rating of Potatoes Taken from the Potato Pile Surface within the Simulated Storages throughout the 1988-89 Storage Season.

	Bin #1	Bin #2	Bin #3
Ventilation Rate m^3/tonne-hr	56	112	37*
11-04-88	0.86	0.82	0.74
11-18-88	0.49	0.45	0.41
12-02-88	0.45	0.57	0.33
12-16-88	0.49	0.49	0.57
01-04-89	0.37	0.33	0.33
01-27-89	0.41	0.45	0.49
02-06-89	0.57	0.49	0.57
02-16-89	0.70	1.10	0.49

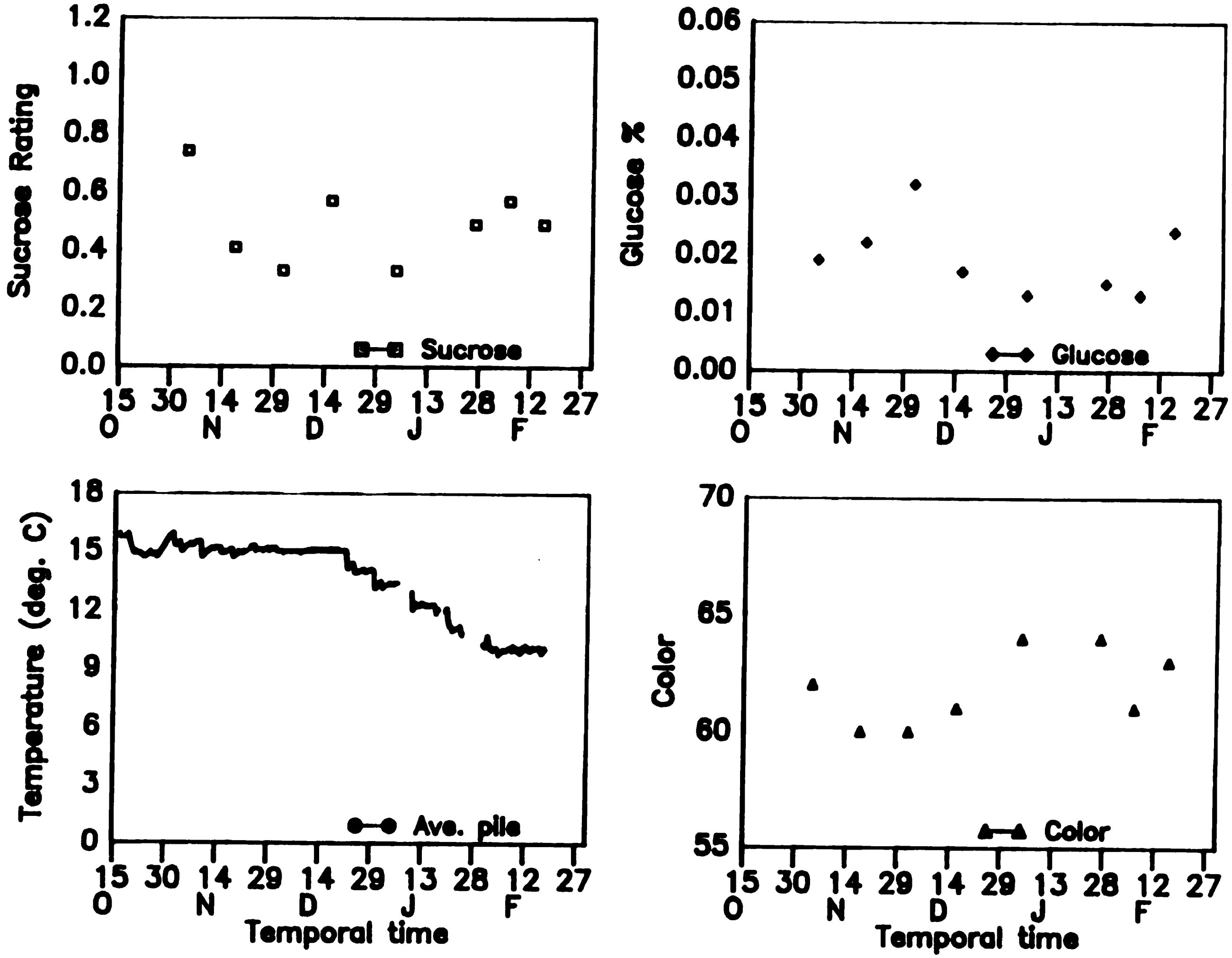
* Average of variable rate for entire storage season.



5.3 Sucrose Rating, Percent Glucose, Chip Color, and Average Temperature for Simulated Storage Bin #1 during the 1988-89 Storage Season.



5.4 Sucrose Rating, Percent Glucose, Chip Color, and Average Temperature for Simulated Storage Bin #2 during the 1988-89 Storage Season.



5.5 Sucrose Rating, Percent Glucose, Chip Color, and Average Temperature for Simulated Storage Bin #3 during the 1988-89 Storage Season.

The following points are suggested by this data:

1) The sucrose rating, which is an indication of the amount of sucrose within the tuber, was near the critical value of 1.0 upon placement into storage in both the 1987 and 1988 growing seasons. A decrease in the sucrose rating occurred from November 4, to November 18, 1988.

2) The sucrose rating generally decreased through January 4, 1989, then began an increase throughout the remainder of the storage season.

3) As shown in Figures 5.3 - 5.5, the average pile temperature was gradually lowered to 10 C on January 4, 1989 where it was maintained until the potatoes were marketed.

4) The percent glucose content was in the acceptable range (% glc < 0.035) throughout the storage season until February 6, 1989, at which time this reading for Bin #2 had increased 0.054%. However the process color had not yet been affected by this increase in glucose content.

5.6 Process Quality Discussion

The potatoes stored in the simulated storage facility were utilized for potato chip production in all three seasons studied. Quality evaluations were performed by the processor, to determine the acceptability of the potatoes to the process industry.

In the 1986-87 storage season, bin #2 was rejected at the processor due to poor quality. The process color of this lot of potatoes was acceptable. However the defects, such as pressure bruise and internal discoloration were not acceptable. During the same storage season, the potatoes stored in bins #1 and #3 were accepted with marginal quality. The Frito-Lay appearance numbers for the simulated storage research bins were all above 10 on a scale where 0 is excellent and 15 is not acceptable.

I hypothesize that the reason for this poor quality was a combination of circumstances which took place both before and during storage. In September 1986, Michigan received 14 inches of rain in a 14 hour period, thus the potatoes were harvested from saturated soil. Free water was evident on the surface of most of the potatoes used to fill the simulated storage facility. The potato condition going into storage required that fresh air be heated and passed through the pile to remove this surface moisture. However, in the 1986-87 storage season, the design of the simulated storages was such that outgoing exhaust air, which needs to flow at the same rate as incoming fresh air, was required to pass through a pressure louver into the commercial storage bin. The ventilation system in the simulated storage facility was not capable of creating the pressure differential across the louver to allow it to open when the commercial bin was in a ventilation cycle. Therefore, no fresh air was available during the initial storage phase to allow drying of the potatoes. The controllers had required the fresh air louvers to open 100% in an attempt to draw fresh air at different times throughout the storage season, with no fresh air response. As the commercial bin exhaust fan turned on, or the main ventilation fan was shut off, the fresh air was drawn in at high rates and the pile was overcooled. Large temperature fluctuations occurred throughout the storage season, and poor control was the result as previously noted. The average difference between the desired and measured average pile temperature ranged from 1.8 to 2.2 ^{o}C, with a standard deviation ranging from 1.4 to 1.8 ^{o}C. These fluctuations coupled with the condition of the potatoes coming into the storage are assumed to be the cause of the poor quality of the 1986-87 stored potatoes.

The ventilation system of the simulated storage research facility was modified for the 1987-88 and 1988-89 storage seasons. A duct, which allowed exhaust air to pass through the commercial bin to a work area in the storage facility was installed. Exhaust fans were also installed in each simulated storage bin and activated whenever fresh air was required. To determine whether the ventilation rate was what the computer requested, air flow sensors were installed in the fresh and recirculation air inlets. The fresh-air flow was used as the feedback for the louver control (instead of the position of the louvers as was done in the 1986-87 storage season). These modifications provided the required temperature and air movement to maintain potato quality throughout the storage season.

In the 1987-88 and 1988-89 storage season, the potatoes were marketed from the simulated storage facility at high levels of quality following 115 to 142 days of storage. All potato lots attained a process color of 60 or higher on an Agtron scale calibrated at 0 (M-00) and 90 (M-90). The appearance numbers for the 1987-88 season ranged from 0 to 3, while during the 1988-89 season this number ranged from 0 to 8.

The information presented in Tables 5.9 - 5.11 represents the tuber sugar content and process color of potatoes taken from the surface of the potato pile for analysis throughout the storage season. This data is also presented per bin along with average pile temperature in Figures 5.3 - 5.5.

The process color of the potatoes in the storages ranged from 60 to 62 at the beginning of the 1988-89 storage season. Internal discoloration, however, was noted in the stem end of the tubers. The sucrose rating was also near the critical level of 1.0, ranging from 0.74 to 0.86. glucose levels were below the maximum allowable level of 0.035 %, ranging from 0.019 to 0.022 %. A pre-conditioning management scheme, as defined by Sowokinos (1988), was utilized to prepare the potatoes for long term storage. The pile temperature of the simulated storage bins was maintained at the 15.6 ^{o}C level through December 2, 1988 when the process color ranged from 60 to 66, and the sucrose rating had dropped to a range from 0.33 to 0.57. The glucose levels remained relatively stable throughout this period of storage, and ranged from 0.009 to 0.032 % on December 2, 1988.

The desired average pile temperature of the simulated storage bins was lowered to 10 ^{o}C at a rate of 1 ^{o}C per week beginning on December 3, 1988. This process lasted until January 10, 1989. Process Color and internal sugar level readings were taken on January 4, 1989, at an average potato pile temperature of 10.6 ^{o}C. The process color ranged from 62 to 64, the sucrose rating was the lowest of the 1988-89 season ranging from 0.33 to 0.37, and the glucose percentage was at an acceptable level ranging from 0.011 to 0.015 %.

The holding temperature of 10 ^{o}C is low by industry standards for the Atlantic variety of potatoes. This variety is known by commercial growers as only a short term storage variety which would not attain acceptable process color at storage temperatures below 12.8 ^{o}C. An increase in sucrose rating occurred from January 4, 1989 until the potatoes were marketed on March 2 or 3, 1989. The process color of the potatoes had not yet been affected by the low storage temperature. Sowokinos (1988) suggests that the sucrose rating is a forecasting tool to determine the processability and storability of potatoes. The theory is based on the fact that the twelve carbon, non-reducing disaccharide, Sucrose is hydrolyzed into two six carbon reducing sugar molecules by the enzyme invertase. These reducing sugars are subjected to non-enzymatic browning through the Millard reaction upon processing at high temperatures (190 to 200 ^{o}C). Thus, it is reducing sugar content, as measured by the percent glucose reading, that determines the process color of potatoes processed for potato chips and fries. Sowokinos argued that the presence of excess sucrose during the storage season (sucrose rating above 1.0) will result in an accumulation of glucose, thus decreasing the processability of potatoes from storage. Based on this information, it is hypothesized that the process color of the potatoes would have begun to decrease if the potatoes were held in storage until April or May. Further work is required to determine a temperature management strategy that will result in maintaining acceptable process color from the Atlantic variety throughout long term storage.

5.7 Environmental Control Results

The results of the temperature and relative humidity control evaluation are presented in Tables 5.12 and 5.13.

Table 5.12 Average and Standard Deviation of the Difference Between the Desired and Measured Average Pile Temperature for the Simulated Storage Research Facility for Three Storage Seasons.

	Bin #1	Bin #2	Bin #3
Ventilation Rate m^3/tonne-hr	56	112	variable
1986-87	1.8 (1.4)	2.2 (1.8)	2.1 (1.6)
1987-88	0.2 (0.1)	0.2 (0.3)	0.2 (0.2)
1988-89	0.2 (0.4)	0.2 (0.1)	0.2 (0.2)

Table 5.13 Average and Standard Deviation of the Difference Between the Desired and Measured Inlet Relative Humidity for the Simulated Storage Research Facility for Three Storage Seasons.

	Bin #1	Bin #2	Bin #3
Ventilation Rate m^3/tonne-hr	56	112	variable
1986-87	4 (2)	3 (4)	4 (2)
1987-88	4 (1)	5 (3)	4 (3)
1988-89	9 (4)	4 (3)	6 (5)

5.8 Environmental Control Discussion

The control of the simulated storage environment was performed by a FANCOM 1056 environment control computer. The two storage parameters that were controlled were the potato pile temperature, and the ventilation air relative humidity. The computer was instructed to operate a humidifier placed at the air inlet to the potato pile when the relative humidity was below the setpoint of 92 % during the 1986-87 storage season, and 95 % during the 1987-88 and 1988-89 storage seasons. The average difference between measured and desired relative humidity ranged from 3 to 9 % over the three storage seasons studied, with a standard deviation ranging from 1 to 5%. The inaccuracies of the sensor could account for variations of up to 4 % at a temperature of 10 ^{o}C and a relative humidity of 98%.

The temperature of the potato pile was controlled using fresh air for cooling, and small resistance heaters for heating. Heating was not required throughout most of the storage time studied due to the heat generation of the potato pile. The temperature variation noted in the average potato pile for the 1986-87 storage season was due to the failure of the ventilation system during the process of drawing fresh air for cooling as explained previously. The problem may have been compounded by the 0.5 ^{o}C accuracy of the sensors used. In the following two storage seasons, 0.1 ^{o}C sensors were used, and the average difference between the desired and measured average pile temperature was 0.2 ^{o}C.

5.9 Ventilation Fan Operation Results

The ventilation fan operation for the 1987-88 and 1988-89 seasons is outlined in Tables 5.14 and 5.15. The 1986-87 data were not analyzed due to the lack of ventilation measurement.

Table 5.14. Fan Time Operation for the Simulated Storages, 1987-88 Storage Season.

	Bin #1	Bin #2	Bin #3
Time, Days	85	134	142
Airflow (m^3/tonne/hr)	56	112	52*
Fan Time			
Hours	267 **	1381	2352
%	13	43	69
Number of Cycles:			
Pile Temp. Diff.	46	92	126
Fresh Air Required	68	146	238
Cycle Time hr.			
Pile Temp. Diff.	2.4	6.4	12.0
Fresh Air Required	2.3	5.4	3.5
Cycle Reason, %			
Pile Temp. Diff.	40	43	64
Fresh Air Required	60	57	36

* Variable airflow, value is average airflow for season
** Ventilation experiment ended on December 29, 1987 due to potato quality considerations.

Table 5.15. Fan Time Operation Analysis for the Simulated Storages, 1988-89 Storage Season.

	Bin #1	Bin #2	Bin #3
Time, Days	136	136	137
Airflow (m^3/tonne/hr)	56	112	37*
Fan Time			
Hours	2483	2260	2205
%	76	69	67
Number of Cycles:			
Pile Temp. Diff.	267	263	432
Fresh Air Required	244	215	344
Cycle Time hr.			
Pile Temp. Diff.	4.3	1.8	2.4
Fresh Air Required	5.5	8.3	3.3
Cycle Reason, %			
Pile Temp. Diff.	46	21	47
Fresh Air Required	54	79	53

* Variable airflow, value is average airflow for season

Observations based on the information presented in Tables 5.14 and 5.15 are listed below:

1) The fan time increased for all bins from the 1987-88 to the 1988-89 season.

2) The ventilation rate of the variable speed fan averaged less than 56 m^3/tonne/hr for both storage seasons studied.

3) Proportionately more ventilation time was required in bin #2 to bring in fresh air then to correct pile temperature differentials for both seasons studied.

4) Fans cycled an average of 1, 1.8, and 2.6 times per day in storage for the 1987-88 season, for bins #1, #2, and #3 respectively, while 3.8, 3.5, and 5.7 cycles per day was the average for the 1988-89 storage season.

5.10 Ventilation Fan Operation Discussion

The main ventilation fan was used to move the tempered air through the potato pile. Each fan was turned on any time fresh air was required, or when the temperature differential between two pile sensors exceeded 1.0 ^{o}C in the 1986-87 storage season (or 0.5 ^{o}C in the 1987-88 and 1988-89 seasons).

The volume of air used for controlling the temperature within the simulated storages was measured using air volume sensors during the 1987-88 and 1988-89 season. The data from the simulated storages on the amount of ventilation used indicated that the 1988-89 storage season required more ventilation then the 1987-88 season. The increase in ventilation time may be attributed to the longer period of high temperature required for the pre-conditioning phase of storage. In the 1988-89 season, the pile temperature was maintained at the 16 ^{o}C level for the first 8 weeks of storage, while this temperature was only maintained for 4 weeks in the 1987-88 season. During periods of high temperature storage, the metabolism of the tuber is higher than it is at lower temperatures. This was also evident in the lower weight loss figures for the 1987-88 storage season as compared with the 1988-89 season. Another difference between the potatoes stored in the 1987-88 and 1988-89 seasons was the drought conditions which the developing tubers survived during the 1988 growing season.

The on time of the main ventilation fan ranged from 2.4 to 12.0 hours for pile temperature differential correction, and from 2.3 to 5.4 hours for drawing fresh air during the 1987-88 season. The same information collected from the 1988-89 season revealed that a range of 1.8 to 4.3 hours per ventilation event was required for pile temperature differential corrections while the ventilation time required to draw fresh air ranged from 3.3 to 8.3 hours/cycle. The main difference between the 1987-88 and 1988-89 storage seasons was the average number of ventilation events per day in storage. During the 1987-88 season, the bins averaged 1.0, 1.8, and 2.6 ventilation events per day, while 3.8, 3.5, and 5.7 events per day were required to control the temperature of the potatoes in the simulated storages.

The practice of commercial potato storage ventilation in Michigan varies considerably from one operator to another. One storage manager may ventilate 15 minutes per hour during the holding period of storage, while another may advocate four cycles of 2 hours each day. The reason for this variation stems mostly from the experience of each storage manager in storing the potatoes produced on their own land. The conditions under which the potatoes are produced has an effect on the respiration of the tubers, which will change the ventilation management procedures required for each potato crop. The control computer applied the basic theory for storage ventilation: the removal of respiration by-products.

Data on bin #1 (56 m^3/tonne-hr) collected during the initial months of the 1987-88 storage season indicated that ventilation fan operation was required only 13 % of the first 85 days in storage. Periods of 10 days occurred when no ventilation was required. During these periods without ventilation, natural convection caused an accumulation of moisture in the upper 1 m of the potato pile. On December 29, 1987, the automatic ventilation of the experiment was terminated, and manual operation of ventilation fans was used to maintain product quality at an acceptable level. During this storage period, the potato pile was not generating heat at a standard rate, and pile temperature uniformity was within the desired range of 0.5 ^{o}C. The potatoes metabolic rate seemed to have slowed to a level which required little ventilation to maintain a desirable environment. This behavior was not noted during the 1986-87 or the 1988-89 storage seasons, and was also not the case in bins #2 or #3 during the 1987-88 storage season. The storage temperature during this period of low metabolism was 16 ^{o}C, which normally supports high metabolic rates in potatoes.

The data indicated that a lower percentage of ventilation time was required to eliminate pile temperature differentials in bin #2 (112 m^3/tonne-hr) than bin #1 (56 mh3/tonne-hr) or bin #3 (variable) throughout both storage seasons studied . This suggests that higher ventilation rates may be more effective at the preventing prolonged pile temperature differentials. An explanation for this may be the distance from the air inlet to the point at which the air reaches thermal equilibrium with the surface of the tuber. At higher ventilation rates thermal equilibrium is attained further from the air inlet, if at all. If this is the case, tubers at different levels in the storage are subjected to more uniform ventilation air conditions. This argument, as well as the data from the simulated storages would suggest that a higher ventilation rate would be better suited to the correction of temperature differentials.

Bin #3 was equipped with a variable speed fan that was operated by the controller for the 1987-88 and 1988-89 storage seasons. The ventilation rate was determined as previously discussed, and was proportional to the problem measured within the potato pile. The fan was capable of delivering from 0 - 112 m^3/tonne-hr. The average ventilation rate used was 54 and 37 m^3/tonne-hr for the 1987-88 and 1988-89 storage seasons respectively. During the 1987-88 storage season, the fan ran more hours than either bins #1 or #2. Less time was spent on ventilation of bin #3 for the 1988-89 storage season than either bins #1 or #2.

The influences within the control computer were changed between the 1987-88 and 1988-89 storage seasons in bin #3 to more effectively control the variable speed fan. The ventilation rate required for the correction of pile temperature differentials was increased by a factor of two. The data indicated that the average ventilation time for pile temperature differential correction was 12.0 hours during the 1987-88 season. The ventilation time required to correct pile uniformity problems during the 1988-89 season was 2.4 hours. The reduction in the ventilation time for pile uniformity correction in bin #3 for the 1988-89 season would indicate that the ventilation rate used for the 1988-89 storage season was more effective at obtaining a uniform pile temperatures than the rate used for the 1987-88 storage season.

5.11 Temperature Change Analysis Results

Over the period of the 1988-89 storage season, ten 0.5 ^{o}C temperature changes were performed per bin to bring the average pile temperature from 15 ^{o}C to 10 ^{o} C. The data recorded during these temperature change periods is reported in Table 5.16.

Table 5.16. Average and Standard Deviation of Time, Relative Humidity and Temperature Differential for 0.5 ^{o}C Temperature Change during the 1988-89 Storage Season.

Bin Number	Time Hours	Relative Humidity Percent	Temperature Diff. (C)
1	5.6 (1.7)	84 (2)	0.6 (0.3)
2	11.2 (0.8)	91 (3)	0.6 (0.3)
3	5.6 (2.3)	89 (1)	0.7 (0.6)

A statistical analysis performed on the data in Table 5.16 yielded the following significant (95% level) differences:

1) The temperature change took less time for both bins #1 and #3 then for bin #2.

2) The relative humidity of the inlet air during the temperature changes was less for bin #1 then bin #2 and bin #3.

5.12 Temperature Change Discussion

The response of the potato pile to this step temperature change was monitored, and the results were previously presented. The variable speed fan in bin #3 was set up to operate in a low airflow mode during cooling periods, and its operation was similar to that of the fan in bin #1. Temperature changes took less time in bins #1 and #3 (95 % significance level) then in bin #2.

The cooling of potatoes which consist of approximately 80 % water, occurs by simultaneous heat and mass transfer processes. An analysis of the Biot number, as calculated previously, yields information which suggests that both the conduction of heat through the potatoes and the convection of heat from the surface of the potatoes must be considered. Mass transfer is limited by the permeability of the tuber skin and the vapor pressure deficit (Villa, 1973). The condition of the inlet air determines the ratio of the amount of energy which can be transferred through the heat and mass pathways. If cooling is conducted with high humidity air, the heat transfer path carries the bulk of the energy which is removed. Low humidity cooling air increases the vapor pressure deficit, thus increasing the amount of energy passed throughout the mass transfer pathway.

The relative humidity of the inlet air was significantly higher (95 % level) for the 1988-89 storage season in bin #2 (91 %) than the relative humidity of the cooling air used in bin #1 (84 %). There were no statistically significant difference between bins on the average temperature driving potential. A mean separation of 0.13 ^{o}C existed between bin #2 (0.62 ^{o}C) and bin #3 (0.75 ^{o}C). The increased amount of time required to cool the potatoes in bin #2 over bin #1 may be attributed in part to the difference in inlet relative humidity. However time differences of the magnitude found experimentally are only partially explained by the observed differences.

5.13 Temperature Change Model

The model developed which simulated energy transfer as parallel heat and mass transfer was used to help define the role of each form of energy transfer in the cooling of a potato pile. This model calculated the time required for a temperature change of 0.5 ^{o}C in a column of potatoes 1 meter square by 4 meters deep. Table 5.17 presents a series of times to remove the energy required for this temperature change.

Table 5.17. Time Required for a Temperature Change from 12 ^{o}C to 11.5 ^{o}C in a 4 m^3 Column of Potatoes with Inlet Conditions of 11.0 C, 90 % RH, a 0.25 ^{o}C Temperature Gradient within the Potato, and Various Airflow Rates.

Air Flow Rate m^3/tonne-hr	Time to Cool hours
28	7.5
56	5.4
84	4.5
112	4.0
140	3.7
168	3.5

The model was then used to determine the effect of varying the inlet conditions and air flow rates on the time required for the temperature change of 0.5 °C previously defined. Figures 5.6, 5.7 and 5.8 present the results of simulation runs with different combinations of ventilation rate, temperature gradient within the potato pile and inlet relative humidity levels.

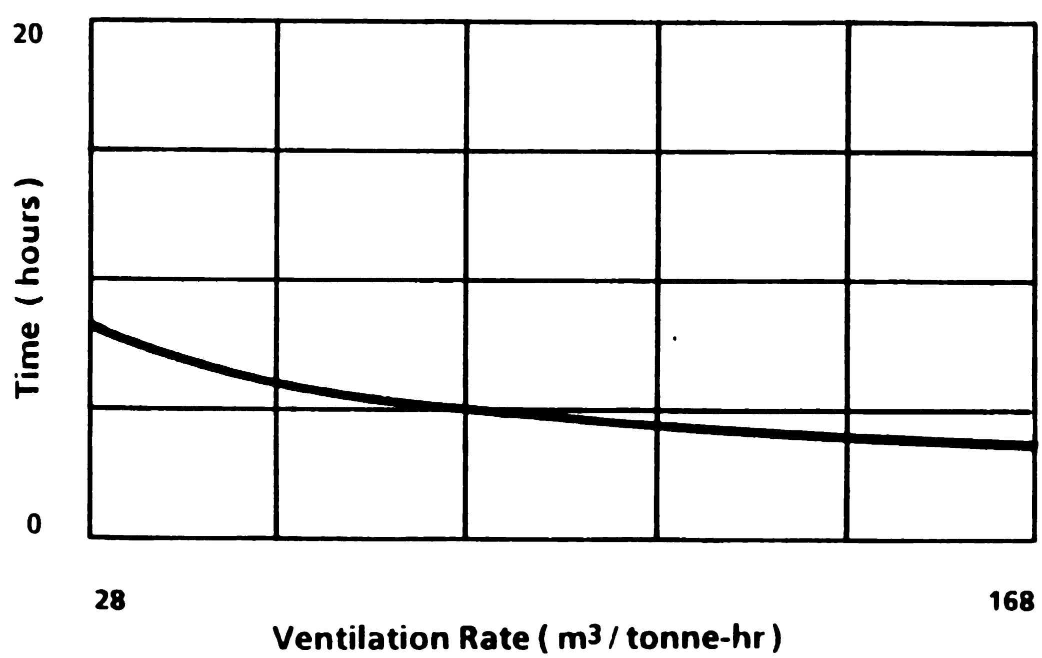


Figure 5.6 Predicted Time Required to Complete a 0.5 °C Temperature Change in a Four Cubic Meter Column of Potatoes, with a 0.5 °C Internal Temperature Gradient, Inlet Relative Humidity of 90 % and Various Airflow Rates.

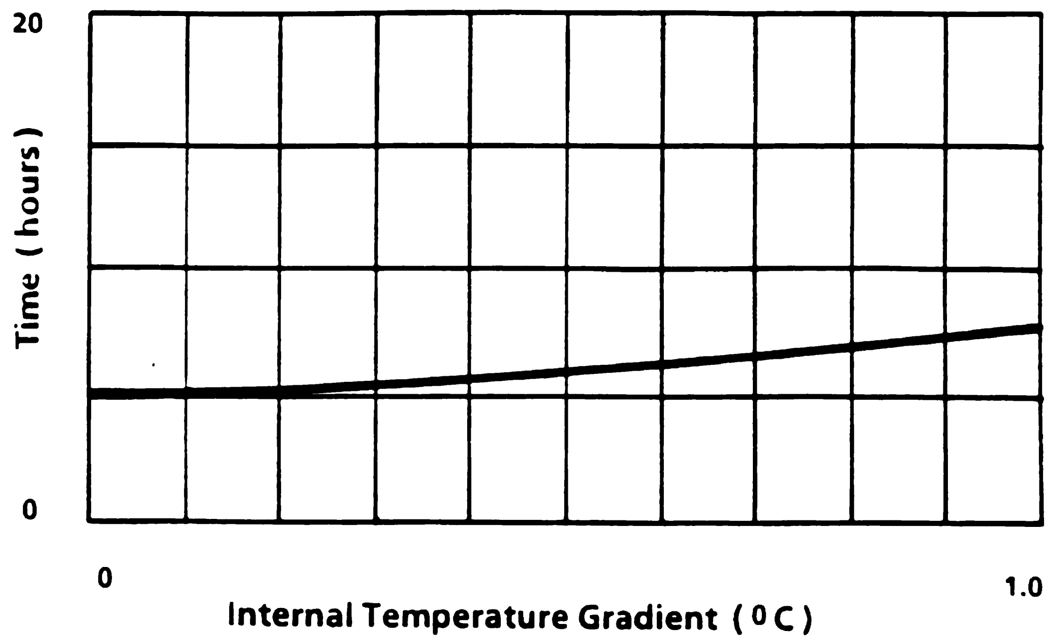


Figure 5.7 Predicted Time Required to Complete a 0.5 °C Temperature Change in a Four Cubic Meter Column of Potatoes with an Airflow Rate of 56 m^3/tonne-hr, an Inlet Relative Humidity of 90 %, and Various Internal Temperature Gradients.

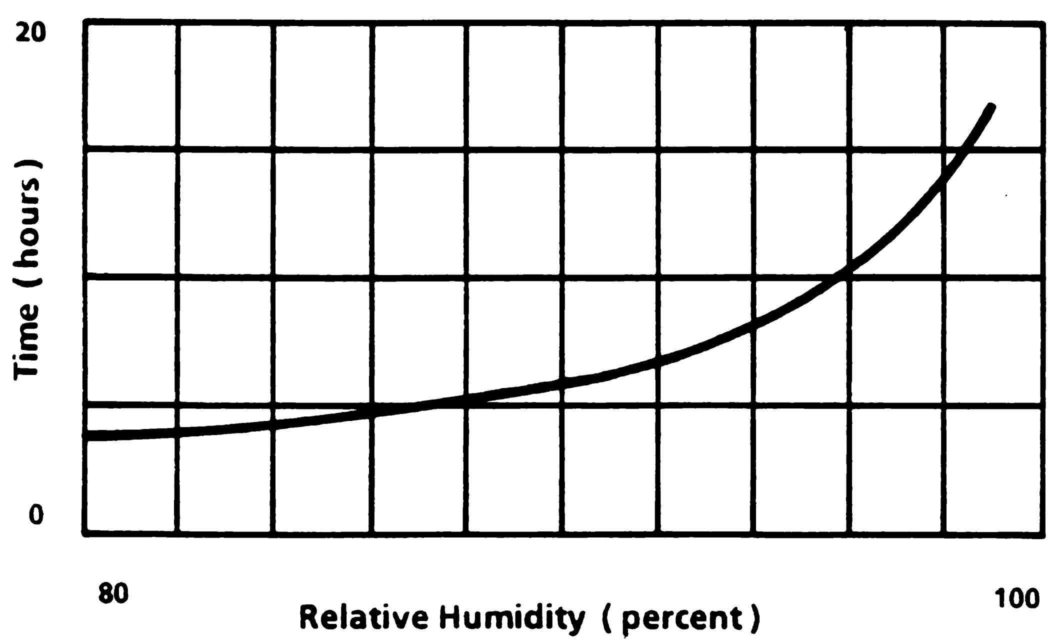


Figure 5.8 Predicted Time Required to Complete a 0.5 °C Temperature Change in a Four Cubic Meter Column of Potatoes with a 0.5 °C Internal Temperature Gradient, an Airflow Rate of 56 m^3/tonne-hr, and Various Inlet Relative Humidity Levels.

The model was also used to determine the amount of mass transferred during the cooling process studied. The inlet relative humidity, temperature gradient within the potato, and the airflow rate were varied over the ranges shown in Figures 5.6 through 5.8. This set of model runs resulted in a common volume of mass transferred (over all conditions studied) of 2.2 kg.

5.14 Temperature Change Modeling Discussion

A simple temperature change model was developed to determine the effects of the varying airflow rates and inlet air conditions on the time required to cool a 4 m^3 column of potatoes from 12 to 11.5 ^{o}C. The model predicted a cooling time of 5.4 hours to make this temperature correction using a ventilation rate of 56 m^3/tonne-hr, an inlet temperature of 11.0 ^{o}C, an inlet relative humidity of 90 %, and an internal temperature gradient within the 7.6 cm diameter potato of 0.25 ^{o}C. This prediction compared favorably with the measured 5.6 hour average time required to make a 0.5 ^{o}C temperature change in bin #1 of the simulated storage facility.

The model predicted a time of 4.0 hours for the previously described temperature change using a 112 m^3/tonne-hr ventilation rate, which did not compare well with the experimentally determined time of 11.2 hours. The experiment seems to have been influenced by some factor that is not currently explainable. It is interesting to note that the model predicts that a 29% reduction in the time needed to remove the energy from the potato column, from 5.4 to 4.0 hours, requires a 100 % increase in airflow. This indicates that the cooling process as simulated by this model at the described inlet conditions is primarily controlled by factors which are not affected by the ventilation rate.

The model predicts that an increase of inlet relative humidity from 80 to 95 % will result in an increase in cooling time from 2.8 to 7.0 hours at a ventilation rate of 56.1 m^3/tonne-hr, an inlet temperature 1.0 ^oC below the average potato temperature and an internal temperature gradient of 0.5 ^oC. Increasing the inlet air relative humidity decreases the vapor pressure deficit, which is the driving potential for the moisture transfer process. This large increase in cooling time would indicate that the moisture transfer pathway is carrying a majority of the energy removed during the cooling process studied.

Varying the temperature gradient within the potato tuber during the cooling process shifts the temperature driving potential from 100 % convective potential to 100 % conductive potential. The model predicts a time increase from 5 hours to 8 hours to accomplish the temperature change as the 1.0 ^oC temperature differential is shifted from 100 % convection (tuber surface to air temperature) to 100 % conduction (tuber center to tuber surface temperature). This would indicate that resistance to heat transfer through a conduction pathway is greater than the resistance posed by the convection pathway at a ventilation rate of 56 m^3/tonne-hr and an inlet relative humidity of 90 %. As the ventilation rate was increased, the time to cool by convection would decrease, while the time to cool by conduction would remain constant.

Throughout a cooling cycle, the temperature gradient within the potato will begin at 0 ^oC, and proceed to a steady state value determined by the temperature of the inlet air and the conductive heat transfer coefficient of the potato. As the internal temperature gradient is increased, an increasing portion of the energy transferred during the cooling process must pass through the heat conduction pathway.

The amount of mass transferred during the model studies discussed above was constant at 2.2 kg per cooling cycle. The mass flow rate varied one order of magnitude over the relative humidity range studied. However, the time varied one order of magnitude inversely to the mass flow rate. Thus the overall mass transferred was not changed. This simulation model indicates that the mass flow rate varies inversely as the time required for the energy transfer to cool the column of potatoes. This would substantiate the previous discussion that the mass flow rate, as determined by the vapor pressure deficit is a critical parameter in determining the energy transfer and the cooling rate of potatoes.

5.15 Finite Difference Control Model Results

The modified finite difference temperature and weight loss simulation was compared with data collected from the storages. Figure 5.9 presents plots of the measured and predicted values for the average pile temperature during a steady state control period. The experimental data was taken from a time period in January 1989.

The simulation was compared to a temperature change period during January of the 1988-89 storage season. The simulation run is presented in Figure 5.10 for the 56 m^3/tonne-hr ventilation rate, and Figure 5.11 for the 112 m^3/tonne-hr ventilation rate.

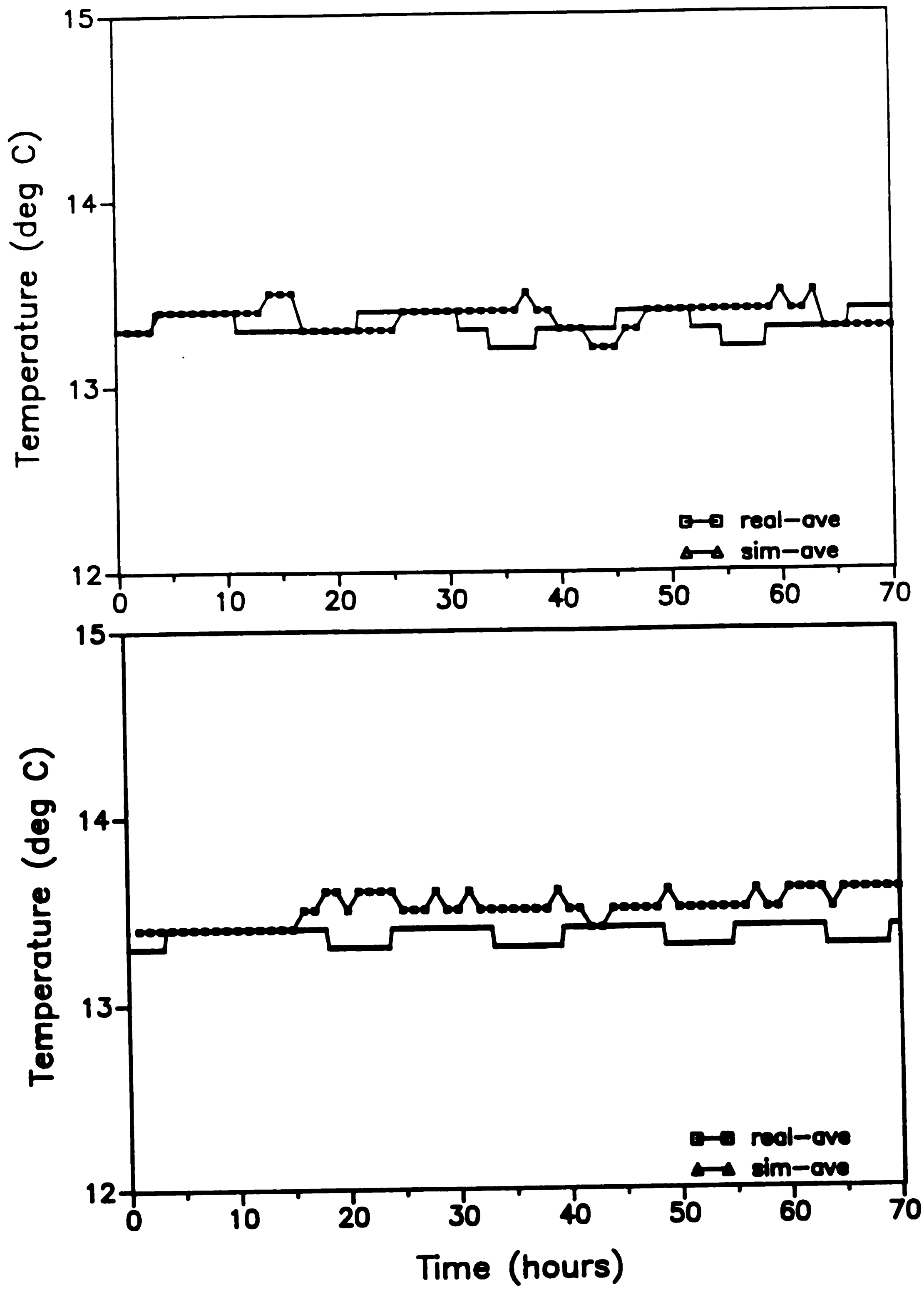


Figure 5.9 Comparison of the Simulated and Real Average Pile Temperatures during a Steady State Storage Period for the 1988-89 Storage Season at an Airflow Rate of 56.1 (Top) and 112.2 m^3/tonne-hr (bottom).

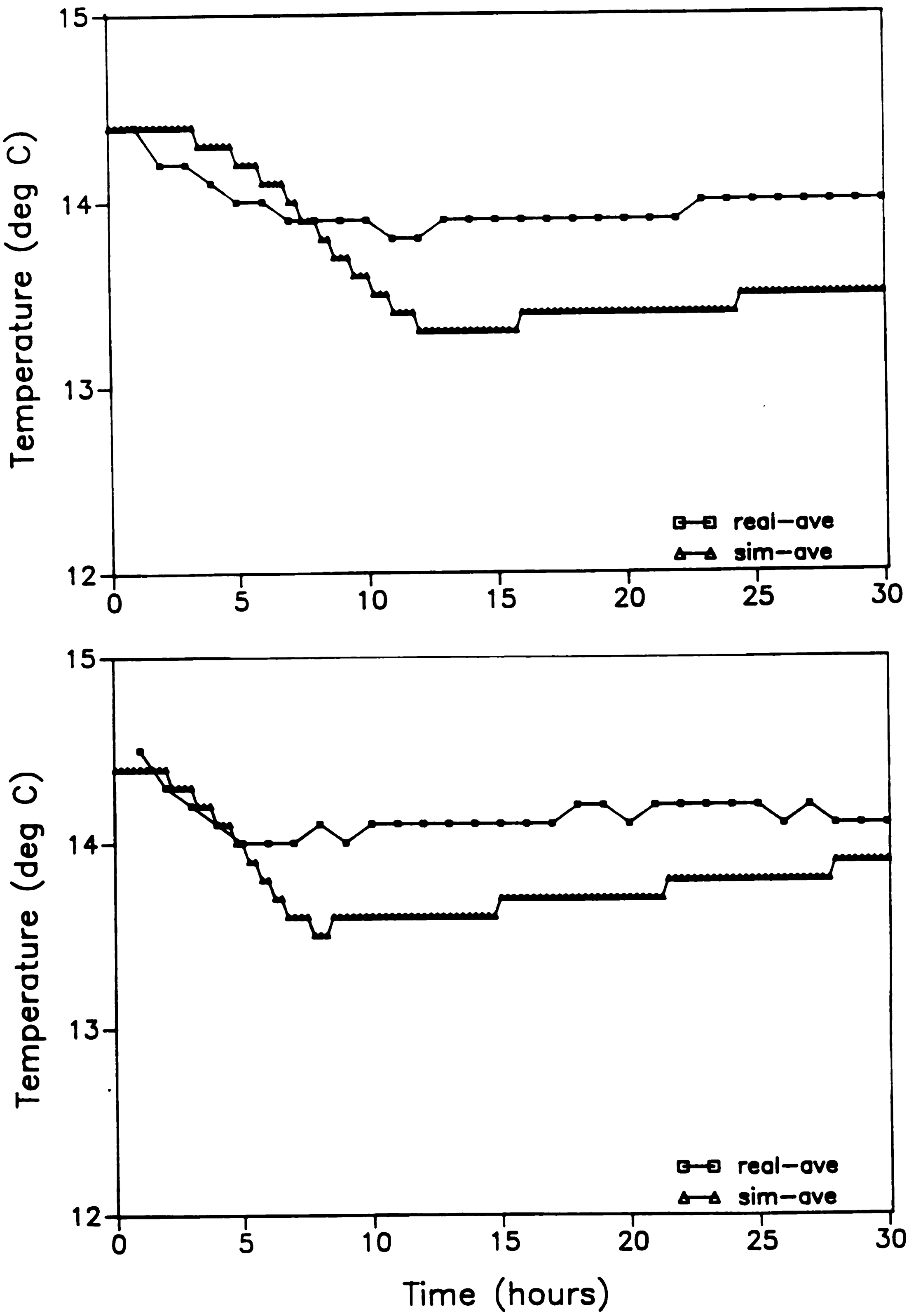


Figure 5.10 Comparison of the Simulated and Real Average Pile Temperatures during a Temperature Change Period for the 1988-89 Storage Season at an Airflow Rate of 56.1 (Top) and 112.2 m^3/tonne-hr (bottom).

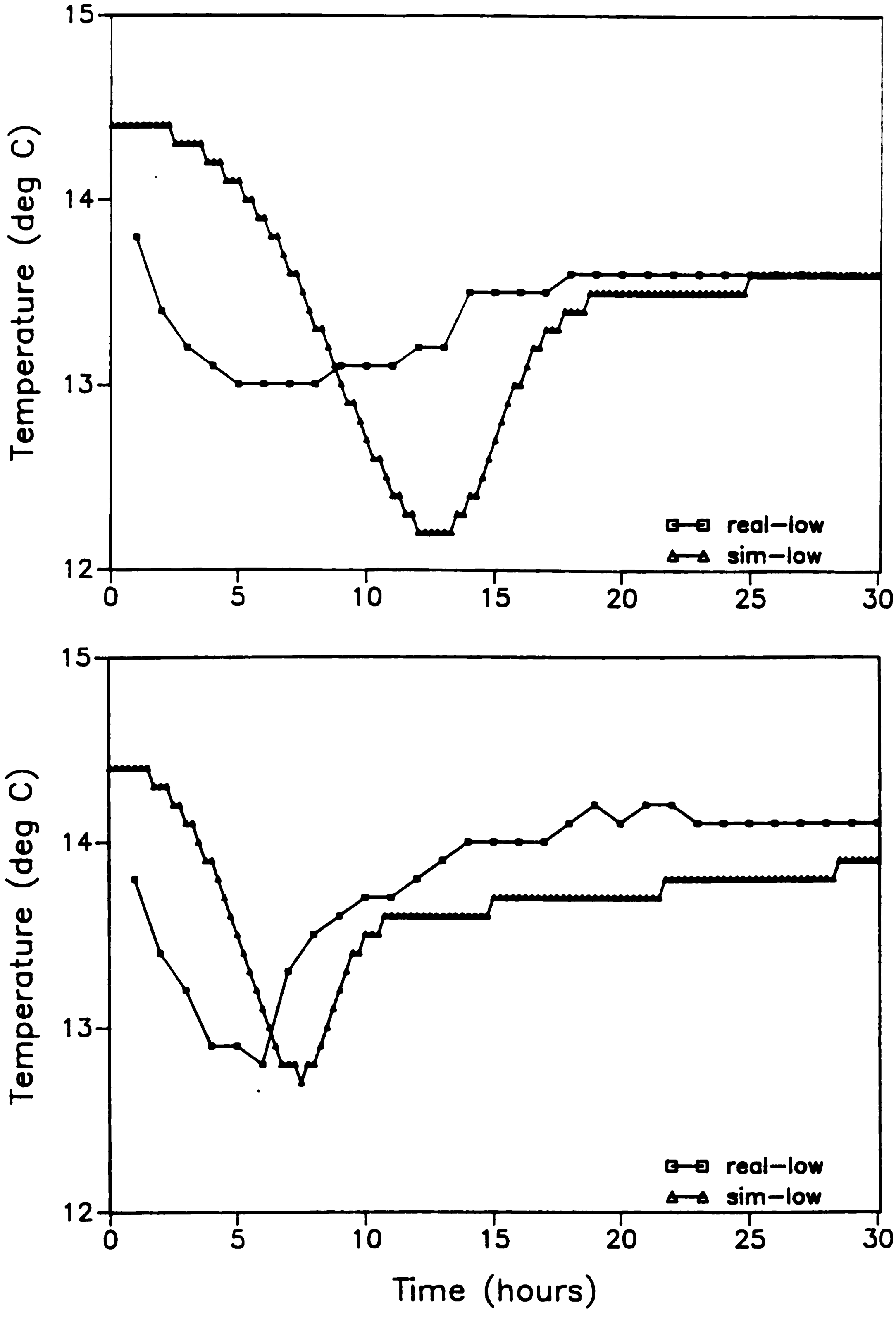


Figure 5.11 Comparison of the Simulated and Real Pile Temperature at a Distance of 1.22 m from the Storage Floor during a Temperature Change Period for the 1988-89 Storage Season at an Airflow Rate of 56.1 (Top) and 112.2 m^3/tonne-hr (bottom).

5.16 Finite Difference Control Model Discussion

The finite difference temperature and weight loss prediction model developed by Lerew (1978) was modified by the addition of a temperature and humidity control algorithm similar to the FANCOM 1056 environmental control computer. The heat generation equation was also modified to match the heat generation measured from the potatoes used for this experiment. The predicted vs. measured potato temperatures were compared with data collected during the 1988-89 storage season. The steady state simulation results indicated that the temperature simulation of the potato storage responded similarly to the temperature history of the experimental potato storage studied.

A comparison was made between the control simulation and the experimental data for a temperature change period of the simulated storage facility. The simulation predicted average pile temperature was changed 0.5 ^{o}C in the same time that the actual average pile temperature was changed. However a temperature overshoot of 0.6 ^{o}C was noted in the simulation (Figures 5.10 and 5.11). This indicates that the simple control routine used to approximate the FANCOM 1056 controller was not closing the fresh air louver quickly enough.

The FANCOM control program utilizes a minimum pulse and pulse repeat time to control the fresh air louver for cooling. The controller pulse and pulse repeat times are varied above the minimum value based on the louver position adjustment required. This feature, which allows increased the controller to adjust the air inlets quickly if large louver position changes are required, was not included in the simulation model written to evaluate the controller. erhaps this difference is the cause of the temperature overshoot noted in the simulation of the potato storage.

5.17 Simulation of a Condensation Problem

The modified finite difference simulation was used to study a problem of potential condensation on the surface of potato tubers. The simulation study was performed on a 4 m deep column of potatoes with 2 m of warm potatoes (21 ^{o}C) placed on top of 2 m of cool potatoes (10 ^{o}C). The simulation model predicts the volume of moisture in the ventilation air. If the air comes into contact with a cool surface, a calculation is made on the amount of moisture deposited on the cool surface. A typical plot of predicted water film thickness on the cool potato surfaces versus the position in the column is presented in Figure 5.12. This data was generated by simulation runs with ventilation modeled as complete recirculation, and with fixed inlet conditions. The amount of time required to remove the condensation from the tuber surface using different air flow rates and inlet conditions is presented in Table 5.18.

Table 5.18 Predicted Weight Loss and Time Required to Remove Condensation from the Surface of Potato Tubers Utilizing Various Air Inlet Conditions and Ventilation Rates.

Ventilation Rate	Inlet Air Conditions		Time	Weight Lost
	Temp.	RH		
m^3/tonne-hr	(^oC)	(%)	hrs.	Percent
56	Recirculation		-----	-----
28	15.5	65	100	0.95
56	15.5	65	45	0.80
112	15.5	65	20	0.35
28	15.5	80	160	0.95
56	15.5	80	95	0.92
112	15.5	80	40	0.55

The simulation of this condensation problem yielded the following predictions.

1) In the complete recirculation mode, the condensation was not removed from the surface of the tubers within the 250 hour simulation.

2) The simulation predicted that high air flow rates would remove surface condensation in less time with less weight loss.

5.18 Discussion of a Condensation Problem

The modified temperature and weight loss simulation was used to study different ventilation system management strategies to alleviate condensation from the surface of potato tubers. The problem studied was one which occurs during the filling of a potato storage bin in cool weather. As the grower harvests potatoes throughout the day, the

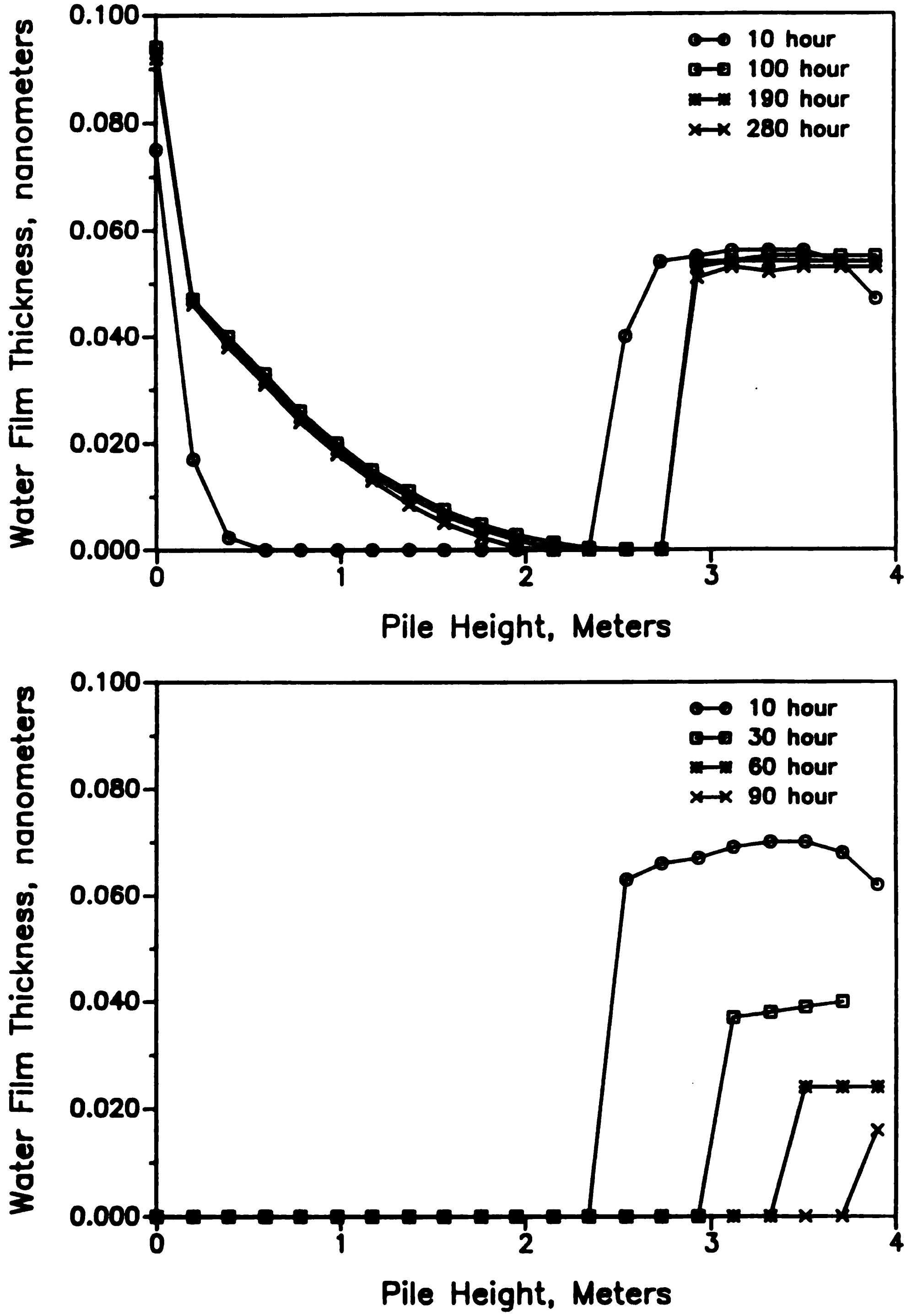


Figure 5.12 Water Film Thickness on the Tuber Surfaces Simulated within a Four Meter Deep Pile with Two Meters of 21 °C Temperature Potatoes on Top of Two Meters of 10 °C Temperature Potatoes at a Ventilation Rate of 56 m^3/tonne-hr.
(Top : Complete Recirculation)
(Bottom : Inlet Conditions, 15.5 °C, 80% RH)

tuber pulp temperature increases as solar radiation heats up the soil. At the interface between batches of potatoes harvested on successive days in a storage bin, cool potatoes harvested in the morning at a pulp temperature of in the range of 10 ^{o}C are placed in direct contact with potatoes harvested the previous day with a pulp temperature in the range of 21 ^{o}C. The potential exists for condensation on the surface of the cooler potatoes piled on top of the warmer potatoes along the angled face of the pile. The effectiveness of different ventilation conditions could be measured by the simulation; The simulation could also be extended to the problem of removing surface moisture from potatoes coming from wet soil.

The simulation of this problem included varying the ventilation rate and inlet air relative humidity to determine the most effective means of removing the condensation from the surface of the tubers, with a minimum weight loss.

The simulation model predicted that using the ventilation system in the complete recirculation mode during this phase of storage, which is a common practice, will result in the transfer of moisture from the upper level of the pile to the lower levels of the potato pile. Thus the moisture is distributed over the surface of all potatoes in the pile. The moisture was not removed from the tuber surfaces over the 250 hour simulation time.

Further simulation work indicated that if the inlet relative humidity were set at 65%, the time required to remove the condensation from the pile was reduced as compared to setting the relative humidity at 80%. The inlet air was set at the average temperature between the two potato pulp temperatures. Changing the inlet relative humidity changes the water holding capacity of the ventilation air. Increasing water holding capacity of the ventilation air, which was set at the average of the potato pulp temperature used in the simulation, would account for the reduced time required to remove the condensation from the surface of the tubers.

Simulations were also performed at different airflow levels. The results indicated that as the airflow rate was increased, the time required to remove the condensation was proportionally reduced. The total volume of moisture that must be removed is constant for all simulations. Thus if the ventilation air conditions are fixed, the time required to remove the condensation should vary inversely with the volume of air passed over the surface of the potatoes.

6. Summary and Conclusions

Three years of research were conducted on the storage of potatoes with ventilation systems designed with different ventilation rates. The following conclusions were drawn in an attempt to quantify the differences in storage performance based on ventilation rate.

1) Average weight loss within the simulated storage research bins was not a function of ventilation rate.

2) Weight loss was more uniform from the top to the bottom of the potato pile at high ventilation rates.

3) The pre-conditioning management strategy outlined by Sowokinos (1987) produced high quality potatoes (cv. Atlantic) for storage at 10 ^{o}C for 135 days.

4) The environmental control of the simulated storage research bins was effectively carried out using the FANCOM 1056 environmental control computer. A controller was developed specifically for the potato storage industry by FANCOM B.V. utilizing information gathered from this study.

5) The simulation runs performed to determine an adequate management strategy for removing moisture from the surface of potato tubers indicated that high ventilation rates (112 m^3/tonne-hr) performed better then low rates in terms of time required for moisture removal and estimated weight loss during this time.

6) The result of calculations with the model developed indicates that the time required for a temperature change of the magnitude studied was primairly controlled by latent heat transfer, and was not adversely affected by changes in ventilation rate or internal temperature gradients within the potatoes.

The goal of this research was to determine the effect of different rates of through-the-pile ventilation for potato storage in Michigan, justify current ventilation recommendations, and determine a probable cause of the differing ventilation recommendations found throughout the world. The previously stated conclusions of this research indicate that the current ventilation recommendation in Michigan is higher than required for the holding phase of storage. The ventilation of a potato storage, however, is also dependent on the condition of the potatoes going into the storage. Storage ventilation rate recommendations are primarily affected by the condition of the potatoes at harvest time. In West Germany and The Netherlands where the requirement to dry potatoes coming from the field is commonly cited (Hesen, 1989; Leppack, 1989), recommended ventilation rates are in the range of 100 to 150 m^3/tonne-hr. In Michigan, where "fall harvest conditions vary" (Cargill, 1989) ventilation rate recommendations are in the range of 38 to 56 m^3/tonne-hr. In the Pacific Northwest, where harvest conditions are "dry and warm" (Waelti, 1989), ventilation rates in the range of 22-32 m^3/tonne-hr are recommended.

The current ventilation recommendations in Michigan are acceptable for the state of potato storage monitoring that exists. Each storage season presents a different problem to be controlled by the ventilation system. The lack of monitoring systems within potato storage bins to determine if condensation is occurring, or if potato pile temperatures are out of range presents the need for excessive ventilation to assure that potatoes are not lost. As monitoring systems are employed, the ventilation rate may be varied depending on measured ventilation needs to conserve energy and reduce storage costs.

7. Suggestions for Future Research

Differences exist between potato storage ventilation recommendations throughout the world. Previous discussion indicated some possible causes for these differences. An attempt was made to justify the current recommendations in the state of Michigan. The next logical step in research is to monitor the economic costs, in terms of energy consumption, which are required by these different ventilation strategies throughout the storage season. The result of a study of this nature would indicate the economic consequences of storage ventilation. A result of this study might be that using variable rate ventilation system designed to meet both the requirements of conditioning the product after harvest, and maintaining this quality once attained, would be a desirable alternative to using one ventilation rate. A monitoring and control system would be required to determine the needs of the potato pile throughout the storage season.

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