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DEVELOPMENT OF A TEMPERATURE-WEIGHT LOSS
MODEL FOR BULK STORED POTATOES

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DEVELOPMENT OF A TEMPERATURE-WEIGHT LOSS MODEL FOR BULK STORED POTATOES

By

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ABSTRACT

DEVELOPMENT OF A TEMPERATURE-WEIGHT LOSS MODEL FOR BULK STORED POTATOES

By

Lloyd Eugene Lerew

Simulation of the temperature and weight loss of bulk stored potatoes, based on principles of heat and mass transfer, permits optimum control of the storage conditions of potatoes. General patterns which may be masked by biological variability in experiments are discernible using the model.

Three general models for unidirectional forced ventilation of biological products were formulated based on assumptions regarding the temperature within the product: (1) continuous thermal equilibrium between the air and product, (2) uniform temperature within the product with finite convective heat transfer between the air and product, and (3) finite convective heat transfer at the surface of spherical products with internal temperature gradients. Each model consisted of a set of partial differential equations and of relationships for heat generation and evaporation rates. The equations were solved using numerical finite difference techniques.

Expressions for the heat generation and weight loss rates of well-suberized potatoes were taken from the literature and applied to the three models. Based on simulated results and theoretical

considerations, it was shown that modeling of temperature gradients within the tubers was not necessary within the range of ventilation rates normally applied. The assumption of continuous thermal equilibrium between the air and potato tubers was similarly shown to be invalid for large temperature variations. Hence, the uniform product temperature model was chosen for further development as a model of forced convection in bulk stored potatoes. Comparison of results from this model with experimental data from laboratory and commercial-sized storages gave acceptable agreement.

During unventilated periods, the air and potatoes were assumed to reach thermal and moisture equilibrium and heat conduction within the air and potatoes was simulated. Bulk flow of air (free convection currents) was not modeled.

Equations were formulated to express the time-temperature relationship of heat generation and resistance to water vapor diffusion during the suberization period. These equations were added to the model and the first month of storage for a 4 m bed of potatoes was simulated using a variety of control systems and ventilation rates.

In all cases, immediate cooling from 17° to 7°C with a maximum 2°C differential resulted in undesirably large weight loss gradients with high weight loss at the air inlet. Continuous ventilation at rates ranging from 20 to 70 m^3 of air/h/m^3 of potatoes resulted in excessive weight loss at the completion of cooling.

The existence of an optimal time clock setting-ventilation rate combination was shown. Higher than optimum airflow resulted in excessive weight loss while lower airflow failed to maintain the desired temperature.

Thermostatic control was shown to maintain the desired temperature with minimum weight loss at any given ventilation rate within the range tested. However, low ventilation rates with this type of control resulted in longer time periods at higher temperatures and hence greater heat generation and weight loss.

The results demonstrated the broad range of applications of the potato storage model. Development of the model aided in making suggestions for future research which have the greatest potential for enhancing the accuracy of predictions and for extending the range of the potato storage model.

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LIST OF SYMBOLS

A	Area, m^2
a	Specific surface area, m^2/m^3
B	Arrhenius frequency factor, h^{-1}
Bi	Biot number (= hr/k), dimensionless
b	Constant
c	Specific heat, J/kg °C
D	Diameter, m
D_{wa}	Molecular diffusivity of water vapor, m^2/h
E	Activation energy, cal/g-mole
e	Eccentricity, equation (5.4)
F	Function (unspecified)
H	Humidity ratio, kg_w/kg_a
h	Convective heat transfer coefficient, J/h m^2°C
h_D	Convective mass transfer coefficient, m/h
h_{fg}	Latent heat of vaporization, J/kg_w
h'_w	Apparent overall convective mass transfer coefficient [= $(Mh_D)/(R_oT_A)$] Kg/Nh
J_H	Chilton-Colburn J-factor for heat transfer (Table 4.3), dimensionless
J_D	Chilton-Colburn J-factor for mass transfer (Table 4.3), dimensionless

K	Resistance to airflow, dimensionless or rate constant, h^{-1}
K_D	Mass transfer coefficient
k	Thermal conductivity, J/h m °C
L	Bed depth, m
M	Molecular weight, g/g-mole
m	Cumulative weight loss, kg/m^3
$\dot{m}$	Weight loss rate, kg/h m^3
m'	Weight loss rate, %/wk
N	Number of radial nodes
P	Total pressure, N/m^2
P_i	Vapor pressure inside tuber, N/m^2
P_r	Prandtl number $(= \frac{c\mu}{k})$, dimensionless
P_s	Saturated vapor pressure, N/m^2
P_v	Vapor pressure of air, N/m^2
Q	Heat generation rate, J/h kg
$\dot{q}$	Heat transfer rate, J/h m^3
R	Resistance to flow of water vapor, N m h/kg
Re	Reynolds number $(= \frac{\rho v \varepsilon}{\mu a})$, dimensionless
RI	Rot index, m h
R_o	Gas constant, $(N/m^2)\ m^3$/g-mole °K or cal/g-mole °K
r	Radial coordinate, m
$r\delta$	Skin parameter (product of membrane thickness, δ and resistance, r), m

S	Cross-sectional area, m^2
Sc	Schmidt number ($= \frac{\mu}{\rho D_{wa}}$), dimensionless
S_g	Specific gravity
s	Weight of sprouts, %
T	Air temperature, °C
t	Time, h
V	Volume, m^3
VPD	Vapor pressure deficit, N/m^2
v	Average interstitial velocity, m/h
w	Weight, g
X	Mass fraction
x	Depth coordinate, m
Y	Equation 4.65, dimensionless
Z	Equation 4.66, dimensionless

Greek

β_1	Tuber width, m
β_2	Tuber thickness, m
β_3	Tuber length, m
γ	Area which behaves as a permeable membrane, fraction
γ'	Area which behaves as a free water surface, fraction
Δ	Difference or differential
δ	Thickness, m
ε	Void space, fraction

Θ	Product temperature, °C
μ	Viscosity, kg/m h
ρ	Density, kg/m^3

<u>Subscripts</u>

A	Absolute
a	Dry air
ave	Average
b	Bulk
c	Center
d	Dry matter
i	Initial or inlet
n	Index
o	Final or outlet
p	Product
s	Surface
sat	Saturated
v	Water vapor
w	Liquid water

1. INTRODUCTION

World production of potatoes, excluding China, averages over 245 million metric tons per year (American Potato Yearbook, 1976). Of this total, the U.S.S.R. produces about 38%; Eastern Europe, 29%; Western Europe, 20%; and North America, 7%. Japan, India and South America account for most of the remaining 5%. Total production is stable with a steady decrease in the area planted being compensated by improved yields (van der Zaag, 1976). Figure 1.1 shows the utilization of the world and U.S. potato crops. Nearly 50% of the total production in Europe is utilized as stockfeed (van der Zaag, 1976).

The potato is a biochemically complex, living organism of considerable importance to the human food supply and world economy. The biological value of potato protein is higher than other plant protein and nearly as high as that of egg protein (Burton, 1974a). Table 1.1 lists the amino acids provided by potatoes and the requirements for an average adult male as presented by Burton (1966). According to Burton, a mixture of one egg with 600 g of potato supplies 75% of the minimum daily protein requirement of a 70 kg male but only 17% of the energy requirement (about 500 kcal).

Potatoes are also good sources of essential vitamins, particularly vitamin C. Burton (1974a) estimated that potatoes supply

Table 1.1. Requirements of essential amino acids and the extent to which these may be supplied by potatoes (from Burton, 1966).

Amino acid	Requirement of average adult male (70 kg) g/day to maintain N balance[1]	Average amount provided by 1 kg raw potatoes (g)[2]	Approx. kg of potatoes to provide daily requirement				
			Boiled	Mashed[3]	Baked in Skin	French Fries	Chips
Tryptophane	0.28	0.32	0.9	0.9	0.6	0.4	0.3
Lysine	0.84	1.23	0.7	0.7	0.4	0.3	0.3
Leucine	0.95	1.33	0.7	0.7	0.5	0.3	0.3
iso-Leucine	0.84	1.37	0.6	0.6	0.4	0.3	0.2
Methionine	0.45 (0.60)	0.32	1.4 (1.9)	1.4 (1.9)	0.9 (1.2)	0.6 (0.8)	0.5 (0.7)
Cystine[4]	0.39 (0.30)	0.15	2.6 (2.0)	2.6 (2.0)	1.6 (1.2)	1.1 (0.8)	0.9 (0.7)
Phenylalanine	0.64	0.89	0.7	0.7	0.5	0.3	0.3
Tyrosine[5]	0.46	0.76	0.6	0.6	0.4	0.3	0.2
Threonine	0.56	0.81	0.7	0.7	0.4	0.3	0.3
Valine	0.84	1.05	0.8	0.8	0.5	0.4	0.3

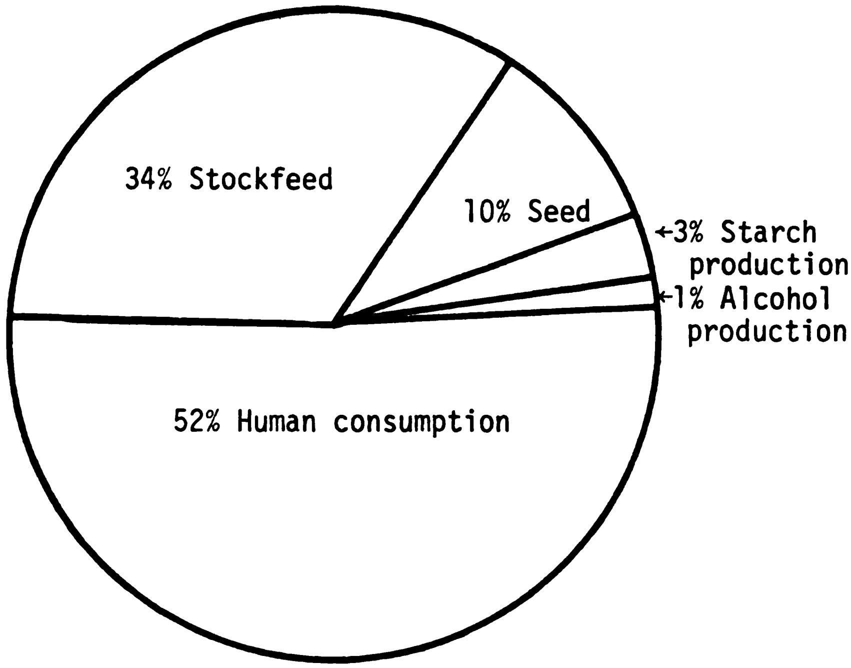
[1]To maintain N balance or slight excess.

[2]Average N content of the potatoes was 0.32% and 63.7% of this was protein-N.

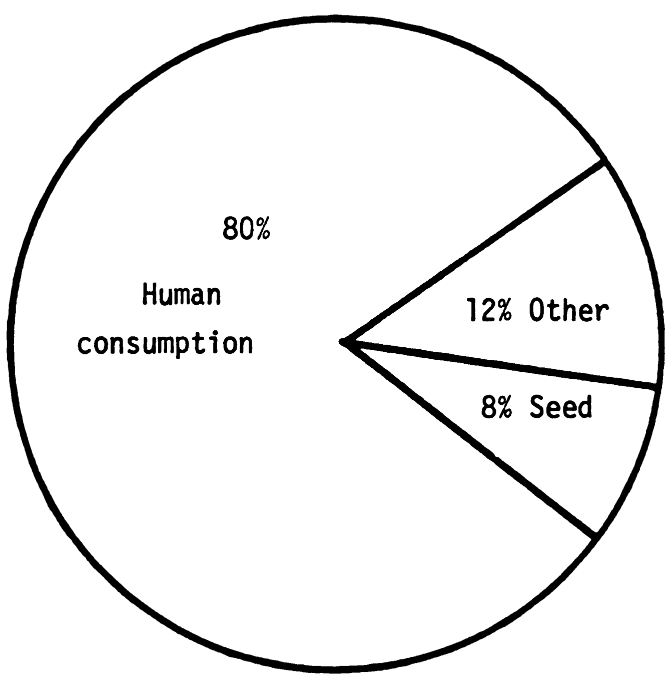
[3]Four g each of butter or margarine and milk have been assumed to be added. Although milk has, weight for weight, some 50% more N than potatoes, the amount added is too small to affect appreciably the approximate values given.

[4]Cystine is a partial substitute for methionine and the figures in parentheses are adjusted to be roughly in the same proportion as that in which these amino acids occur in the potato.

[5]Not essential, but reduces the requirement of phenylalanine, which in the absence of tyrosine, was given as 1.08 g/day.



World utilization of potato crop
(from van der Zaag, 1976)



U.S. utilization (from American Potato Yearbook, 1976)

Figure 1.1. World and U.S. potato crop utilization.

nearly one-third of the vitamin C in the diet in Great Britain where surveys indicate that the nutritional value of potatoes is as widely misunderstood by consumers as it is in the United States.

The disadvantage of potatoes as a staple foodstuff, compared with cereals, is their low content of dry matter and associated low energy value (about 70 calories/100 g).

Van der Zaag (1976) estimated that 25% of the potatoes produced worldwide as ware or seed potatoes are used as stockfeed due to wastage. This represents a considerable food value. In some cases, wastage as a result of storage failures is so severe that the resulting product is not acceptable as stockfeed (personal observation). Such wastage represents a total loss from the food chain.

The economic impact of storage losses is far reaching. Potato processors experience losses in terms of increased processing costs or decreased finished product quality as a result of changes which occur during storage which do not affect the grade nor the price of the raw product (McKinney and Thiessen, 1974). Losses resulting in diversion of potatoes intended for human consumption may increase costs to consumers as well as decreasing the income of the storage owner. In Europe and the U.S.S.R., where a large portion of the crop is used for stockfeed, corn and barley are economically tied to potatoes (van der Zaag, 1974). Increases in the stockfeed supply which result from wastage of potatoes intended for consumption may affect the world grain trade.

In addition to the losses suffered by storage owners as a result of rotting, physiological breakdown, or irreversible biochemical changes causing the diversion of potatoes intended for consumption into other market channels at lower prices, storage owners incur economic losses as a result of total weight losses which result from the normal evapotranspiration which continues throughout the storage period (Sparks and Summers, 1974).

Because of their importance to the food supply, economically and nutritionally, improved storage techniques which decrease the losses and wastage of potatoes benefit all of society.

1.1 The Storage Structure

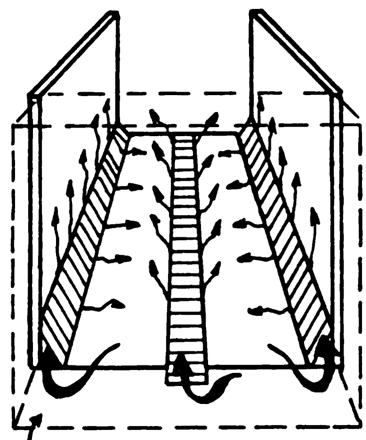
One of the factors contributing to the general worldwide acceptance of the potato as a food staple is the relative ease with which it can be maintained in an edible form. This is not surprising if one considers the potato tuber to be a storage organ naturally adapted to survive (Burton, 1972). For centuries, potatoes have been stored in excavated pits or caves. In these environments, the temperature remains cool but above freezing, the humidity remains high and adequate ventilation can occur through natural convection.

Although simple storages may still be the most economical for a single family unit, they are not practical for the volume grower or processor. In addition, a tuber in edible form may be far removed from salable form.

Modern potato warehouses are generally composed of a series of individual bins. Each bin typically measures 6 to 9 meters wide by 24 to 36 meters long with a pile depth of 3 to 5 meters and holds 250 to 1,000 tons of potatoes (Cargill, 1976).

Each bin is equipped with an air distribution system usually similar to those depicted in Figure 1.2. The plenum chamber containing the fans and other air conditioning equipment such as heating and humidifying elements is located at one end of the bin. After passing through the distribution system and potato pile, the air returns to the plenum or to exhaust ports over the pile. The amount of air recirculated is controlled by manual or automatic dampers as shown in Figure 1.3. Small fans (Cargill, 1976) or electric heaters (Hylmö and Wikberg, 1976) are often used on the ceiling above the pile to prevent drip or formation of condensation.

Control necessary for the fan, heaters, humidifiers and dampers depends upon the air conditions outside and conditions inside above and below the potatoes (Cloud, 1976b). The control system must be able to identify (a) when the bin temperature is above ambient, (b) when the bin has reached the desired temperature, and (c) when the ambient is too cold (Bartlett, 1972). Thermostats, differential thermostats, humidistats, time clocks, motor starters and relays may be involved. The degree of automation is highly variable and is generally correlated with the complexity of the control system.



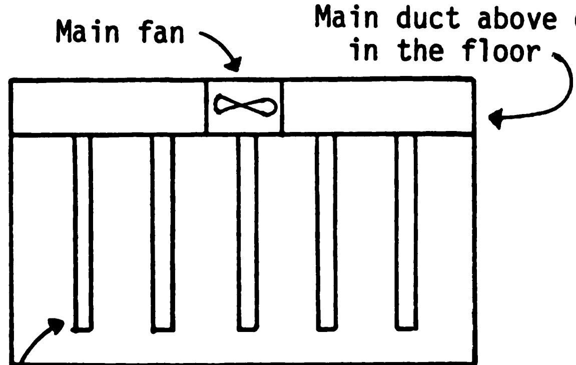


Figure 1.2. Air distribution systems for through-the-pile ventilation (from Cloud, 1976a).

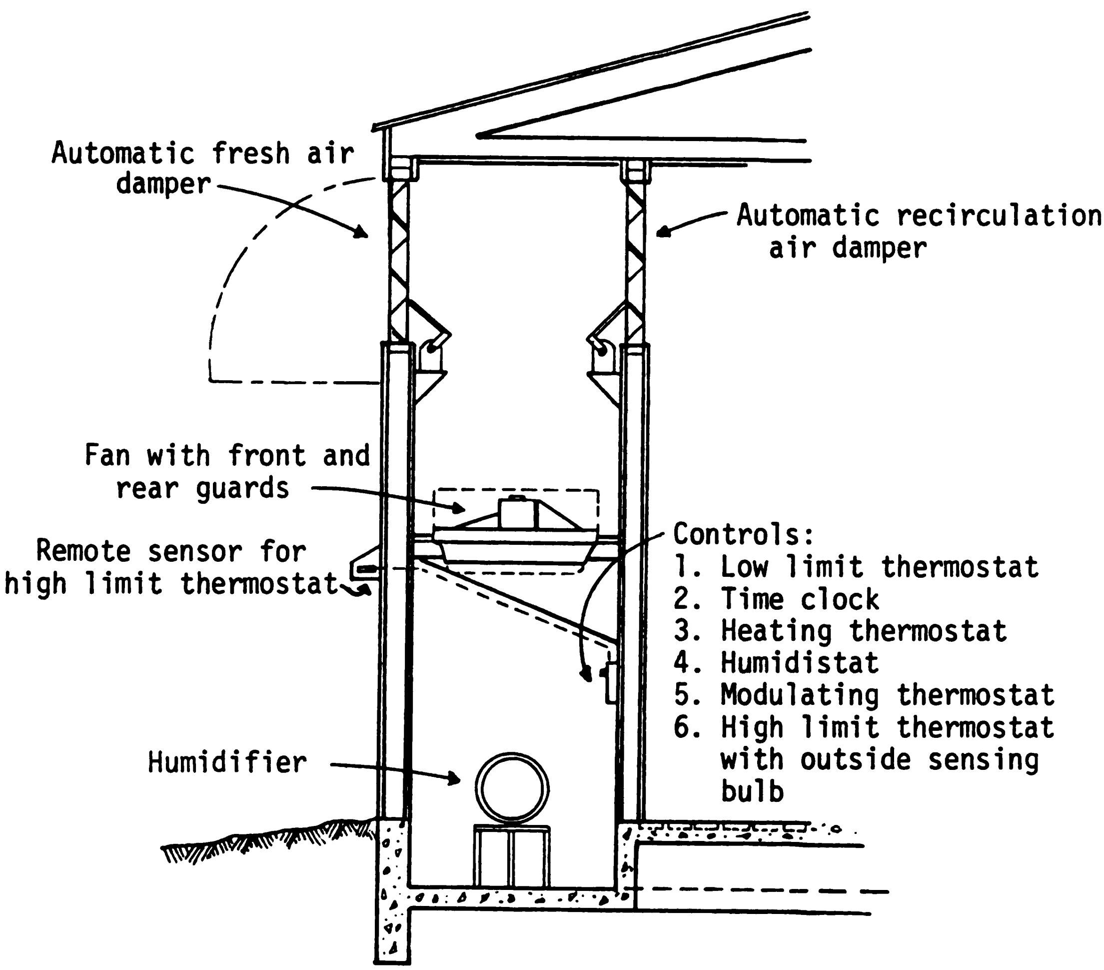


Figure 1.3 Plenum chamber with automatic control (from Mitchell and Rogers, 1976).

If the storage is to be operated at temperatures below the prevailing ambient, a refrigeration system and appropriate controls are included. Refrigeration systems may also be included for use in cooling the potatoes to the desired holding temperature immediately after harvest in areas where the ambient temperature remains warm (Wilson, 1976). Hylmö and Johansson (1976a) discussed the possibility of using artificial cooling for seed potato storage.

Cargill (1976) edited a detailed volume on the design, construction, handling and environmental control of potato storages.

1.2 Management of the Storage

Potatoes do not improve in quality during storage. While the ability to prevent quality deterioration is affected by the storage facility, it is much more dependent upon the management of the facility.

The potato storage period can be divided into several distinct periods. It is generally agreed that the environmental controls applied to each period should reflect the goals of the period. There are, however, opposing viewpoints regarding the end effects upon tuber quality and economic advantage of the various management techniques which can be applied.

1.2.1 Drying Period

Rotting of potatoes in storage is nearly always associated with the presence of a free water surface (Ophuis, 1957; Burton, 1963a; Cromarty and Easton, 1973; Pérombelon and Lowe, 1975;

Grähs et al., 1977; Lund and Kelman, 1977). Therefore, should the tuber surfaces be wet (not moist) when placed into storage, a substantial risk of severe loss exists. Ventilation rates of 100 m^3 of air/m^3 potatoes/hour with separate storage and early sales are recommended by Meijers (1971) for wet potatoes in the Netherlands. Ventilation should continue at high rates for several days until all adhering soil is air dry (Hesen, 1970).

Burton (1963a) pointed out the difficulty of drying the contact areas between tubers which are wet when loaded into the storage bin.

1.2.2 Suberization, Curing, or Preconditioning Period

If the potato surfaces are dry when placed into storage, no drying period is necessary.

The first stage is then the curing or wound healing period which is important in limiting evaporative weight loss and attack by pectolytic bacteria. Excess ventilation should be avoided to prevent needless moisture loss. Freshly harvested potatoes lose water rapidly, particularly if the tubers have not reached full maturity or have been damaged (Kolattukudy and Dean, 1974). Ophuis (1957) ventilated immature and mature tubers at a rate of 300 m^3 air/m^2/h. The weight loss of the immature samples was 4%-6% during the first month while that of the mature samples was 1%-3%. Both samples lost 1/2% to 2/3% during subsequent months. Burton (1963a), experimenting with tubers exposed to free air circulation, reported weight loss rates of about 0.7%/week/mm Hg vapor pressure deficit (VPD) for freshly dug stock dropping to 0.2%/week/mm Hg VPD after the first few weeks. Larsson (1973) found that approximately one-third of the weight which was lost during six to seven months of storage was lost during the first two or three weeks.

Mechanical damage to the skin results in increased evaporative losses (Ophuis, 1957; Larsson, 1973). After complete healing, the moisture loss of mechanically damaged potatoes is nearly identical to that of undamaged tubers. The importance of mechanical damage with regard to weight loss during the early storage period is evident from the surveys of Twiss and Jones (1965) and Hudson and Orr (1977). Twiss and Jones reported that in Great Britain nearly one-third of the potatoes leaving the farm had suffered mechanical damage deeper than could be removed by a single peeling and another one-third exhibited wounds which could be thus removed. Hudson and Orr found damage of 24.1%, 64.5% and 73.2% in Norchip, Kennebeck and Viking, respectively, in commercial harvesting and bin filling operations in the Red River Valley. Much of this damage was termed slight to moderate and was not sufficient to lower the grade of the potatoes.

Suberization of the periderm begins while the tubers are still in the soil after vine kill. Suberin, a polymer composed of fatty acid and phenylpropane derivatives (Kolattukudy and Dean, 1974; Dean and Kolattukudy, 1977), plugs the intercellular spaces being laid down in two continuous bands within the cell walls around a lenticel or wound (Fox et al., 1971). If completed, a barrier forms which effectively prevents attack by pectolytic bacteria. Under proper conditions, a wound periderm is then formed.

Temperature and humidity affect the rate of suberization and wound periderm formation (Artschwager, 1927; Singh and Mathur, 1938; Wigginton, 1974). Artschwager found marked suberization but no periderm formation at temperatures below 7°C at 70% relative humidity after 53 days. At 12°C and 94% relative humidity, two layers of suberized cells and periderm formation were evident after 9 days. Singh and Mathur found microscopically visible suberization after 3 and 9 days at 7° and 18°C, respectively. Wound periderm formed after 6 days at 18°C. At 7°C no periderm formation was evident after 12 days. Wigginton (1974) reviewed much of the earlier work on wound healing and confirmed a three-fold increase in rate of healing from 5° to 10°C and from 10° to 20°C with high relative humidities. He found considerable variation from tuber to tuber but only slight varietal differences.

Kolattukudy and Dean (1974) suggested that the phenolic components of suberin prevent pathogen entry while the aliphatic constituents prevent water loss.

Burton (1963a) recommended a few weeks at 10°-15°C for the curing period in Great Britain. Meijers (1970) recommended a minimum temperature of 15°C with 90% or higher relative humidity for two or three weeks with ventilation one night out of every 8-10 in the Netherlands. Butchbaker et al. (1972) reported that the common practice in the Red River Valley is to store the freshly harvested potatoes at 13° to 16°C with high relative humidity for one or two weeks. Schippers (1971a), working in New York with small quantities of Katahdin, found temperature to be of minor importance provided it is not below 7.5°C. He recommended 100% relative humdity. Sparks et al. (1968) advocated ventilation during curing at a rate of 0.31 m^3/min/ton and high relative humidity with the temperature lowered to 7.2°C for Russet Burbank potatoes in Idaho. The experimental work with small lots of other varieties by Butchbaker et al. (1972) also resulted in minimum weight losses with continuous ventilation (0.31 m^3/min/ton) at 7.2°C, 85% relative humidity rather than 14 days of no airflow (10°C) followed by ventilation with 0.50 m^3/min/ton at 7.2°C, 85% relative humidity.

All researchers seem to agree that the relative humidity should be maintained near saturation during the suberization period for minimal weight losses.

The activity of the pectolytic bacteria are unaffected by the humidity of the air unless free water is present as a result of wet potatoes placed into storage, condensation on the surfaces while in storage, or exudate from rotting potatoes (Cromorty and Easton, 1973; Van den Berg and Lentz, 1973; Nash, 1975; Pérombelon and Lowe, 1975). If wet potatoes or potatoes showing signs of wet rot are put into storage, a drying period of ventilation with low humidity air must precede high humidity curing.

Researchers recommend widely varying ventilation schedules and temperatures during the suberization period. Partially this is due to the different ambient conditions expected at harvest time in various geographic locations. In warmer regions, it may not be possible to attain low temperatures without artificial cooling with refrigeration, or high relative humidities of the ventilation air may be difficult to achieve. A few days of cool weather which permit lowering the temperature of the storage might be followed by warm humid weather. If ventilation is continued, condensation will occur on the tuber surfaces and the potential for rotting will be high, particularly if the wound healing processes are not well advanced. If suberization is achieved at higher temperatures with little or no ventilation, the ambient temperature should then be lower and the following period (cooling) may be carried out with less risk.

Both high temperature-low ventilation and low temperature-continuous ventilation storage management have been used successfully to suberize potatoes. Some experimental evidence exists (Butchbaker et al., 1972) that total weight losses are less with the low temperature approach. In general, higher temperatures are expected to increase the rates of the biochemical reactions involved in healing wounds and decreasing skin permeability. By the same reasoning, high temperatures may result in faster physiological aging and the onset of senescence.

Walkof and Chubey (1968) performed a series of tests using small numbers of several varieties of tubers to determine the relationship of storage temperature to chipping quality (e.g., color). Mature and immature tubers were stored at 5°C or "preconditioned" at 21°C immediately after harvest for varying lengths of time before being stored at 5°C. They concluded that preconditioning for several weeks at high temperatures effectively improved the chipping potential of potatoes stored at 5°C.

Singh et al. (1975) reported that Kennebeck and Russet Burbank potatoes preconditioned for six weeks at 18.3°C produced chips of acceptable color after storage for five months at 4.4° and 7.2°C. Reducing sugar concentrations were higher at the lower temperatures. Due to weight loss considerations, storage at 10°C was found to be superior to storage at either 4.4° or 7.2°C for three months or less.

Iritani and Weller (1976) found that a "pre-holding" temperature of 8.9°-10°C was optimal for Russet Burbanks stored at 5.6°C with respect to later accumulation of reducing sugars.

Optimal conditions during the initial storage period clearly depend on a number of factors. These include the condition of the potatoes (level of maturity, degree of damage, presence of free water), the intended length of storage and the intended final use (determines eventual storage temperature). The cost of providing quantities of air of the desired temperature and humidity versus the expected increased return from a greater weight of salable potatoes, and the level of acceptable risk must also be considered.

1.2.3 Cooling Period

Before beginning the main storage or holding period, potatoes must be cooled to the desired temperature. As previously discussed, this may occur as part of the suberization period or as a distinctly separate period following suberization.

Unless refrigeration equipment is used, the time and rate of this period depend upon the ambient conditions. The dangers associated with cooling during short cool periods followed by continued ventilation during warm humid periods have already been mentioned. The ideal situation is a continuous decrease of the bulk storage temperature without lengthy interruptions during which the metabolic heat generated by the tubers can increase the temperature (Meijers, 1970).

The vapor pressure exerted by water within the lenticels and intercellular spaces is nearly equal to that exerted by a free water surface at the same temperature (Burton, 1972). Water in saturated air at a lower temperature will exert a lower vapor pressure. As heat flows from the warmer potato, the air temperature will rise, the saturated vapor pressure of the air will rise and the relative humidity of the air will become less than 100%. Water vapor will flow from the potatoes to the air. Hence, cooling air which is saturated before entering the potatoes will still evaporate water from the tubers (Hylmö et al., 1975a, 1975b). The rate of evaporation will be proportional to the VPD (Schippers, 1971c).

To minimize the VPD and resulting weight loss, it is generally recommended that cooling with ambient air should begin when the temperature difference between the warmest spot in the potato pile and the ambient air is no more than 2°C (Ophuis, 1957; Nash and Lennard, 1970; Meijers, 1971). Similarly, when using refrigeration to cool the potatoes, the inlet air should be no more than 2°C cooler than the potatoes (Meijers, 1971). During periods of free convection the zone of maximum temperature is usually between 0.2 m and 0.5 m below the top surface (Burton, 1963a).

The velocity of the air or fan capacity determines the amount of heat which can be removed from the storage during any given time period. Bennett et al. (1960) indicated that the rate of heat removal at 20 $m^3/h/m^3$ was essentially equal to that at 40 $m^3/h/m^3$, the rate in the latter case being controlled by the conduction of heat to the potato surface. Recommended ventilation capacity is therefore related to the climatic conditions expected and type and size of the tubers. Regions with short periods of cool weather, primarily at night, use higher capacity fans to take full advantage of the periods. Ophuis (1957) suggested 100 $m^3/h/m^3$ of potatoes in the Netherlands. This was more recently reconfirmed by Meijers (1970, 1971) and by Hesen (1970). Sundahl (1971) recommended 50 $m^3/h/m^3$ of potatoes for box storages in Sweden. Hylmö and Johansson (1976a) recommend a fan capcity of 70 m^3/m^2h independent of pile height for bulk storages in Sweden. They noted that half this capacity may be adequate after suberization and cooling. Statham (1971) advised using fans with capacities no less than 50 $m^3/h/m^3$ for Great Britain. Nash and Lennard (1970) tested ventilation rates of 27, 64, and 80 $m^3/h/m^3$ of potatoes in Scotland. They reported that 27 $m^3/h/m^3$ was inadequate, particularly for cooling the top layers.

In the United States, Bennett et al. (1960) recommended a minimum ventilation capacity of 20.2 $m^3/h/m^3$ for Long Island, Lundstrom (1971) advised 17.6-25.2 $m^3/h/m^3$ for cold storages (< 7.22°C) and 25.2-37.8 $m^3/h/m^3$ for warm storages (> 7.22°C) in the Red River Valley, while Sparks and Summers (1974) found 12.6 $m^3/h/m^3$ to be adequate in Idaho.

In still air or at extremely low flow rates (free convection), the rate of weight loss by the tubers is limited by the saturation point of the air. At ventilation rates above some critical value, the rate of weight loss is determined by the apparent permeability of the skin. Burton (1963a) estimated the critical ventilation rate for unsprouted, well suberized tubers in the middle of the storage season to be on the order of 8 $m^3/h/m^3$ while that of freshly harvested potatoes was about 27 $m^3/h/m^3$. This implies that the weight loss rate due to evaporation at airflows above the critical value are relatively unaffected by velocity. Confirmation is provided by Ophuis (1957), Toko (1960), Statham (1971), Butchbaker et al. (1973), Villa (1973), and Iritani et al. (1977).

Optimum management policy during the cooling period is not apparent. High ventilation rates for short time periods with saturated air slightly cooler than the mass of potatoes seems a good choice. The total time and the potential for evaporation will both depend upon the temperature difference between the cooling air and potatoes. Large differences will decrease the time necessary to achieve the desired temperature (tending to decrease evaporation losses) but will also increase the VPD during that time (tending to increase the evaporative losses). The skin permeability is of great importance, again raising the possibility of cooling during suberization. The influence of latent heat of vaporization upon the cooling process must also be considered (Hylmö et al., 1975a).

1.2.4 Holding Period

The primary problem during the holding period is the selection of the best control method and ventilation rate.

The holding temperature is largely determined by the intended use of the potatoes. Seed potatoes, which must be kept from sprouting without the use of chemical inhibitors, are generally stored between 2° and 4.4°C (Meijers, 1971; Christensen, 1976). Ware potatoes are held within the range of 4°-7°C, processing potatoes from 5°-12°C.

After the desired storage temperature has been reached, the primary goal is to maintain uniform temperature and high humidity. Ventilation is necessary from time to time to remove metabolic heat generated by the potatoes as well as heat entering the storage via conduction or air exchange. In colder climates, it may be necessary to supply additional heat to compensate for that lost by conduction through the walls or by air exchange. It may also be necessary to lower the humidity of the air in the storage to prevent condensation on inadequately insulated walls and ceilings.

Sprouting will occur in potatoes stored above 4°C after the characteristic varietal dormancy or rest period has elapsed. Sprouts are 30 to 40 times more permeable to water than the surface of a mature tuber (Burton, 1963a) and can quickly account for increased weight loss. The coefficient of resistance to airflow may increase by an order of magnitude for sprouted potatoes (Burton, 1963a).

A variety of sprout suppressors are available. Regulations governing the use of sprout suppressors vary from nation to nation. In the United States, maleic hydrazide and Isopropyl-N-Chlorophenyl-carbamate (CIPC) are the most common inhibitors. Maleic hydrazide is applied to the foliage of actively growing plants as the tubers approach market size. Unfortunately, the grower must plan his market strategy far in advance in order to treat only those tubers expected to be stored for long periods. CIPC is a strong inhibitor which can be applied through the storage ventilation system after wound healing.

Twiss and Jones (1965) in surveying losses in British storages found that sprouting is no longer a problem.

Ware and processing potatoes are stored at temperatures which permit sprouting in order to prevent undesirable carbohydrate changes. The fact that low temperature storage results in increased concentrations of sucrose and reducing sugars (fructose and glucose) is well documented. These result in an undesirable sweet taste in ware potatoes and reactions during frying which produce brown colors in such products as chips and french fries.

Maintenance of the desired holding temperature involves the same considerations discussed in respect to initial cooling. Control can be achieved by using a time clock and air proportioning system to obtain the desired inlet air temperature on a regular basis. In other cases, the ventilation schedule is based on storage temperature and availability of ambient air of the proper temperature. Control systems range from completely manual to fully automatic.

Researchers generally agree that ventilation beyond that required to cool or maintain uniformity within the storage should be avoided. Sparks (1973) reported less weight loss for potatoes stored with intermittent ventilation than for those stored with continuous ventilation at 85% and 95% rh. Wilson et al. (1962) experimenting with commercial sized storage facilities suggested that total shrinkage will be least when ventilation is restricted. Bennett et al. (1960) and Meijers (1971) caution storage operators to keep ventilation to a minimum.

Hylmö and Johansson (1976a) warn against long intervals between ventilation which may result in high concentrations of CO_2 or condensation of water whenever warm air currents caused by natural convection contact cooler potatoes.

Although most United States researchers agree that humidification of the ventilation air is a good practice, Nash (1975), in Scotland, found that humidification used intermittently with outside air was ineffective by comparison with ventilation using outside air alone. Conversely, in tests involving total recirculation and refrigeration, humidifcation was effective. Meijers (1971) does not recommend humidifiers for storages in The Netherlands; he cites their expense and the possible stimulation of condensation and disease organisms.

1.2.5 Warming and Reconditioning Period

Handling of cold potatoes increases the incidence of discolorations and cracking. Ophuis et al. (1950) found that the susceptibility of potatoes to discoloration (blue bruise) increased with time in storage. High dry matter content, low potassium content and heavy soils also correlated with increased amounts of discoloration, the effect being very varietal dependent. Warming the tubers to 12°-13°C for one day before handling decreased the incidence of blue discolorations. Warming to higher temperatures or for longer times had no effect. Kasmire et al. (1972) reported that heating potatoes to 12.8°-15.6°C before handling reduced total cracks by 25% to 30% and large cracks by 50% to 55%. Pätzold (1974) found greatly reduced levels of damage for potatoes stored at 4°C and warmed to 20°C for two weeks before handling.

The literature is replete with studies on the "conditioning" or "reconditioning" of potatoes after storage as a means of decreasing the concentration of reducing sugars to levels which result in light colored processed products or desweetening for table use. These studies show widely varying degrees of success. As a result, the recommended holding temperatures are such that sugar contents normally remain within acceptable limits. Nevertheless, samples taken from commercial storage bins occasionally prove to be unacceptable and the potatoes are then warmed to a temperature of 15°-20°C for several weeks in an attempt to recondition them.

Warming the potatoes with forced air ventilation may lead to excessive weight loss or severe rotting. If warm air with a high relative humidity is cooled by contact with cold potatoes, condensation may result. If warm dry air is used to warm the potatoes, a large VPD and high rate of weight loss will exist, particularly near the air inlet where the potatoes are also warm.

Samotus et al. (1973) transferred 2-kg samples of potatoes after storage at 1°C storage with 85%-95% humidity for time periods of 3-22 weeks to 20°C with nearly 100% humidity for two weeks. Fifteen varieties (strains) were included in the test. The results showed that losses during the two weeks of reconditioning accounted for 25%-39% of the total losses occurring during storage and reconditioning. The latter percentage applied to three weeks of storage while the former resulted after 22 weeks of storage.

Singh et al. (1975) also reported high weight losses during reconditioning, especially for Kennebec potatoes. For minimal weight losses, they recommended storage at 10°C so that there is no need for reconditioning.

Miyamoto et al. (1958) applied an assortment of ventilation and modified atmospheres to Russet Rural potatoes after storage at 4.4°C. They concluded that poor ventilation did not produce satisfactory chips and was accompanied by serious decay where high relative humidity was induced. Ventilation with air of approximately 85% relative humidity was reported to give far more satisfactory chips than ventilation with air approaching saturation.

It seems clear that warming potatoes before handling is to be recommended if weight loss and condensation can be controlled. It is not evident, however, under what circumstances longer holding periods at warm temperatures are to be recommended for adjustments to the carbohydrate balance.

The successful management of a potato storage from loading to unloading involves careful consideration of many factors. The condition of the tubers at harvest, anticipated time in storage, and intended final use are the most important determinants. These, along with decisions regarding the level of acceptable risk, determine the operational management of the available equipment.

The optimal management of a potato storage requires more intimate knowledge of potatoes and their interactions with the environment than is currently available to storage operators. Optimal storage also depends upon a knowledge of the future state of the market. This is not available except in the case of contracts at fixed prices. In spite of this, the ability to predict the cost/benefit ratio of varied management practices or types of equipment should aid successful operators in approaching the optimum.

1.3 The Potato in Storage

Aside from economic considerations, the overall goal of potato storage is to preserve the potato's ability to serve as a clone for further production or to preserve its appearance and composition so that it is esthetically and nutritionally acceptable as food or feed.

The potato in storage is a living organism in which a complex of biochemical reactions are proceeding continually. The rate of each reaction is generally dependent upon previous treatment of the tuber and the current environment. Previous treatment determines relative concentrations of reacting species, catalysts, intermediates, inhibitors and so forth. The current environment determines the equilibrium state towards which the reactions proceed, the concentration of external constituents (O_2, CO_2, etc.)

and the temperature or energy level available for reaction. Irrespective of the environment provided, the end result of continuous storage will be the inevitable senescence and death of the organism. This occurs from irreversible changes within the tuber. In some cases, these changes are the failure of the mechanisms provided by nature to protect the potato against attack by other organisms, e.g., bacteria and fungi.

The goal of potato storage is, therefore, to provide an environment which retards progress towards senescence and enhances the tuber's ability to ward off attack by other organisms. Previous treatment, from planting to harvesting and handling into storage, determines the biochemical and physiological state of the tuber and thus its response to the storage environment and the limits of its storability.

A knowledge of the potato's biochemistry and physiology is therefore necessary to determine the storage environment most consistent with the above goals. Kimbrough (1925) stated: "Considerable progress has been made concerning potato storage, but ideas still differ about the best storage conditions to prevent the losses due to shrinkage and to preserve the culinary value of the tubers. . . . we must know more about the physiology of the tuber while in storage." This statement is still true.

Each variety will, of course, respond differently to environmental stimuli. The following is, therefore, a general discussion of the physiological aspects of potato tubers and of tuber pathogens which are currently thought to be of importance to and directly affected by storage.

In broad terms, the potato can be considered to consist of two components--water and dry matter. Water normally comprises 72%-82% of the harvest weight. Since potatoes are sold on a total weight basis, losses of both water and dry matter are to be avoided. At this point it is assumed that losses in water which are large enough to greatly affect the physiological response of the tubers do not occur in properly managed storages. The effect of management upon the water loss was covered in the previous section. This section will, therefore, deal primarily with the dry matter component of the potato and changes in the dry matter content.

1.3.1 Dry Matter Content

Dry matter normally comprises 18%-28% of the fresh tuber weight (Burton, 1966). Table 1.2 gives the range and normal values of the various constituents as reported by Burton for mature, unstored potatoes. Whereas the content of most constituents remains constant during storage (Knudsen, 1965, 1966), sugar content may change considerably. In addition, there is a net loss of carbohydrates due to respiration.

Specific gravity has been used as a method for the rapid estimation of starch and dry matter content for many years (Burton, 1966). The results are approximate since specific gravity is also affected by intercellular space (Davis, 1962; Kushman and

Table 1.2. Approximate composition of the dry matter of potatoes (from Burton, 1966).

	Percentage in the Dry Matter[1]	
Constituent	Range (Approx.)	Normal Value (Approx.)
Starch	60–80	70
Reducing sugars	0.25–3[2]	0.52–2[2]
Sucrose	0.25–1.5[2]	0.5–1[2]
Citric acid	0.5–7	2
Total N	1–2	1–2
Protein N	0.5–1	0.5–1
Fat	0.1–1	0.3–0.5
Fibre	1–10	2–4
Ash	4–6	4–6

[1]The dry matter normally comprises about 18–28% of the fresh weight, dependent upon factors discussed in the text. Average value about 23%.

[2]These figures are representative of mature unstored tubers. The content of sugar is very markedly affected by the stage of maturity and by temperature of storage. It is quite possible for the total sugar content of potatoes stored at -1 °C to be of the order of 30% of the dry matter, and for that of unstored immature tubers to be over 5% of the dry matter.

Haynes, 1971). Agle and Woodbury (1968) found the specific gravity-dry matter relationship to be affected by production area, variety and length of storage.

Dry matter content is affected by many factors during the growing season. Lana et al. (1970) reported significant variations in specific gravity between varieties, between field locations and between years. Intercellular space differences were not reported. Burton (1966) discussed the effect of fertilizers, irrigation, light intensity, and other factors on dry matter content.

In addition to the differences among varieties, locations, and years, variations exist within individual tubers. Recent work by Sayre et al. (1975) and Baijal and van Vliet (1966) confirmed the earlier work reviewed by Burton (1966): that dry matter content increases from the periphery inwards as far as the inner cortical tissue and outer medulla and decreases from there inwards to the center. There is also a gradual decrease within each of the above zones from the heel (attachment) end to the rose end. Baijal and van Vliet reported that differences increase during storage. Sayre et al. indicated that french fries from the center of the long axis of a potato tended to be of poor quality with solids content less than 17%.

Other factors have been correlated to dry matter content or specific gravity. Hudson (1975) found that varieties with low specific gravities, large cells and intercellular spaces were more susceptible to bruise damage. Biehn et al. (1972) suggested that Katadin tubers with high dry matter content are generally less susceptible to soft rot than tubers with lower dry matter content.

1.3.2 Respiration

Dry matter content gradually decreases by respiration. Potato tubers are capable of aerobic and anaerobic respiration. During aerobic respiration, atmospheric oxygen is combined with carbohydrates to form CO_2, H_2O, and energy for other metabolic processes. Burton (1974b) found that although the respiratory quotient may vary considerably over short periods of time, its average value over extended periods is nearly 1.0.

The primary respiratory pathway is as yet unknown. Laties (1964) reported the tricarboxylic acid cycle (TCA) to be inoperative in fresh slices and active in aged slices while the pentosephosphate shunt increased several times in magnitude. Lange et al. (1970) reported the TCA cycle to be effective in suberizing tissue and inhibited in proliferating tissue. Van der Plas et al. (1976) studied the respiration rates of mitochondria from potatoes stored at 7° and 16°C. They found that during storage and after wounding with subsequent incubation a rearrangement takes place in the electron transport system of the mitochondria.

The typical response of respiration rate to temperature is shown in Figure 1.4. The minimum rate at about 5°C with rapidly increasing rates at lower temperatures and gradually increasing rates at higher temperatures has long been a topic of interest (Hopkins, 1924; Wright, 1932).

Potatoes which are moved to warm temperatures after storage at cold temperatures exhibit a "respiratory burst" as shown in Figure 1.5. The increased respiration rate may be more than twice the rate normally associated with the higher temperature, gradually decreasing to the normal rate after two to three weeks. This respiratory burst is not correlated with carbohydrate concentration (Craft, 1963; Paez and Hultin, 1970; Burton, 1974b). The mechanism involved in the respiratory burst has not been explained.

Figures 1.6 and 1.7 illustrate the influence of maturity at time of harvest on the respiration rate of Majestic potatoes stored at 10°C as well as the respiratory rise associated with sprouting. Burton (1974b) stated that the

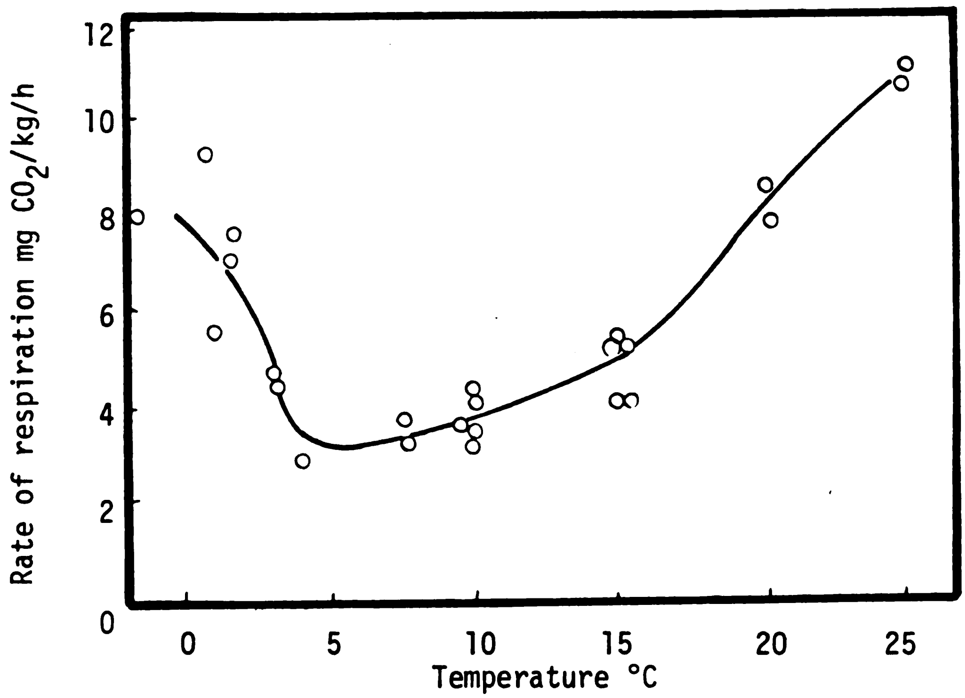


Figure 1.4. Respiration of potato tubers at various storage temperatures. The points relate to a number of varieties and investigations (from Burton, 1966).

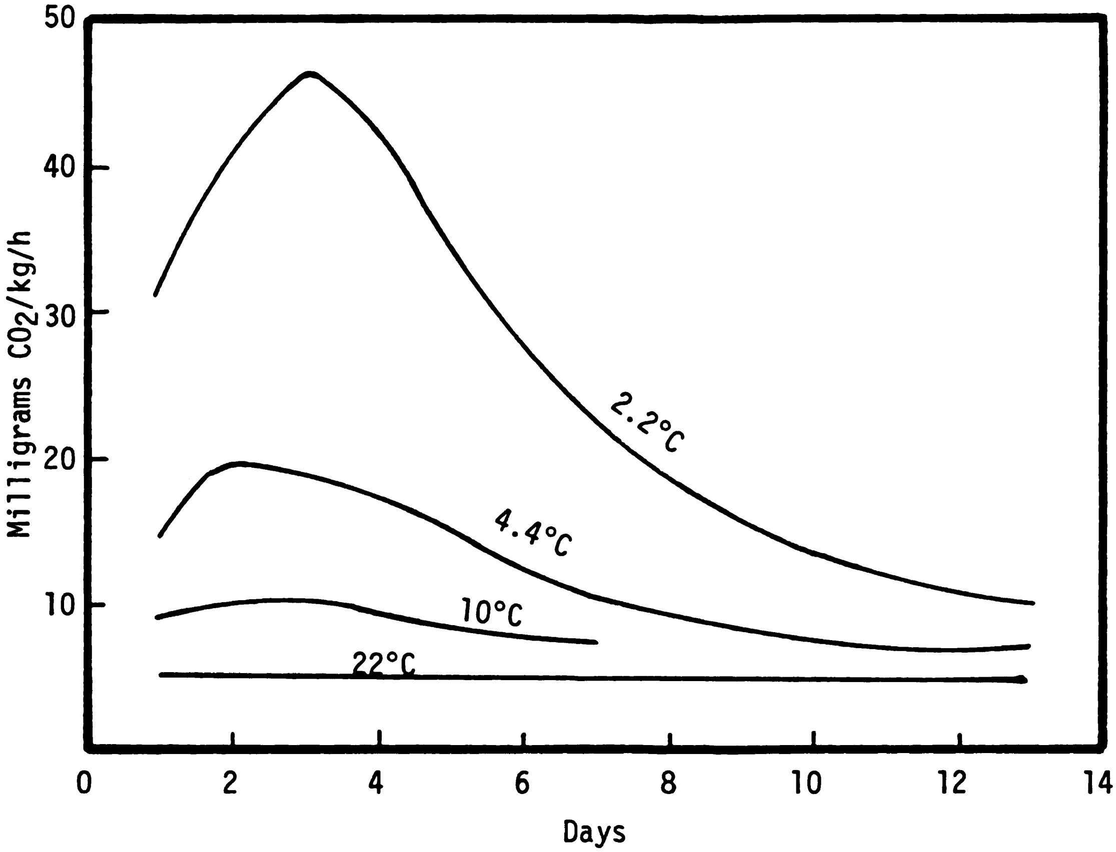


Figure 1.5. Effect of storage temperature on rate of respiration at 22°C. Previous storage temperatures given over each curve (from Kimbrough, 1925).

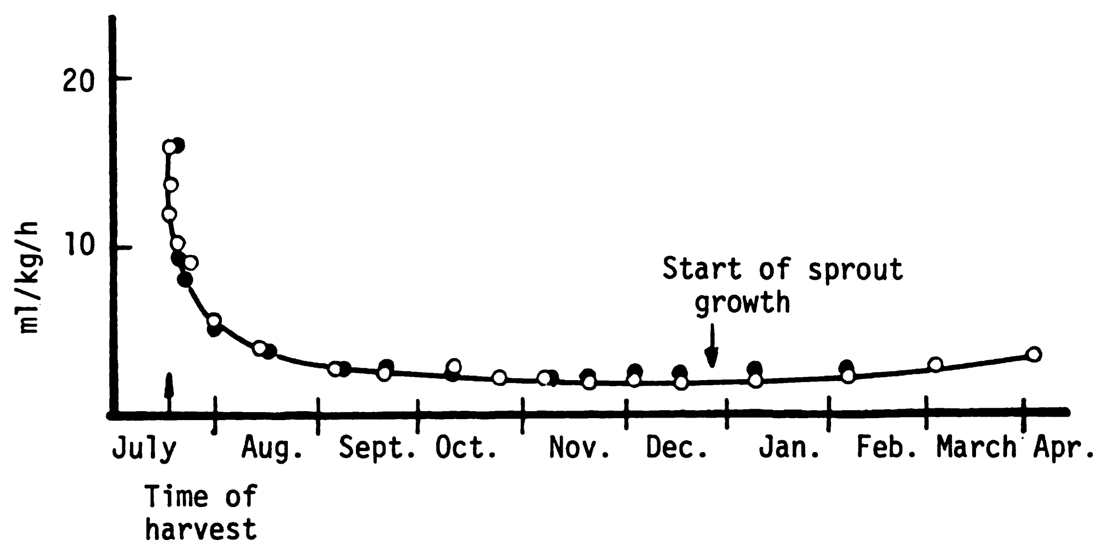


Figure 1.6. Oxygen uptake (o) and carbon dioxide output (•) of immature tubers (var. Majestic) during storage at 10°C (from Burton, 1974).

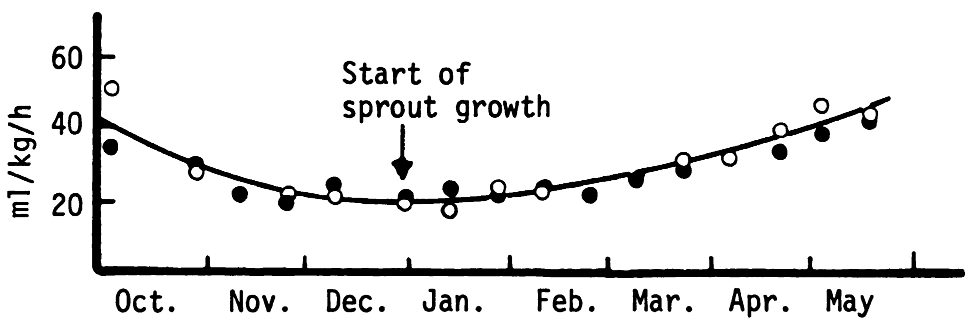


Figure 1.7. Oxygen uptake (o) and carbon dioxide output (•) of mature tubers (var. Majestic) during storage at 10°C (from Burton, 1974).

respiration rate is an index of the rate of metabolic turnover. Both the immature tuber and the tuber breaking dormancy (sprouting) show greater rates of metabolic activity than the mature dormant tuber.

A mature tuber is no longer attached to living foliage. It receives no sucrose or other nutrients from the foliage and begins an independent life, relying upon starch reserves. Suberization of the periderm begins and the potato tends toward an equilibrium determined by the soil conditions (Burton, 1960). With harvesting it enters a new environment and tends toward a new equilibrium. An immature tuber is still attached to living foliage and is transforming translocated sucrose into starch. Its equilibrium state is determined by the condition of the foliage and the soil (Burton, 1963b). If harvested, it requires far greater adjustment to the new environment than a mature tuber. Although the biochemical mechanisms are not known, evidence other than the respiration rate points to high metabolic activity during this adjustment (Singh and Mathur, 1938).

Wounding, or even gentle handling, of tubers results in substantial increases in the respiration rate. This increase may also be compared to the rate of overall metabolic activity (Borchert, 1971). A respiration rate of 7-10 times that of an intact tuber has been reported for tuber slices (Craft, 1963; Burton, 1966). This response has been studied in detail in attempts to determine the respiration pathways (Laties, 1964;

Lange, 1970; Borchert and McChesney, 1973); such work usually involves tuber slices. Burton (1974b) reported that handling associated with washing and drying of tubers could temporarily increase their rate of O_2 uptake by as much as 20%.

Craft (1963) divided respiration into three categories: basal, stimulated basal, and developed respiration. Basal respiration represents the normal level exhibited by a mature, sound, dormant tuber at any particular temperature. Basal respiration may be stimulated by a number of treatments: previous anaerobiosis, bruising, chemical vapors, cold storage temperatures, cutting, heating, irradiating, or wounding. Developed respiration occurs several hours after cutting or wounding and is approximately proportional to the area of the cut. Developed respiration is intimately related to repair.

In total weight loss, respiration is of minor importance (Singh and Mathur, 1938; Burton, 1966; Hylmö et al., 1975a). Burton reported weight losses due to respiration of 0.12% during the first month of storage and 0.08% per month thereafter for sound, mature, dormant stocks at 10°C. This represents a 1.2% loss of dry matter during the first month, 0.8% per month thereafter and 1.5% per month when sprouting is well advanced.

Dry matter losses are of particular concern to the processing industry, where they directly affect yield and quality of the product. With the exception of potatoes for canning, processors desire high solids content. Low dry matter content is desirable in canning stocks to prevent disintegration during processing and turbidity of the liquor (Burton, 1966).

1.3.3 Food Value

Water in potatoes has, of course, no nutritional value. However, potatoes are a valuable source of amino acids, B group vitamins, vitamin C and calories (Burton, 1974a). They also may be the source of compounds detrimental to health.

Burton (1966) reviewed the limited work which has been done regarding changes in nitrogen fractions in potatoes during storage. Although many changes occur, most are slight or without a consistent significant pattern. Exceptions are arginine, alanine, and proline. Arginine and proline are observed to increase while alanine content rises to a maximum and falls sharply. Appreciable changes are associated with the synthesis of tissue during sprouting. Although rapid changes occur in the relative fractions of nitrogen in immature tubers, the end result is that the crude composition after storage is much the same whether the tubers are harvested mature or immature.

Burton (1966) also reported insignificant changes in B vitamins in the absence of sprouting.

Ascorbic acid or vitamin C can be synthesized, reversibly converted to dehydroascorbic acid, or degraded to various other compounds during storage. Burton (1966) lamented that this cannot be commercially controlled given our present state of knowledge.

In general, ascorbic acid content is determined by a temperature-labile balance between synthesis and loss. The balance is tilted toward loss by decreasing temperatures. Losses are particularly rapid during the initial stage of storage.

Losses in the carbohydrate fraction of dry matter due to respiration represent an overall loss of calories. The magnitude of this loss was discussed in the previous section.

Potatoes contain a potentially toxic, steroid alkaloid--solanidine. This compound occurs mainly in combinations as the glycoalkaloids α-chaconine and α-solanine. Glycoalkaloids are potent cholinesterase inhibitors. The precise toxic level is unknown, but ingestion of large amounts results in nausea, cramps, and vomiting (Burton, 1974a). Fatalities are rare.

Glycoalkaloid concentrations in potatoes depend upon variety, stage of development and environmental conditions (Wu and Salunkhe, 1976). Crank et al. (1974) stated that normal solanine concentrations are less than 12 mg/100 g fresh tuber. The USDA terminated seed certification of seedling #B5141-6 (Lenape) in 1970 after its introduction in 1967; Lenape typically contained more than 20 mg/100 g of solanine (Crank et al., 1974).

Wu and Salunkhe (1976) found that mechanical injury (brushing, cutting, chopping, puncturing, and hammering) as well as light stimulated the synthesis of glycoalkaloids. The extent of stimulation depended upon cultivar, type of injury, storage temperature and length of storage. High storage temperatures resulted in higher concentrations.

Renwick (1972, 1973) caused a flurry of research activity in Great Britain by publishing a lengthy hypothesis that women of childbearing age, for whom conception is possible, should avoid imperfect potatoes. An apparent geographical correlation between severity of late-blight attack and incidence of anencephaly and spina bifida cystica (neural tube malformations) created the concern. Poswillo et al. (1972, 1973a, 1973b) fed concentrates prepared from blighted and rotted tubers to rats and marmosets (*Callithrix jacchus*). They found that cranial defects were not reproduced. (Marmosets are frequently used in teratogenic studies as a model for man.) Roberts et al. (1973) studied the parents of infants born with and without neural tube malformations and found no association between the consumption of potatoes and incidence of the malformation. Kinlen and Hewitt (1973) compared Scottish data for potato blight and incidence of anencephalus and found no temporal correlation. Swinyard and Chaube (1973) and Emmanuel and Sever (1973) also considered aspects of the hypothesis but their results were inconclusive. Burton (1974a) stated that there is no real evidence to implicate potatoes in neurological malformations.

1.3.4 Carbohydrates

The most important change in dry matter composition during storage is the final content of sucrose and reducing sugars (fructose and glucose). If the sucrose content is too high, an undesirable sweet taste occurs in table stock potatoes. In potatoes used for processing, especially fried products, the reducing sugars are critical. Concentrations of 1% may result in dark colored, unacceptable products. As indicated previously, storage temperature and overall management are largely determined by the potatoes' intended use and levels of sugars considered permissible for that use.

Occasionally a new variety is introduced which appears to be adapted to low temperature storage without the need for reconditioning (Hyde and Walkof, 1962; Lauer and Shaw, 1970). Unfortunately, no such variety has yet proved to be a totally acceptable cultivar.

A thorough review of the literature on sugars in potatoes would include work published as early as 1882. It would also include more than one hundred works from the past decade. This is not such a review. The amount of work being reported on the carbohydrate balance in potatoes reflects the importance of the problem to the industry and the fact that the biochemical mechanisms remain largely unknown. Emphasis here will be placed on recent work which contributes to the discovery of the latter.

Figure 1.8 shows the biochemical pathway believed to be active in establishing the carbohydrate balance within potatoes (Burton, 1966). Sucrose, which is translocated from the foliage during growth, is first split into glucose and fructose. The

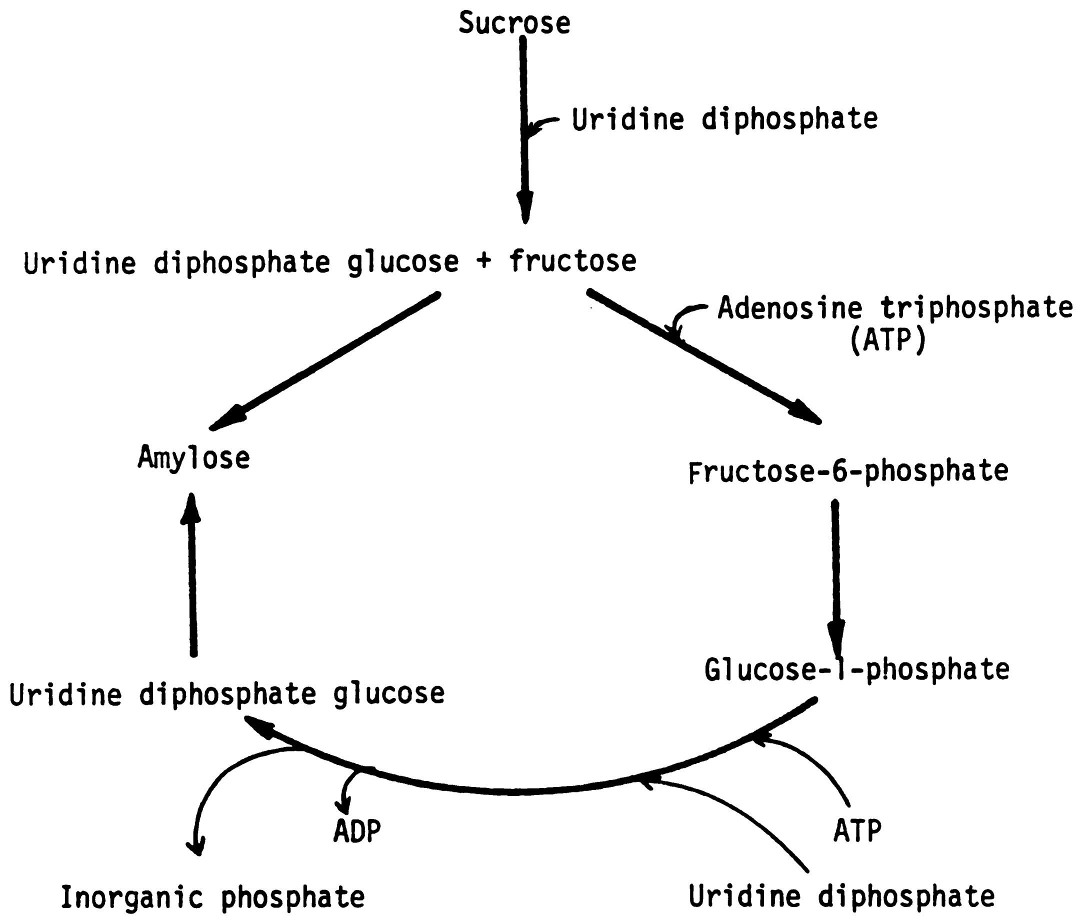


Figure 1.8. Biochemical pathway of amylose formation from sucrose believed to be active in potatoes (from Burton, 1966).

glucose and the fructose, after a series of reactions which convert it to glucose, are then transformed into amylose and stored as starch. Although Figure 1.8 shows only the starch synthesis pathway, the overall reactions are reversible. The concentrations of sucrose, glucose, fructose, and starch as well as other intermediates represent the balance between starch synthesis and degradation at any particular time.

Ohad et al. (1971) using electron microscopy followed changes in cell morphology of potatoes during growth and storage. They found young starch granules present within the plastid membranes 46 days after germination. During growth of the granule, the amyloplast extrudes into the vacuolar space while still attached to the cytoplasmic region by a "stalk." Later, the stalk is broken, the vacuolar membrane is torn, and the granule enters the vacuole. The granules are still surrounded by two intact membranes and continue to increase in size.

In spite of disparities in the literature, several general patterns have emerged. Problems of increase in sucrose or reducing sugar content can be attributed to one of three categories: (1) increases due to immature harvest, (2) increases induced by low temperatures, and (3) senescent sweetening.

The reducing sugar content of immature tubers is relatively low, serving only as intermediates to convert sucrose to starch. The sucrose content of immature tubers is high. Burton (1965) stated that the rate of translocation of sucrose into the tuber outstrips the rate of one or more of the reactions involved in starch synthesis. In particular, the capacity to convert sucrose to hexose and hexose phosphate appears to be limited.

If immature tubers are placed in storage, a rapid rise in the concentration of reducing sugars is often observed, particularly at low temperatures. Ohad et al. (1971) discovered that membranes around starch granules disintegrated at temperatures of 4°C but remained largely intact at 25°C. Kissmeyer-Nielsen and Weckel (1967) suggested that the higher levels of reducing sugars found in immature potatoes shortly after harvest were due to conversion of the high sucrose content to reducing sugars. This is consistent with results reported by Burton (1965) for storage temperatures of 10° and 20°C. Ohad et al. (1971) found only a slight increase in free sugars at 25°C, but a much greater induced increase at 4°C. Walkof and Chubey (1969) suggested preconditioning at high temperatures could improve the chipping potential of early harvested tubers.

Storage of mature tubers at low temperatures usually results in relatively high concentrations of reducing sugars, high sucrose contents, and unacceptable fried products. Cold soil temperatures during harvest have been shown to produce similar effects (Kissmeyer-Nielsen and Weckel, 1967; Stewart and Couey, 1968; and Burton and Wilson, 1970).

Ohad et al. (1971) found storage at 4°C induced changes in the amyloplast membranes which appeared as changes in structural continuity as well as buoyant density and electrophoretic patterns of proteins. Electron microscopy showed the membranes around the starch granules to be fragmented or to have disappeared after storage at 4°C while at 25°C most of them remained intact during 30 days of storage. Ohad et al. (1971) did not determine whether the membranes would be repaired if cold stored potatoes were warmed. However, it seems that changes in membrane permeability to degradative enzymes and substrates might be responsible for cold induced changes in the starch and sugar contents.

Jarvis et al. (1974) studied variations in free sugar and lipid contents in ten potato varieties during low temperature (4°C) storage. They found increases in digalactosyl diglyceride possibly associated with amyloplasts and frequently observed when plants are frost hardened. This compound is associated with the resistance of membranes to both chilling and freezing damage.

After long-term storage, as the tubers begin to break dormancy, sucrose content increases; a senescent sweetening often associated with sprouting. Application of sprout inhibitor does not inhibit the rise in sucrose. Van Vliet and Schriemer (1963) reported sucrose increases at high (10°-15°C) and low (4°-5°C) temperatures with sprouting independent of sprout suppression. Reducing sugars may also increase during the dormancy break (Burton, 1965; Ronsen and Frogner, 1969).

In general, Burton (1966) stated that senescent sweetening starts earlier and is more rapid the higher the storage temperature.

Both sucrose and reducing sugars increase. Burton (1966) also noted that the date at which senescent sweetening started was much the same in tubers from the same crop whether mature or immature when harvested even though the latter have been in storage for a greater elapsed time. Verma et al. (1974) found senescent sweetening to occur quickly in potatoes stored in warm, ambient conditions in India. Whereas reducing sugar accumulations induced by cold temperatures are removed by storage at high temperatures for two to six weeks, senescence and the accompanying increase in sugars is aggravated by warm temperatures. This may explain reported failures in reconditioning attempts.

The carbohydrate balance in potatoes is clearly dependent upon more than the storage environment. An initial adjustment is observed within a few days of harvest. In the case of immature tubers, the adjustment may be substantial. Experimental data yield very little agreement on precise concentrations which result. Burton (1969) noted that substantial differences in the absolute sweetening effect are observed from year to year. Stricker (1974) studied the influence of nitrogen fertilizer at four sites during two years with two varieties and five storage treatments. He found no significant detrimental effect. Burton (1966), in surveying the literature, found evidence to the contrary. Burton and Wilson (1970) found a strong positive correlation in Great Britain between the north latitude and content of sucrose and reducing sugar to sucrose ratio.

Later in storage, the sugar content of any particular lot of potatoes, although strongly affected by temperature, is dependent upon previous conditions including those of cultivation. Schippers (1975) reported highly significant second-order interactions of variety, temperature, and storage length. After experimenting with alternating periods of high and low temperatures, Burton (1969) concluded that sweetening depends upon the metabolic balance at the time of removal to low temperature. This balance is influenced by variety, locality and conditions of growth, age of the tubers, and prior storage conditions. He further stated that the effects are unpredictable.

Abbott et al. (1974) described the rate of reconditioning as two first-order reactions with significantly different rate constants. The first reaction, which has the higher rate, described the rate during the first week and appeared highly dependent on temperature. The second reaction seemed independent of temperature. Samotus et al. (1974a and 1974b) reported similar results for Polish varieties. They found a falling rate of change in sugar contents more dependent on concentration than temperature. Great varietal differences were also reported.

Although statistical correlations may be helpful in determining the optimum conditions of potato storage, they can also be misleading. Causal relationships are of much greater value. Much additional research appears to be necessary before causal relationships of carbohydrate balances within the potato tuber will be fully understood.

1.3.5 Potato Pathogens

Disease is a major source of losses in potato storages. Burton (1966) stated that disease accounts for greater losses than the combined effects of evaporation of water, respiration and sprouting. Whether this is currently the case in the United States is unknown as data which distinguish among causes of loss are not available. However, if pathogenic losses are not the primary source they are most certainly secondary.

The six types of pathogens described below account for the bulk of losses in temperate regions. Severity of attack is often associated with environmental conditions during harvesting and handling and hence varies greatly from locality to locality and from season to season.

Late blight is an important fungal disease. The causal organism, Phytophthora infestans, first attacks the foliage. Conidia falling to the ground or washed in by rain infect tubers through the lenticels or eyes. There is no evidence that this disease spreads from infected to disease-free tubers but death of the tissue from blight paves the way for secondary bacterial infections (Burton, 1966). Infected tubers show symptoms of the disease within a month. If conditions are dry so that secondary bacterial rot does not spread, losses may be confined to the infected tubers. Late blight can be controlled through the application of fungicides and other cultural practices. Some potato varieties are resistant to infection by late blight.

Dry rot is caused by infection of the Fusarium fungus, Infection occurs by the growth of hyphae from germinating spores on the skin into wounds or occasionally through the lenticels or eyes of sound tubers. This fungus is not capable of penetrating wound periderm. Attack is favored by high infestation of the soil and dry, warm conditions. Dry conditions also contribute to greater damage during harvesting. Invaded tubers do not usually show symptoms until after two or more months of storage. Optimal environmental conditions depend upon the species of Fusarium.
In general, high humidity favors the spread (Burton, 1966). A dry storage atmosphere may hinder the formation of wound periderm and thus favor the spread of dry rot. Degree of susceptibility depends upon the potato variety and fungal strains.

Gangrene is similar to dry rot. Wet soil conditions favor its development and infection is primarily through wounds (Malcolmson and Gray, 1968). The disease is caused by the Phoma fungus which have an optimum temperature for development of 0°-5°C, conditions which adversely affect the formation of wound periderm. Paterson and Gray (1972) noted inhibition of fungal growth in inoculated samples before the first layer of cells was visibly suberized. Unlike dry rot, gangrene can spread in storage to healthy tubers through the eyes or, under moist conditions, through proliferated lenticels. Under favorable conditions, wound periderm formation can outstrip the rot. Phoma also attack the foliage.

Following hot growing conditions, Pythium species may invade bruised or otherwise damaged tubers and result in watery wound rot. Under conditions favorable to spread of this disease the tuber may be completely rotten within a day or two. Contaminated soil may remain infective for several years (Burton, 1966). Tubers which are immature when harvested are particularly vulnerable.

In addition to fungal rots, some bacteria cause or contribute to rotting. The term bacterial soft rot is applied to these. Erwinia (or Pectobacterium) carotovorum is frequently the causal organism. One variety, atrosepticum, is responsible for blackleg in the foliage. A number of other pectolytic species of bacteria such as Pseudomonas, Bacillus, Clostridium, Aerobacter and Flavobacterium are usually present in a rotting mass (Pérombelon and Lowe, 1975). E. carotovorum are apparently unable to penetrate undamaged or suberized layers of periderm (Fox et al., 1971). Pérombelon (1973) surveyed 45 storages in Scotland to determine degree of contamination. Table 1.3 shows the results. The main site of survival of the bacteria is within the lenticels (Bétencourt and Prunier, 1965).

Pérombelon and Lowe (1975) stated that anaerobic and wet surface conditions seem to be a prerequisite for rotting. Lund and Nicholls (1970) demonstrated that only a local dry rot could be produced with inoculation under aerobic conditions. In a nitrogen atmosphere, the soft rot spreads readily showing that O_2

Table 1.3. Contamination by E. carotovora of 45 bulk and crate stored stocks (from Pérombelon, 1973).

SURFACE		LENTICEL	
Contamination Level (Number/Tuber)	Number of Stocks	Contamination Level (Number/Lenticel)	Number of Stocks
0	6	0	9
$<10^3$	10	<10	16
$<10^5$	15	$<10^2$	11
$>10^5$	14	$>10^2$	9

depletion rather than CO_2 accumulation is critical. Under other conditions, however, severe rotting can occur without depletion of the O_2 (Nielson, 1968; Lund and Wyatt, 1972).

Fox et al. (1971) showed that under saturated conditions, lenticels proliferate and provide areas for invasion by the resident bacteria. Burton and Wigginton (1970) found that mature tubers covered by a continuous water film 3×10^{-2} mm thick were anaerobic after 6.5 hours at 10°C or 2.5 hours at 21°C. Hence, wet surface conditions are sufficient to initiate invasion and rotting by bacteria surviving within the lenticels at any stage of storage. Control of bacterial soft rot is almost entirely through proper storage management.

Another bacterial disease, bacterial ring rot, is prevalent in temperate regions. Corynebacterium sepedonicum spread through the vascular systems into the daughter tubers. There may be no external symptoms; however, breakdown may occur which allows the establishment of conditions favorable to soft rotting. Bacterial ring rot is spread by infected seed and certain insects.

Of the six primary pathogenic conditions discussed, bacterial soft rot is the most critical. Infection by other organisms leaves the tuber vulnerable to the bacteria. Soft rot spreads as the liquid exudate from a rotting tuber drips onto neighboring tubers eventually leading to a cone-shaped volume of rot broadening as the rot spreads downward. Although soft rot can be detected by smell, exudate dripping into the air ducts confirms a severe condition. The spread can be stopped by dehydration at substantial cost in evaporation from remaining sound tubers. Therefore, whenever bacterial soft rotting is detected, a salvage operation with immediate sale of the sound tubers is in order.

Any condition which results in the formation of a water film over the surface of a tuber at any time during the storage period may initiate bacteria soft rotting. Leaking roofs, dripping condensation from ceilings, or improper control of ventilation systems are common causes of wet tubers. Fluming or washing tubers has been shown to increase decay potential (Lund and Kelman, 1977).

1.4 Nature of the Problem

Although potatoes are better adapted to long-term storage than many food crops, substantial losses still occur. Losses may be purely economic (water losses) or may represent reduction in food value. In addition, irreversible changes in the carbohydrate balance may force diversion of potatoes intended for processing into other markets.

Recommendations for the management of potato storages vary widely. It is generally conceded that surface drying, suberization, cooling, holding, warming and/or reconditioning are necessary. The duration of each phase, the quantity of airflow, the means of controlling the airflow as well as the desired levels of temperature and humidity are controversial. Much of the disagreement results from variations in experimental work.

Experimentation has shown that potatoes respond as individuals; their biochemical and physiological makeup is so diverse that no two potatoes respond exactly the same way to the same environmental stimuli. Researchers have discovered significant variations in composition among varieties, locations, years, and so forth. Such variations lead directly to differences in response to storage treatments. Many of the differences reflect weather and microenvironmental conditions surrounding the tuber during growth which are beyond experimental control.

In some cases, such as respiration of mature undamaged tubers, general patterns have emerged which permit the quantification of the average response expected from treatments even though the exact nature of the response remains unknown. In other cases, such as the carbohydrate balance, quantification is difficult and the response is, according to Burton (1969), unpredictable. In either case, "average" potatoes are not available for experimentation, thus compounding the uncertainty involved in comparing results from researchers in various parts of the world.

Recently, numerous attempts have been made to quantify responses using correlative statistics. Although this approach can be useful in identifying important parameters, results are not reproducible unless all of the causal parameters have been accounted for by direct control or inclusion within the correlation. In many cases, the causal factors are unknown. A statistical correlation on limited amounts of data within a complex system does not prove a cause-effect relationship (see the previous discussion on the teratological aspects of imperfect potatoes).

Of the factors which influence the quality of potatoes in storage, temperature and humidity are considered to be of greatest importance. It is not by accident that temperature and humidity are the two aspects of the environment which are controlled in most storages. Evaporative weight losses are directly related to the temperature and humidity of the air surrounding the tuber. The respiration rate, and other biochemical reactions, are influenced by temperature. Thus, the metabolic heat generated and the dry matter loss as well as changes in the food value of potatoes are directly related to temperature. The activity of rot-causing organisms, rate of periderm formation, and susceptibility to bruise are also influenced by the temperature and humidity conditions within the storage. Although the carbohydrate balance is greatly influenced by its state at harvest, changes in the balance such as cold-induced sweetening or senescent sweetening are directly related to temperature.

If all sources of energy and water can be identified the laws of conservation of energy and mass can be applied to potato storages. If appropriate expressions for the rates of heat and moisture transfer and generation can be devised or estimated, a set of prediction equations results. If the equations can be solved, prediction of the temperature and humidity within the storage follows. Additional relationships expressing the influence of temperature and humidity on, for example, rotting or synthesis and degradation of a nutritional component might lead to further useful predictions.

It is not practical to treat potatoes as individuals in deriving relationships expressing the rates of transfer and generation of heat and moisture nor in deriving relationships which are dependent upon temperature and humidity. One ton of potatoes may contain in excess of 10,000 tubers. An average or limiting relationship must be used which is consistent with the goal of storage not to preserve any particular tuber, but to preserve the bulk of potatoes in the storage in the best condition economically feasible.

A simulation model can be used to study the influence of various potato properties, management schemes, initial conditions and so forth. A model, much faster than the physical system after which it is patterned, permits total control over the properties and conditions of the hypothetical potatoes and eliminates many of the uncertainties involved in experimental tests.

A model does not eliminate the need for experimental work. Experimental work is necessary to determine the average values and range of values which might occur for the temperature and humidity relationships, transfer rates and generation rates. Experimental work on commercial-sized storages determines the validity of the model.

The nature of the potato storage problem with many complex interactions and factors beyond experimental control make the modeling approach coupled with experimental validation a logical choice. A similar approach has worked well in drying and storage of cereal grains (F. W. Bakker-Arkema et al., 1977). In the case of grains, dehydration was desired. The use of prediction models has led to significant changes in the design of drying and handling equipment as well as cost and energy optimization of the processes.

2. OBJECTIVES

The primary objective of this research is to develop a temperature-humidity model for bulk stored potatoes. Validation of the model is an implicit phase of development.

In conjunction with the model development, a thorough review of the literature is made to examine quantifying relationships that have been proposed for temperature-humidity influence on the quality of bulk stored potatoes. This study should pinpoint those areas where additional data or basic research into causal relationships are needed in order to more effectively predict the quality course of potatoes in storage.

Utilization of the resulting model will be demonstrated, applying it to problems involving ventilation and temperature control during the suberization and cooling phases of storage.

The final model should exhibit several characteristics:

1. sufficient computational speed to permit its use in optimization studies;
2. sufficient accuracy to justify management policy decisions based on model results;
3. sufficient flexibility to enable easy incorporation of additional temperature-humidity dependent quality relationships.

3. REVIEW OF LITERATURE ON HEAT AND MASS TRANSFER IN BEDS OF BIOLOGICAL PRODUCTS

Predicting temperature and humidity within bulk stored biological products involves mathematical description of the simultaneous transfer of heat and mass from the product to the air, as well as quantification of the generation of heat and disappearance of mass due to metabolic activity. Many processes involving nonliving or nonorganic products also include the simultaneous transfer of heat and mass. No attempt will be made to review work in these areas except where it is of historical interest. Studies concerning heat and mass transfer from beds of nonorganic materials undergoing exoergic reactions are similarly excluded.

Aurelius (1926) and Schumann (1929) independently published the first significant works on heat transfer in porous beds of solids. They obtained analytical solutions for the cooling or heating rates of solids under conditions of constant temperature and uniform flow for a uniform initial solids temperature. The equations reduce to:

$$\frac{\partial T}{\partial t} = -v_a \frac{\partial T}{\partial x} - \frac{ha}{\rho_a \varepsilon c_a} (T - \Theta) \qquad (3.1)$$

and:

$$\frac{\partial \Theta}{\partial t} = \frac{ha}{\rho_p c_p (1-\varepsilon)} (T - \Theta) \qquad (3.2)$$

where T and Θ are the gas and solids temperatures, respectively, v_a is the interstitial gas velocity, h the convective transfer coefficient, a the surface area per unit bed volume, and ε the bed void fraction. The density and heat capacity of the gas are expressed by ρ_a and c_a, respectively, and by ρ_p and c_p for the solids. Schumann (1929) expressed the solution of these equations in terms of modified Bessel functions of the first kind. Furnas (1930) used graphical methods to solve Schumann's differential equations for a wide range of bed depth and flow-rate. These solutions are exact for systems where the thermal conductivity of the solid particles is large and their size small. It is also assumed that the particle and air properties are constant.

Hougen and Marshall (1947) developed differential equations for time-position-temperature-concentration conditions in both gas and solid during the adsorption of dilute gases flowing through granular beds. An analytical solution and modified Schumann-Furnas charts were developed for isothermal conditions where a linear equilibrium relation exists between the adsorbate contents of the gas and solid. Graphical techniques were applied to situations with nonlinear equilibrium relationships. The isothermal requirement precludes use of this analysis for predicting moisture loss from biological products.

Businger (1954) applied the Schumann-Furnas analysis to heat transfer during aeration of bulk agricultural products (e.g., onions). Neither moisture loss nor internal temperature gradients are included in the analysis.

Van Arsdel (1955) developed the partial differential equations for simultaneous heat and mass transfer in a nonisothermal system. In particular, equations for batch and continuous flow drying configurations operating in the low-moisture range were published. The special case of solely fluid film resistance to heat transfer and internal diffusional resistance to mass transfer was considered. The resulting equations for batch drying are:

$$\frac{\partial X_w}{\partial t} = \frac{\dot{m}}{\rho_p(1-\varepsilon)} \tag{3.3}$$

$$\frac{\partial H}{\partial x} = \frac{\dot{m}}{\rho_a v_a \varepsilon} \tag{3.4}$$

$$\frac{\partial \Theta}{\partial t} = \frac{ha}{\rho_p(1-\varepsilon)c_p}(T - \Theta) + \frac{h_{fg}\,\dot{m}}{\rho_p(1-\varepsilon)c_p} \tag{3.5}$$

$$\frac{\partial T}{\partial x} = -\frac{ha}{\rho_a v_a \varepsilon(c_a+c_v H)}(T - \Theta) \tag{3.6}$$

where X_w is the wet basis moisture content, H the humidity ratio of the air, $\dot{m}$ the experimentally determined moisture transfer rate per unit bed volume, and h_{fg} the latent heat of vaporization.

Van Arsdel solved the system of equations using a predictor-corrector method and a difference-equation method without aid of a computer. He did state that the problem would be well suited for "an automatic program-controlled computer." Only fragmentary experimental data for drying and heat transfer rates were found; thus, Van Arsdel did not present comparisons of predicted and measured values. Since the primary goal was the dehydration rather than the temperature control, no heat generation by the product was included.

Burton et al. (1955) analyzed unventilated piles of potatoes and developed an empirical algebraic relationship for the difference between the average potato temperature, Θ, and average air temperature, T, as a function of metabolic heat generation rate, Q (kgcal/t/h), resistance to airflow, K, heat loss by conduction, and cross-sectional area. For large bulk piles the equation reduces to (Burton, 1963):

$$(\Theta - T)^{2.8} = \frac{K}{8.94 \times 10^{-4}} [Q\rho_p(1-\varepsilon)L]^{1.8} \qquad (3.7)$$

Weight loss and latent heat were not considered. Results of the study are in the form of a graph of air temperature versus average potato temperature for various pile depths of clean, dirty, mature, immature, and sprouted potatoes. The temperature above which uncontrollable overheating might occur was also indicated.

Ophuis (1957) applied Businger's analysis to potato beds to determine airflow rate recommendations. Although comparisons of experimental and predicted values are not presented, Ophuis stated that substantially complete agreement between the calculated and the measured trend was obtained.

During this same time period, several researchers proposed or obtained solutions to simplified grain dryer models. These models (and later work on grain drying) were recently reviewed by Bakker-Arkema et al. (1977). This review includes the work which led to the Michigan State University grain dryer models (Bakker-Arkema et al., 1974). The present study on heat and moisture transfer relationships within potato storages burgeoned from the grain dryer models.

Klapp (1962) developed the mathematical theory and analytical solutions for forced aeration of sugar beet piles, including terms for evaporation of moisture from the beets.

Watson and Staley (1963) studied heat transfer rates in a laboratory scale potato bin. The method of Furnas for the temperature history of the air and solids was used to analyze the data. Apparent values for the heat capacity of the solids and surface coefficient of heat transfer as functions of air velocity were obtained. These are "apparent" values since they include the effects of latent heat of vaporization and heat generation (respiration). Significant temperature gradients were found within the potatoes which accounted for 10% of the maximum temperature difference between the air and potatoes at high airflow rates (~320 $m^3/h/m^2$). At a velocity of 808 m/h with a difference of 20°C between the initial potato temperature and ventilating air temperature the gradient within the tubers was 1.9°C. At a velocity of 57.5 m/h the gradient was only 0.8°C.

Soule et al. (1969) collected data on the precooling of citrus fruit in small bins. Experimentally measured fruit temperatures from several positions in the bin were averaged to obtain one representative fruit temperature. The data were analyzed empirically by determining the coefficients of a third degree polynomial of the form:

$$\frac{\Theta - T_0}{\Theta_1 - T_0} = b_1 + b_2 t + b_3 r^* + b_4 t^2 + b_5 (r^*)^2 + b_6 t^3 + b_7 (r^*)^3 + b_8 t\, r^* \tag{3.8}$$

where r^* is the dimensionless radial position within the fruit and b_1 through b_8 are coefficients. Since cooling was completed within a period of several hours, desiccation, which resulted in 0.5% to 1.0% weight loss, was considered insignificant. Neither latent heat nor heat generation were considered in the data analysis.

Bakker-Arkema (1970) and Rosenau et al. (1970) proposed simplified and realistic cooling models, respectively, for potatoes or other agricultural products. Both models resulted from previous work by Bakker-Arkema and Bickert (1966, 1967) and Bakker-Arkema et al. (1967) in which the deep bed cooling equations were developed and solved numerically for simultaneous heat and mass transfer during cooling with varying inlet air conditions. The simplified model is similar to that presented by Businger (1954). The model presented by Rosenau included internal temperature gradients within irregularly shaped products. Neither model accounted for heat generation. Rosenau applied his model to onions including the effects of moisture loss.

Schumann's theory was extended to solids with low thermal diffusivities by Murata (1971). The solution of the heat conduction equation with radiation was used for determining the product surface temperature in place of the uniform temperature assumption. An approximate analytical solution and numerical solution were presented. Murata found that theoretical results agreed well with experimental results in the cooling of a column of eggs.

Huang and Gunkel (1972) simulated forced air heating of onions in deep beds using equations similar to those of Bakker-Arkema and Bickert (1966). Neither heat generation nor mass transfer was modeled although the fact that the onion temperature never reached the inlet air temperature was attributed to drying and associated evaporative cooling.

Misener (1973) developed a model of temperature and weight loss from a bed of potatoes. The model is similar to models presented by Thompson et al. (1968) and Bloome and Shove (1971) for low-temperature drying of shelled corn. The method assumes that temperature and moisture gradients in a horizontal layer of potatoes in the stack are negligible and that temperature equilibrium is obtained between air and potatoes during the calculation interval Δt. An enthalpy balance which includes heat generation and latent heat of vaporization is taken over a differential layer during time Δt. This balance is solved for the equilibrium temperature. Similarly, a mass balance is used to solve for the air humidity. The model is capable of simulating condensation by using a search technique to solve for the temperature and humidity ratio at saturation. The effect of air velocity on heat transfer is not considered by this model, due to the assumption of thermal equilibrium. This can result in substantial errors, especially at high airflow rates. The model equations and comparisons with experimental data were published by Misener and Shove (1976).

Rice (1974) modeled heat and mass transfer in potato storages using equations very similar to those presented by Bakker-Arkema (1970), with the addition of terms for heat generation and latent heat. The equations published by Rice contain obvious errors. No attempt is made to justify several assumptions implicit in the equations. However, Rice claimed reasonable agreement with experimental results. Temperature gradients within the potato were considered negligible.

Hylmö et al. (1975a,b) developed a model for the temperature distribution in bulk stored potatoes based on the heat balance:

$$\rho_p(1-\varepsilon)(Q-c_p \frac{\Delta\Theta}{t}) = [\frac{\Delta T}{L} (c_a+c_v H_{ave}) + \frac{\Delta H}{L} h_{fg}]\rho_a v_a \varepsilon \qquad (3.9)$$

where $\Delta\Theta$ is the temperature change of the potatoes while ΔT and ΔH are the differences between the inlet and outlet air temperature and humidity, respectively. The left-hand side of equation (3.9) accounts for the heat generation and sensible heat change of the tubers. The right-hand side accounts for the change in enthalpy of the ventilation air. After sufficient time the bed reaches a state of approximate thermal equilibrium. The temperature profile at this steady state has been discussed by Hylmö et al. (1975a). At steady state $\frac{\Delta\Theta}{t} = 0$ and equation (3.9) may be written as:

$$\rho_p(1-\varepsilon)Q = \rho_a v_a \varepsilon(c_a \frac{\Delta T}{L} + \frac{\Delta H}{L} h_{fg}) \qquad (3.10)$$

assuming the term $c_v H_{ave}$ is neglible compared to c_a. Equation (3.10) may be used to estimate the rate of heat generation of a bed of potatoes at steady state. Equations (3.9) and (3.10) include sensible, latent, and generated heat and are simplifications very similar to equations developed in the next chapter.

Hunter (1976a,b) simulated the temperature and humidity distribution within potato storages using an implicit solution of the energy balance:

$$h_{fg} K_D A(P_{surface} - P_v) = Q + hA(T-T_s) \qquad (3.11)$$

where K_D is the mass conductance of the boundary layer while P_{sur} and P_v are the partial pressure of water vapor at the surface and in the air stream, respectively. The left side of equation (3.11) accounts for latent heat of vaporization. The first term on the right side accounts for heat generation while the second term expresses the rate of transfer between the potatoes and air. This model neglects sensible heat changes and assumes constant air and potato temperatures. Equation (3.11) is applied to successive layers to determine the temperature and humidity of the layer. These serve as inputs to the adjacent layer.

After sufficient time with constant inlet conditions, when thermal steady state is reached, equation (3.11) may be valid. However, during heating or cooling and during cooling with intermittent ventilation, sensible heat terms cannot be neglected.

Although several attempts have been made to predict the temperature and weight loss within potato storages, none has proved adequate. In each case, assumptions regarding the attainment of thermal equilibrium or the existence of internal temperature gradients are not consistent with published experimental results. Comparisons of experimental temperatures from potato storages with the curves of Schumann (1929) and Furnas (1930) show substantial agreement in basic shape, indicating the significance of the sensible heat transfer. Deviation from these theoretical curves is due primarily to combined effects of use of heat as latent heat of vaporization, addition of metabolic heat, and the effects of internal gradients on apparent heat capacity. The latter is of particular importance when combined with high rates of airflow and varying inlet conditions.

It appears that a model to be used for the complete range of recommended airflow rates should take into account internal thermal gradients, latent heat, and heat generation.

Very little work has been done on the modeling of unventilated potato storage. Other than the relationship developed by Burton et al. (1955) equation (3.7), no published work was found on mathematical modeling of free convection heat and mass transfer within a potato storage.

4. DEVELOPMENT OF THE MODEL FOR SIMULTANEOUS HEAT AND MASS TRANSFER IN BEDS OF BIOLOGICAL PRODUCTS DURING FORCED CONVECTION

Many of the complex physical realities of a commercial-sized bed of living biological material are not subject to experimental manipulation. Assumptions are therefore made in an attempt to simplify the mathematical relationships to forms which can be solved with available techniques and computing equipment. The justification for the assumptions is the acceptability of the resulting solution when compared with physical reality. Further assumptions, beyond the minimum required to attain a solution, which further reduce the complexity and costs involved in attaining solutions are similarly justified by comparison with real systems. In other words, compromises in theoretical accuracy are made in favor of economic realities.

For the final application of the model to the solution of real problems, the model should be sufficiently general to account for each important relationship over the entire range of conditions. From the viewpoint of speed and cost, the least complex model which adequately mimics reality is preferred.

Model building is an iterative process. Assumptions are made, equations written, solutions found, and comparisons with reality generated. New assumptions which simplify or complicate the equations are then formed and the procedure repeated. The point at which iterations are terminated and a final model results is determined by subjective judgment.

No attempt is made to trace the iterations which resulted in the models presented herein. Rather, the most complex forms are presented and the effects of simplification demonstrated.

In this section, general expressions for transfer rates and generation are used. Relationships specifically developed for potatoes will be dealt with later. General models are formulated for three specific situations:

1. air and product in constant thermal equilibrium;
2. negligible resistance to heat transfer within the product, but finite surface resistance; and
3. products with finite surface and internal resistance to heat transfer.

4.1 Assumptions

The solution of the equations for heat and mass transfer in three dimensions are extremely cumbersome. A properly designed air distribution system, level bed, and uniform filling (which avoids accumulation of dirt and trash at any one location) result in airflow which is essentially uniform and one dimensional. It is, therefore, assumed that:

(1) symmetry exists in the horizontal plane at all levels,

(2) walls are adiabatic with negligible effect on airflow, and

(3) airflow is plug-type entering at the bottom.

The problem is then reduced to bulk flow in one dimension and can be visualized as a vertical column with unit horizontal cross-sectional area as shown in Figure 4.1.

In addition, it is assumed that:

(4) the column is uniform in spacial characteristics from bottom to top.

This implies that no settling, deformation, or volumetric shrinkage of individual particles occurs. Hence, column height (L), cross-sectional area (S), differential thickness (Δx), and void fraction (ε) are constant.

Assumptions regarding the mode of heat transfer are necessary to model development. In particular, it is assumed that:

(5) heat transfer in and from the product occurs via conduction and convection only, and

(6) heat conduction within the air stream is negligible during forced convection.

The analysis is further simplified if physical and thermal properties are taken as constant over the temperature range found in storage (i.e., 0°-30°C). It is also convenient to use average transfer coefficients. Specifically, it is assumed that:

(7) density, specific heat, thermal conductivity, and latent heat of vaporization do not vary significantly with temperature over the range of interest;

(8) the dry air-water vapor stream behaves as an incompressible fluid;

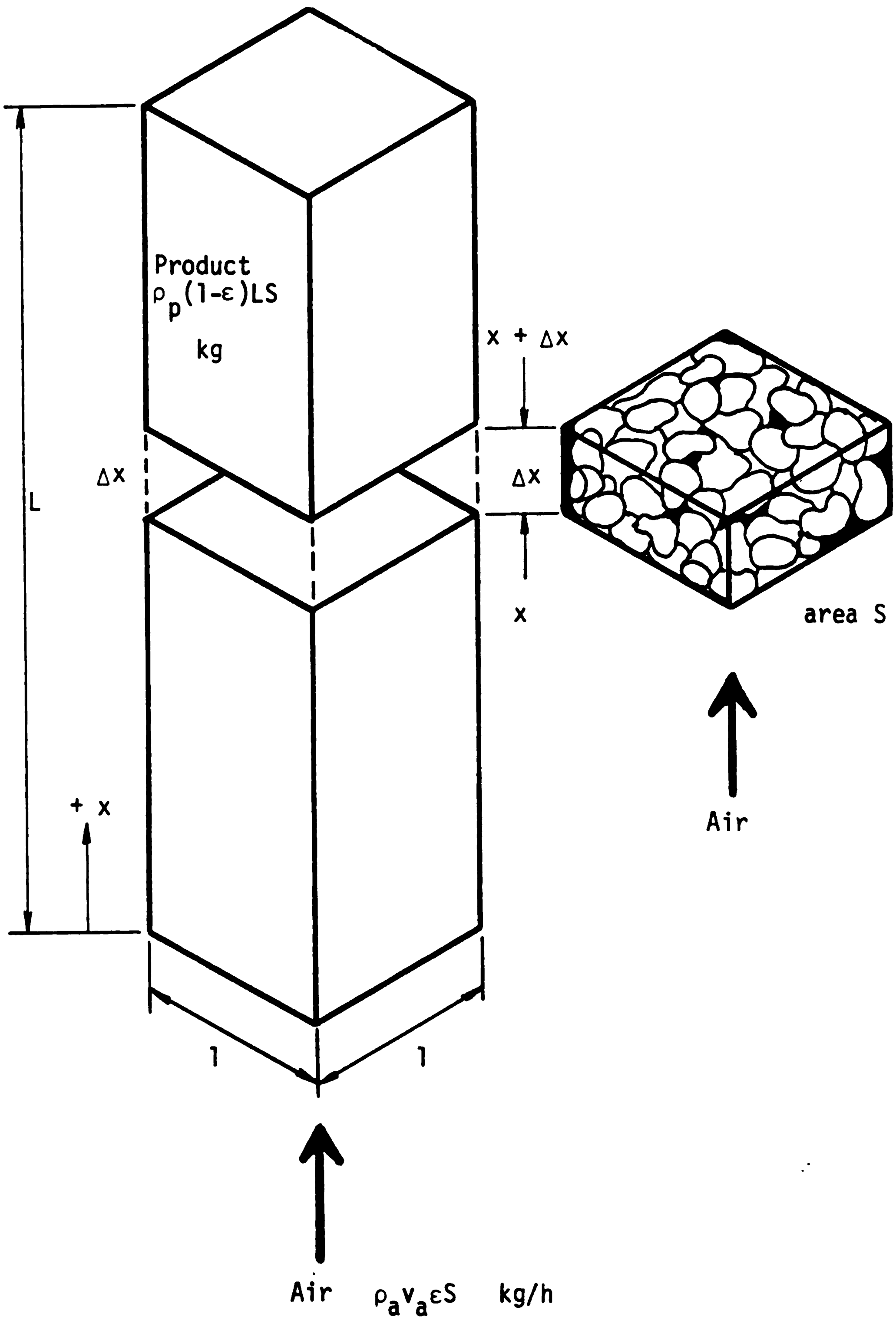


Figure 4.1. Uniform column of product with unit cross-sectional area and differential volume of cross-section S, height Δx.

(9) water vapor in the air is in constant thermal equilibrium with the dry air; and

(10) the convective heat transfer coefficient does not vary over the product surface.

Biological products emit a wide variety of volatiles as a result of respiration and other metabolic activities. With the exception of water vapor, these substances are the result of degradation of dry matter and hence represent mass transfer from the product. Those products which exhibit high rates of metabolic activity, as evidenced by high rates of heat and volatile generation, are necessarily structured to permit rapid gas exchange. Thus, mass of gases other than water vapor and associated weight loss are small compared with the mass of water lost. Therefore, it is assumed that:

(11) heat is generated uniformly throughout each particle

(12) the generation and transport of gases other than water vapor are negligible, and

(13) changes in the mass and composition of the dry matter of the product are negligible.

Biological products may be considered to consist of individual cells containing water in liquid phase and intercellular spaces, where water may exist in either the liquid or vapor phase. If the product is treated in a manner such that rate of evaporation is small, the site of phase change is not critical. On the other hand, if significant evaporation occurs, the magnitude of the latent heat compared to the sensible heat of the product results in substantial changes in the temperature near the site of vaporization.

If continual thermal equilibrium among all system components is assumed, evaporation must be slow or uniformly distributed and the thermal properties must allow for instantaneous adjustment of the temperature throughout. Similarly, if temperature gradients within the product are assumed to be negligible, the evaporation rate must be slow or evenly distributed throughout the product and thermal properties of the product must allow for instantaneous adjustment of the uniform product temperature. If internal temperature gradients are modeled, the site of phase change becomes critical because of the potential influence of the latent heat on the temperature gradient.

The complexity of the internal temperature gradient model is reduced if it is assumed that:

(14) water occurs only in the liquid phase within the product; evaporation occurs at the product surface.

This permits evaporation of water from the product to be treated in a manner similar to evaporation of free water (from condensation) from the product surface.

The structure of high moisture content biological products is such that resistance to flow of water within the product is negligible except in dehydration operations. Therefore, it is assumed that:

(15) resistance to movement of water within the product is small so that internal moisture gradients do not occur.

The high humidity environment of ventilated piles of fruits and vegetables coupled with fluctuations in temperature often results in condensation of liquid water on the product. The following assumptions facilitate the simulation of condensation:

(16) condensation occurs as a continuous film of uniform thickness over the surface of the product,

(17) there is no surface flow or drip of condensation,

(18) free water on the product surface is in thermal equilibrium with the surface,

(19) presence of a free water surface has negligible influence on the bed void fraction, and

(20) adsorption of water by the product is negligible.

The need to model internal temperature gradients adds considerable complexity to the system. Several additional assumptions are made to reduce this complexity while maintaining the essential influence of heat storage within the product requiring varying amounts of time to reach the air stream.

The additional assumptions are as follows:

(21) the product can be represented as uniform spheres with radial conduction only,

(22) particle-to-particle conduction is negligible, and

(23) the product is homogeneous with constant properties throughout.

In the development of thermal equilibrium and uniform product temperature models, conduction of heat from one differential volume to another is considered. For the internal temperature gradient model, only conduction within an individual particle which is representative of all particles or portions of particles resident within a given differential volume is considered. Conduction from one differential volume to another is neglected.

4.2 Derivation of Equations

The contents of a column of biological products can be considered to consist of several components such as dry gases, product dry matter and water in the vapor and liquid phase. Energy and mass conservation equations can be formulated for each component or species over an arbitrarily located differential element such as shown in Figure 4.1. The choice of the number and type of components is arbitrary, but some choices are more easily formulated and result in equations less complex than others.

The approach is to write energy and mass balances describing the system in terms of parameters related to the physical state of the components. Expressions for conservation of energy yield temperature relationships. Mathematical expressions which express the conservation of mass of any component yield relationships in terms of mass fraction or flow rate. The resulting equations describe the simultaneous transfer of heat and mass.

In general, one independent equation must be obtained for each independent state variable. Since the final set of equations must be independent, balances on components which are additive combinations of other components on which balances have been included in the final set have to be avoided. For example, the conservation of mass balance on a product composed of solids, dry gases and water may be written independently or taken as the sum of the balances on total solids in the product, dry gases in the product and water in the product.

In the case of a bed of biological products, the physical state variables are air and product temperatures, air humidity, product weight loss or moisture content, and thickness of the free water film. If thermal equilibrium is assumed, air and product temperature are identical and only one temperature variable is needed.

The models presented here result from energy and mass balances on dry air, water vapor in the air, and (wet) product. Thus, three components are considered.

Three separate cases are of interest with respect to the product energy equation:

1. constant thermal equilibrium between the product and air (infinite convective transfer coefficient with high thermal diffusivity),

2. uniform product temperature with convective transfer between the product surface and air (small Biot number), and

3. convective transfer between the product surface and air with thermal gradients within the product.

In the general analysis, each mass and energy balance includes terms for:

1. bulk flow of the component into (out of) the differential volume,
2. generation (depletion) of the species,
3. transfer to (from) the other components, and
4. accumulation (dissipation) of the species.

The balance takes the form:

net bulk flow + generation + transfer = accumulation

with the sign convention that energy or mass gained by the component under consideration is positive. Table 4.1 summarizes the expressions for bulk flow, generation, transfer, and accumulation used to develop the model equations.

4.2.1 Dry Air Balances

Table 4.1 shows that only bulk flow and accumulation terms are included in the dry air mass balance. Assumption (12) results in no generation or transfer of dry gases. The mass flow rate of dry air is expressed as the product of density (ρ_a), bed void fraction (ε), interstitial velocity, (v_a) and cross-sectional area (S). The net bulk flow can be expressed as the difference:

$$\rho_a \varepsilon v_a S|_x - \rho_a \varepsilon v_a S|_{x + \Delta x}$$

The dry air mass balance is then:

$$\rho_a \varepsilon v_a S|_x - \rho_a \varepsilon v_a S|_{x + \Delta x} = \frac{\partial}{\partial t} (\rho_a \varepsilon S \Delta x) \quad (4.1)$$

Table 4.1. Summary of terms used in the energy and mass balances. (See list of symbols for definitions and units of individual terms.)

	Energy, J/h	Mass kg/h
FLOW		
Dry air	$\rho_a \varepsilon v_a c_a TS$	$\rho_a \varepsilon v_a S$
Water vapor	$\rho_a \varepsilon v_a (c_v T + h_{fg}) HS$	$\rho_a \varepsilon v_a HS$
Product	$-k_p (1-\varepsilon) S \frac{\partial \Theta}{\partial x}$	0
GENERATION		
Dry air	0	0
Water vapor	0	0
Product	$Q\rho_p (1-\varepsilon) S \Delta x$	0
TRANSFER		
Dry air to product	$-\dot{q}_a S \Delta x$	0
Dry air to water vapor		0
Water vapor to dry air	$-\dot{q}_v S \Delta x$	0
Water vapor to product		$-\dot{m}_v S \Delta x$
Product to dry air	$-\dot{q}_p S \Delta x$	0
Product to water vapor		$-\dot{m}_p S \Delta x$
ACCUMULATION		
Dry air	$\frac{\partial}{\partial t} (\rho_a \varepsilon c_a TS \Delta x)$	$\frac{\partial}{\partial t} (\rho_a \varepsilon S \Delta x)$
Water vapor	$\frac{\partial}{\partial t} [\rho_a \varepsilon (c_v T + h_{fg}) HS \Delta x]$	$\frac{\partial}{\partial t} (\rho_a \varepsilon HS \Delta x)$
Product	$\frac{\partial}{\partial t} [\{\rho_p (1-\varepsilon) c_p + \rho_w \delta_w a c_w\} \Theta S \Delta x]$	$\frac{\partial}{\partial t} [\{\rho_p (1-\varepsilon) + \rho_w \delta_w a\} S \Delta x]$

Dividing by Δx and taking the limit as Δx approaches zero leads to:

$$- \frac{\partial}{\partial x} (\rho_a \varepsilon v_a S) = \frac{\partial}{\partial t} (\rho_a \varepsilon S) \tag{4.2}$$

Equation (4.2) is reduced to the well-known form of the continuity equations by assumptions (4), (7), and (8):

$$\frac{\partial}{\partial x} (\rho_a v_a) = \frac{\partial \rho_a}{\partial t} = 0 \tag{4.3}$$

Here, the continuity equation is of little practical value; however, in the more general case where equation (4.3) expresses the relationship between air density and velocity it can be used to simplify the subsequent air stream relationships.

The energy balance on dry air includes terms for bulk flow, transfer, and accumulation (Table 4.1). It takes the form:

$$\rho_a \varepsilon v_a c_a TS|_x - \rho_a \varepsilon v_a c_a TS|_{x + \Delta x} + \dot{q}_a S \Delta x = \frac{\partial}{\partial t} (\rho_a \varepsilon c_a TS \Delta x) \tag{4.4}$$

The term $\dot{q}_a$ represents the energy transferred from (positive) or to (negative) the other system components per unit time per unit bed volume. Enthalpy is arbitrarily defined with respect to zero on the temperature scale. In differential form with constant terms removed from the differentiation [or applying the chain rule and subtracting equation (4.3)] equation (4.4) yields:

$$-\rho_a \varepsilon v_a c_a \frac{\partial T}{\partial x} + \dot{q}_a = \rho_a \varepsilon c_a \frac{\partial T}{\partial t} \tag{4.5}$$

4.2.2 Water Vapor Balances

Table 4.1 indicates that the mass balance on water vapor includes bulk flow, transfer from the product, and accumulation terms:

$$\rho_a \varepsilon v_a HS|_x - \rho_a \varepsilon v_a HS|_{x + \Delta x} + \dot{m}_v S\Delta x = \frac{\partial}{\partial t} (\rho_a \varepsilon HS\Delta x) \qquad (4.6)$$

In differential form after simplifying, equation (4.6) becomes:

$$-\rho_a \varepsilon v_a \frac{\partial H}{\partial x} + \dot{m}_v = \rho_a \varepsilon \frac{\partial H}{\partial t} \qquad (4.7)$$

An energy balance on the water vapor yields:

$$\rho_a \varepsilon v_a H(c_v T + h_{fg})S|_x - \rho_a \varepsilon v_a H(c_v T + h_{fg})S|_{x + \Delta x}$$

$$+ \dot{q}_v S\Delta x = \frac{\partial}{\partial t} [\rho_a \varepsilon H(c_v T + h_{fg})S\Delta x] \qquad (4.8)$$

where the first two terms represent the flow of energy in the water vapor stream, the third term expresses the transfer of energy to or from the water vapor stream, and the final term accounts for energy accumulation in the water vapor in the interstices. The enthalpy of water vapor is taken to be $c_v T + h_{fg}$. The energy transfer term, $\dot{q}_v$, includes transfer to or from the dry air (to maintain thermal equilibrium) as well as transfer of energy associated with the transfer of mass to or from the product.

Using the chain rule with c_v and h_{fg} constant, equation (4.8) can be written as:

$$-\rho_a \varepsilon v_a H c_v \frac{\partial T}{\partial x} - \rho_a \varepsilon v_a (c_v T + h_{fg}) \frac{\partial H}{\partial x} + \dot{q}_v$$

$$= \rho_a \varepsilon H c_v \frac{\partial T}{\partial t} + \rho_a \varepsilon (c_v T + h_{fg}) \frac{\partial H}{\partial t} \qquad (4.9)$$

Multiplication of equation (4.7) by $(c_v T + h_{fg})$ and subtraction from equation (4.9) yields:

$$-\rho_a \varepsilon v_a H c_v \frac{\partial T}{\partial x} - \dot{m}_v (c_v T + h_{fg}) + \dot{q}_v = \rho_a \varepsilon H c_v \frac{\partial T}{\partial t} \qquad (4.10)$$

Addition of equations (4.5) and (4.10) results in the energy balance for moist air which could also be formulated directly. However, the three components of dry air, water vapor, and wet product chosen for this analysis eliminates the need for the more complex equation.

4.2.3 Product Mass Balance

The assumptions and Table 4.1 indicate that the product mass balance includes only transfer and accumulation terms:

$$\dot{m}_p S \Delta x = \frac{\partial}{\partial t} [\rho_p (1 - \varepsilon) S \Delta x] + \frac{\partial}{\partial t} [\rho_w \delta_w a S \Delta x] \qquad (4.11)$$

Here $\dot{m}_p$ is positive for the addition of water. The first term on the right accounts for evaporation of water from within the product. The second term on the right expresses the change in the superficial thickness of the free water surface, δ_w. Free water may be present initially or result from condensation. One of these terms is always zero.

Equation (4.11) can be written as:

$$\dot{m}_p = (1 - \varepsilon) \frac{\partial \rho_p}{\partial t} + \rho_w a \frac{\partial \delta_w}{\partial t} \tag{4.12}$$

In general,

$$\dot{m}_p = \begin{cases} (1-\varepsilon) \dfrac{\partial \rho_p}{\partial t} = F_1(T,H,\Theta_s,t) \text{ when VPD} > 0.0,\ \delta_w = 0.0 & (4.13a) \\ \rho_w a \dfrac{\partial \delta_w}{\partial t} = \begin{cases} -\acute{h}_w a[P_s(\Theta_s)-P_v] \text{ when VPD} > 0.0,\ \delta_w > 0.0 & (4.13b) \\ \max\ (\dot{m}_v) \text{ such that } H \leq H_{sat}(T) & (4.13c) \end{cases} \end{cases}$$

$$\dot{m}_v = -\dot{m}_p \leq \left[\rho_a \varepsilon v_a \frac{\partial H}{\partial x} + \rho_a \frac{\partial H}{\partial t}\right]\Bigg|_{H = H_{sat}(T)} \tag{4.13d}$$

Equation (4.13a) represents a relationship for the rate of loss of water by evaporation from the product as a function of ambient temperature, humidity, surface temperature, and time. For high moisture products evaporation rate is usually expressed in terms of the vapor pressure deficit (VPD) between the saturated condition at the surface temperature of the product and the vapor pressure of the air. This equation applies only if the VPD is positive and no surface film is present (i.e., surface water must be completely evaporated before water is lost from the product).

Evaporation of water from within the product is the only circumstance which results in a change of the product density. As used here, the product density, ρ_p, is not a physically measurable parameter with time. With the assumptions that have been applied, ρ_p accounts for changes in water content only and does not account for changes in the dry matter and interstitial volume. Here, ρ_p is related to product moisture content (wet basis) by:

$$\rho_p = \rho_d/(1 - X_w), \quad \rho_d = \text{constant} \tag{4.14}$$

Total weight lost (m) at any position within the bed at any time is expressed as:

$$m = (\rho_{pi} - \rho_p)(1 - \varepsilon)S\Delta x \tag{4.15}$$

Equations (4.13b) and (4.13c) express the rate of evaporation and condensation of a free water film, respectively. Equation (4.13b) is derived for the evaporation of a free water surface by Villa (1973). The film thickness, δ_w, is always greater than or equal to zero. Equation (4.13c) indicates that a maximum rate of transfer of moisture to the air stream exists, e.g., that rate which results in saturation. If the air is super-saturated, max ($\dot{m}_v$) is less than zero and condensation must occur.

The maximum rate of moisture transfer to the air (or minimum from the product) is determined by equation (4.13d). This equation constrains the rate of mass transfer to a value which avoids super-saturation of the air. If $\dot{m}_p$ is given by equation (4.13d) is positive, condensation must occur. Equation (4.13d) is derived from equation (4.7) and evaluated for $H_{sat}(T)$.

Vapor pressures, saturated humidities and other psychrometric properties are found using the FORTRAN package published by Bakker-Arkema et al. (1977).

4.2.4 Product Energy Balance --Thermal Equilibrium

For thermal equilibrium between all components (dry air, water vapor, and product), Table 4.1 shows terms for conduction, respiration, transfer, and accumulation. Hence (since θ = T):

$$-k_p(1-\varepsilon)S \left.\frac{\partial T}{\partial x}\right|_x + k_p(1-\varepsilon)S \left.\frac{\partial T}{\partial x}\right|_{x+\Delta x} + Q\rho_p(1-\varepsilon)S\Delta x + \dot{q}_p S\Delta x$$

$$= \frac{\partial}{\partial t}[\rho_p(1-\varepsilon)c_p TS\Delta x] + \frac{\partial}{\partial t}[\rho_w \delta_w a c_w TS\Delta x] \qquad (4.16)$$

where k_p is the thermal conductivity of the product tissue and the rate of heat generation per unit mass is given by Q. Upon application of the assumptions and simplifying:

$$k_p(1-\varepsilon)\frac{\partial^2 T}{\partial x^2} + Q\rho_p(1-\varepsilon) + \dot{q}_p = [\rho_p(1-\varepsilon)c_p + \rho_w \delta_w a c_w]\frac{\partial T}{\partial t}$$

$$+ (1-\varepsilon)T\frac{\partial \rho_p c_p}{\partial t} + \rho_w a c_w T\frac{\partial \delta_w}{\partial t} \qquad (4.17)$$

The first term accounts for conduction through the bulk of biological products whenever a nonconstant gradient exists. The area for this conduction, A_p, is the area intersected by a horizontal plane passing through the column. Integration of this area times dx from x to x + Δx should result in V_p, the volume occupied by product:

$$V_p = (1 - \varepsilon)S\Delta x = \int_x^{x+\Delta x} A_p dx = A_p \Delta x \qquad (4.18)$$

or

$$A_p = (1 - \varepsilon)S \qquad (4.19)$$

The second term in equation (4.17) expresses the rate of heat generation.

Product heat capacity may be expressed as the mass fraction of water times c_w plus the mass fraction of solids times the heat capacity of the solids:

$$c_p = X_w c_w + X_d c_d = \frac{\rho_d}{\rho_p}(c_d - c_w) + c_w \qquad (4.20)$$

It follows that:

$$\frac{\partial \rho_p c_p}{\partial t} = c_w \frac{\partial \rho_p}{\partial t} \qquad (4.21)$$

and the last two terms on the right-hand side of equation (4.17) are equivalent to $c_w T \dot{m}_p$ by equation (4.12). If this substitution is made and the resulting equation added to equations (4.5) and (4.10) (the energy balances for the dry air and water vapor, respectively), the result is the total system enthalpy balance for continuous thermal equilibrium:

$$-\rho_a \varepsilon v_a c_a \frac{\partial T}{\partial x} - \rho_a \varepsilon v_a H c_v \frac{\partial T}{\partial x} + \dot{q}_a + \dot{q}_v + \dot{q}_p$$

$$- \dot{m}_v (c_v T + h_{fg}) - \dot{m}_p c_w T + k_p (1-\varepsilon) \frac{\partial^2 T}{\partial x^2} + Q \rho_p (1-\varepsilon)$$

$$= \rho_a \varepsilon c_a \frac{\partial T}{\partial t} + \rho_a \varepsilon H c_v \frac{\partial T}{\partial t} + [\rho_p (1-\varepsilon) c_p + \rho_w \delta_w a c_w] \frac{\partial T}{\partial t} \quad (4.22)$$

By the sign convention followed here, conservation of mass and energy, respectively, requires:

$$\dot{m}_p + \dot{m}_v = 0 \quad (4.23)$$

$$\dot{q}_a + \dot{q}_v + \dot{q}_p = 0 \quad (4.24)$$

Equation (4.22) can then be simplified as:

$$-\rho_a \varepsilon v_a (c_a + c_v H) \frac{\partial T}{\partial x} + k_p (1-\varepsilon) \frac{\partial^2 T}{\partial x^2} + Q \rho_p (1-\varepsilon) + \dot{m}_p [T(c_v - c_w) + h_{fg}]$$

$$= [\rho_a \varepsilon (c_a + c_v H) + \rho_p (1-\varepsilon) c_p + \rho_w \delta_w a c_w] \frac{\partial T}{\partial t} \quad (4.25)$$

Equation (4.7), the water vapor mass balance, satisfies the requirement of an independent equation for H, the absolute humidity. Equations (4.13a-d) and (4.15) satisfy the requirements for ρ_p and m, the product density and weight loss, as well as δ_w, the free water film thickness. The mass of dry air is constant as stated by equation (4.3). Thus, all mass components and interactions have been accounted for.

The system temperature is given by equation (4.5), (4.10), or (4.17), the energy balances on dry air, water vapor, and product, respectively. Each of these energy balances contains a term for the energy transfer to or from the other system components ($\dot{q}_a$, $\dot{q}_v$, $\dot{q}_p$) which has not been mathematically defined. The total system energy balance, equation (4.25), which results from adding equations (4.5), (4.10), and (4.17), may also serve to give the system temperature and does not require definition of a transfer rate.

Hence, equations (4.7), (4.13a-d), (4.15), and (4.25) with equation (4.20) to relate c_p to ρ_p, an expression for F_1 in equation (4.13a), and appropriate boundary and initial conditions form the model for thermal equilibrium with heat generation and conduction through the bed.

4.2.5 Product Energy Balance --Uniform Product Temperature

For the case of uniform product temperature not in equilibrium with the air, an energy balance yields equation (4.16) in terms of product temperature, Θ, instead of T. After the substitution resulting from equation (4.21) is made, the following equation results:

$$k_p(1-\varepsilon)\frac{\partial^2\Theta}{\partial x^2} + Q\rho_p(1-\varepsilon) + \dot{q}_p - \dot{m}_p c_w \Theta = [\rho_p(1-\varepsilon)c_p + \rho_w \delta_w a c_w]\frac{\partial\Theta}{\partial t} \qquad (4.26)$$

Multiplying equation (4.5) by $(Hc_v)/(c_a)$ and subtracting equation (4.10) gives:

$$\dot{q}_a \frac{Hc_v}{c_a} - \dot{q}_v + \dot{m}_v(c_v T + h_{fg}) = 0 \tag{4.27}$$

Solving this for $\dot{q}_v$ and substituting into equation (4.24) with $\dot{m}_p = -\dot{m}_v$ results in:

$$\dot{q}_p = -\dot{q}_a \left(\frac{c_a + c_v H}{c_a}\right) + \dot{m}_p(c_v T + h_{fg}) \tag{4.28}$$

The total rate of energy transfer from the product is also given as the sum of the convective heat transfer and the enthalpy associated with the moisture transferred:

$$\dot{q}_p = ha(T - \Theta) + \dot{m}_p(c_v T + h_{fg}) \tag{4.29}$$

The amount transferred to the dry air is then given as:

$$\dot{q}_a = - \frac{c_a}{c_a + c_v H} ha(T - \Theta) \tag{4.30}$$

Equations (4.5), (4.7), (4.13a-d), (4.15), and (4.26) are independent equations for air temperature, humidity ratio, product density and free water film thickness, weight loss, and product temperature, respectively. Equations (4.29) and (4.30) define the heat transfer rates for equations (4.26) and (4.5), respectively, while equation (4.20) relates product specific heat to moisture content or density. These eight equations with appropriate initial and boundary conditions and an expression for F_1 in equation (4.13a) form the model for uniform product temperature.

4.2.6 Product Energy Balance-- Internal Temperature Gradient

Several additional assumptions are applied to simplify the prediction of internal temperature gradients. In particular, the conduction of heat within the product is not handled the same as in the previous analyses. In the case of thermal equilibrium or uniform product temperature, conduction of heat from one differential volume to another was considered. In this case, only conduction within an individual particle which is representative of all particles or portions of particles resident within a given differential volume is considered. Conduction from one differential volume to another is neglected. Therefore, comparison of the equations developed in the previous sections with those developed here, must be done with $k_p = 0$ in the former such that the only difference is the existence of thermal equilibrium, uniform temperature, or thermal gradients within the particle.

Figure 4.2 shows a segment of a spherical shell of thickness Δr arbitrarily located within the product. The energy balance includes terms for the conduction of heat into and out of the shell, flow of heat associated with the flow of water, generation of heat, and the accumulation of heat:

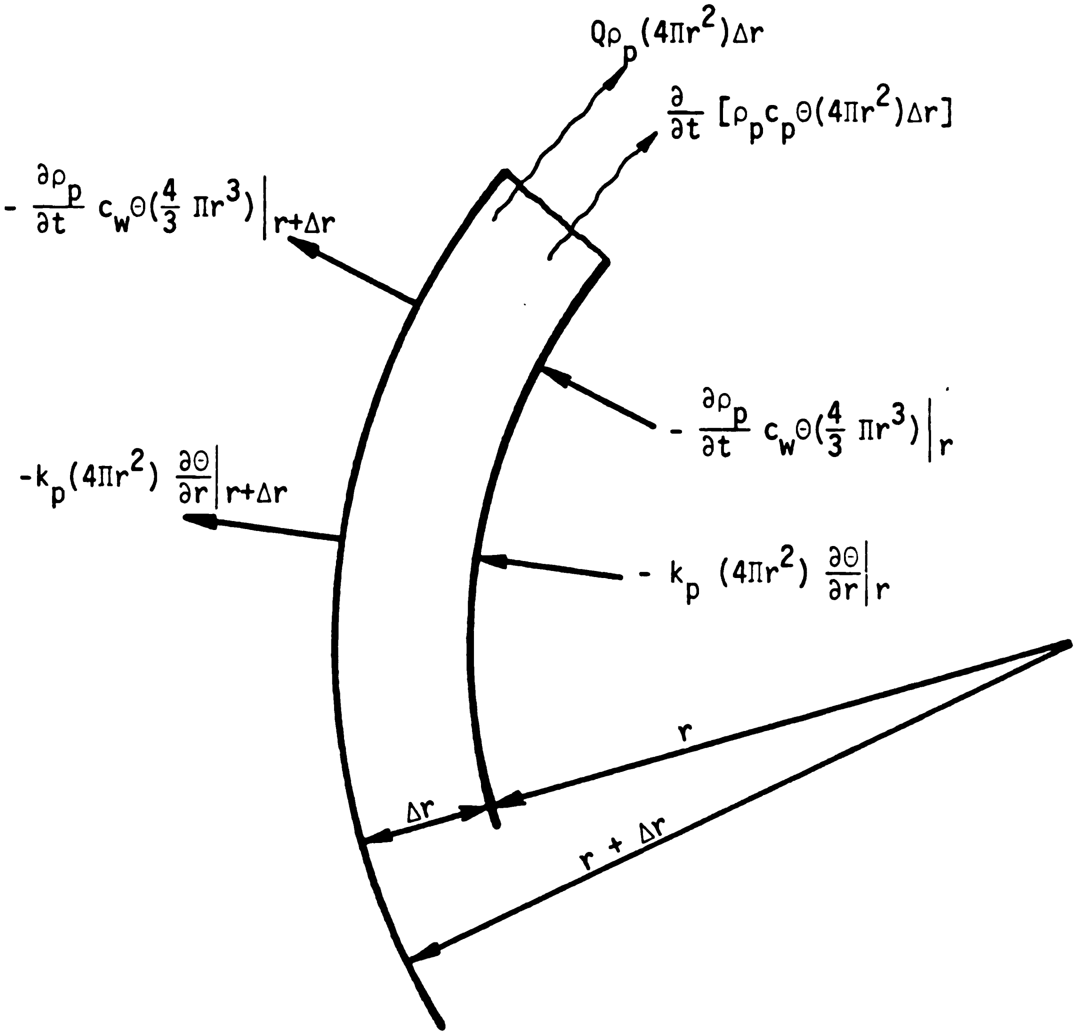


Figure 4.2.--Spherical shell of thickness Δr at an arbitrary location within the product showing heat transfer, generation, and accumulation.

$$-k_p(4\Pi r^2)\left.\frac{\partial\Theta}{\partial r}\right|_r + k_p(4\Pi r^2)\left.\frac{\partial\Theta}{\partial r}\right|_{r+\Delta r} - \frac{\partial\rho_p}{\partial t} c_w\Theta(\frac{4}{3}\Pi r^3)\Big|_r$$

$$+ \frac{\partial\rho_p}{\partial t} c_w\Theta(\frac{4}{3}\Pi r^3)\Big|_{r+\Delta r} + Q\rho_p(4\Pi r^2)\Delta r = \frac{\partial}{\partial t}[\rho_p c_p\Theta(4\Pi r^2)\Delta r] \qquad (4.31)$$

Since a uniform moisture distribution has been assumed, ρ_p is not a function of r and

$$k_p \frac{\partial}{\partial r}[r^2 \frac{\partial\Theta}{\partial r}] + \frac{1}{3} c_w \frac{\partial\rho_p}{\partial t} \frac{\partial}{\partial r}(\Theta r^3) + Q\rho_p r^2 = r^2 \frac{\partial}{\partial t}(\rho_p c_p \Theta) \qquad (4.32)$$

Further manipulation yields:

$$k_p [\frac{\partial^2\Theta}{\partial r^2} + \frac{2}{r} \frac{\partial\Theta}{\partial r}] + c_w \frac{\partial\rho_p}{\partial t} \frac{r}{3} \frac{\partial\Theta}{\partial r} + Q\rho_p = \rho_p c_p \frac{\partial\Theta}{\partial t} \qquad (4.33)$$

which is the well-known spherical heat conduction equation with terms for the sensible heat of water lost and heat generation (second and third terms on the left-hand side, respectively).

The boundary conditions for equation (4.33) are:

at the center, $\left.\frac{\partial\Theta}{\partial r}\right|_{r=0} = 0$ (4.34)

and at the surface,

$$-k_p \left.\frac{\partial\Theta}{\partial r}\right|_{r=r_s} = -\frac{1}{a}[\dot{q}_p - \frac{\partial\rho_p}{\partial t}(1-\varepsilon)c_w\Theta] + \rho_w c_w \delta_w \frac{\partial\Theta}{\partial t} \qquad (4.35)$$

The latter results from an energy balance at the surface which includes terms for the conduction of heat to the surface, the sensible heat in the water moving to the surface, the convective transfer of heat to the air stream, the sensible and latent heat of the water lost, and the change in the sensible heat of the free water surface.

Equations (4.5), (4.7), (4.13a-d), (4.15), (4.20), (4.29), (4.30), (4.33), (4.34), and (4.35) with an expression for F_1 in equation (4.13a) and additional boundary and initial conditions constitute the model for internal temperature gradients.

4.3 Solution of the Equations

Examination of the equations developed in the previous section for the three cases of thermal equilibrium, uniform product temperature and thermal gradients reveals that the following are common to all three cases:

$$\frac{\partial H}{\partial t} = -v_a \frac{\partial H}{\partial x} - \frac{\dot{m}_p}{\rho_a \varepsilon} \tag{4.36}$$

$$\dot{m}_p = \begin{cases} (1-\varepsilon) \dfrac{\partial \rho_p}{\partial t} = F_1(T,H,\Theta_s,t) \text{ when VPD} > 0,\ \delta_w = 0 & (4.37a) \\ \rho_w a \dfrac{\partial \delta_w}{\partial t} = \begin{cases} -h_w' a[P_s(\Theta_s)-P_v] \text{ when VPD} > 0,\ \delta_w > 0 & (4.37b) \\ \min\ (\dot{m}_p) \text{ such that } H \leq H_{sat}(T) & (4.37c) \end{cases} \end{cases}$$

$$\dot{m}_p \geq -[\rho_a \varepsilon v_a \frac{\partial H}{\partial x} + \rho_a \varepsilon \frac{\partial H}{\partial t}]_{H_{sat}} \tag{4.37d}$$

$$c_p = \frac{\rho_d}{\rho_p} (c_d - c_w) + c_w \tag{4.38}$$

$$Q = F_2(\Theta, t) \tag{4.39}$$

These equations are written in a form which facilitates discussion of solution techniques. Equation (4.36) is a rearrangement of equation (4.7). Equation (4.37a-d) is a slight rearrangement of equation (4.13a-d) with $\dot{m}_v$ replaced by $-\dot{m}_p$. Equation (4.38) is identical to equation (4.20) while equation (4.39) is an appropriate temperature dependent expression for the rate of heat generation by the product per unit mass-unit time.

In addition to equations (4.36) through (4.39), the following temperature equations apply:

for thermal equilibrium ($T = \Theta$),

$$\frac{\partial T}{\partial t} = \{-\rho_a \varepsilon v_a (c_a + c_v H) \frac{\partial T}{\partial x} + k_p (1-\varepsilon) \frac{\partial^2 T}{\partial x^2} + Q\rho_p (1-\varepsilon) + \dot{m}_p [T(c_v - c_w)] + h_{fg} \} / \{\rho_a \varepsilon (c_a + c_v H) + \rho_p c_p (1-\varepsilon) + \rho_w c_w a \delta_w \} \tag{4.40}$$

for uniform internal product temperature,

$$\frac{\partial T}{\partial t} = -v_a \frac{\partial T}{\partial x} - \frac{ha(T-\Theta)}{\rho_a \varepsilon (c_a + c_v H)} \tag{4.41}$$

and,

$$\frac{\partial \Theta}{\partial t} = \{k_p(1-\varepsilon) \frac{\partial^2 \Theta}{\partial x^2} + Q\rho_p(1-\varepsilon) + ha(T-\Theta) + \dot{m}_p[c_v T - c_w \Theta + h_{fg}]\}$$

$$/ \{\rho_p c_p(1-\varepsilon) + \rho_w c_w a \delta_w\} \tag{4.42}$$

for internal gradients, equation (4.41) with,

$$\frac{\partial \Theta}{\partial t} = \frac{k_p}{\rho_p c_p} \left(\frac{\partial^2 \Theta}{\partial r^2} + \frac{2}{r} \frac{\partial \Theta}{\partial r}\right) + \frac{c_w}{\rho_p c_p} \frac{r}{3} \frac{\partial \rho_p}{\partial t} \frac{\partial \Theta}{\partial r} + \frac{Q}{c_p} \tag{4.43}$$

and boundary conditions,

$$\left.\frac{\partial \Theta}{\partial r}\right|_{r=0} = 0 \tag{4.44}$$

$$\left.\frac{\partial \Theta}{\partial r}\right|_{r=r_s} = \frac{ha(T-\Theta) + \dot{m}_p(c_v T - c_w \Theta + h_{fg})}{k_p a} - \frac{\rho_w c_w \delta_w}{k_p} \frac{\partial \Theta}{\partial t} \tag{4.45}$$

Equation (4.40) is a rearrangement of equation (4.25). Equation (4.41) results from (4.5) and (4.30) while (4.42) results from (4.26) and (4.29). Equations (4.43) and (4.44) result from (4.33) and (4.34), respectively. Combination of equations (4.29) and (4.35) gives equation (4.45).

Table 4.2 lists the expected form of the boundary and initial conditions. The inlet air conditions are not expected to be constant. Any type of initial product temperature and moisture gradient may be imposed on the bed. The humidity is physically constrained by the surface temperature of the product such that $T_{dew\ point} \leq \Theta$ while the free water film thickness must be small enough to prevent bulk flow (drip). For the internal gradient model, different initial temperature gradients within the product might be applied at each level. In cases where conduction from adjacent differential volumes is permitted, the top of the pile is assumed to be insulated while the bottom gradient is constant.

Inspection of the model equations and initial and boundary conditions shows that a number of physical and thermal properties and auxiliary relationships must be specified. Table 4.3 lists the relationships applied to spherical products for model testing. Application of geometric formulas requires a knowledge of average product weight, density and bed void fraction to determine volume, diameter and specific surface area. Heat and mass transfer coefficients are determined using the Colburn J as given by Bird et al. (1960). The rate of moisture loss by the product is adapted from Villa (1973). Heat generation is given as a linear function of temperature for the initial model tests.

The thermal and physical properties required by the model equations and the auxiliary equations listed in Table 4.3 should be evaluated at an average temperature within the range at which

Table 4.2. Boundary and initial conditions needed by the models.

State Variable	At x=	At t=	Thermal Equilibrium	Uniform Temperature	Temperature Gradient
T	x	0	$T\ (x)$	$\theta_i\ (x)$	$\theta_{s,i}\ (x)$
H	x	0	$\min \begin{cases} H\ (x) \\ H_{sat}\ [T\ (x)] \end{cases}$	$H\ (x)$ $H_{sat}\ [\theta_i\ (x)]$	$H\ (x)$ $H_{sat}\ [\theta_{s,i}\ (x)]$
θ	x	0	$T\ (x)$	$\theta_i\ (x)$	$\theta\ (x,0,r) = \theta_i\ (x,r)$
ρ_p	x	0	$\rho\ [X\ (x)]$	$\rho\ [X\ (x)]$	$\rho\ [X\ (x)]$
c_p	x	0	$c\ (\rho_{px})$	$c\ (\rho_{px})$	$c\ (\rho_{px})$
δ_w	x	0	$\delta_{wi}\ (x)$	$\delta_{wi}\ (x)$	$\delta_{wi}\ (x)$
T	0	t	$T_i\ (t)$	$T_i\ (t)$	$T_i\ (t)$
H	0	t	$H_i\ (t)$	$H_i\ (t)$	$H_i\ (t)$
$\frac{\partial\theta}{\partial x}$	0	t	b	b	—
$\frac{\partial\theta}{\partial x}$	L	t	0	0	—
$\frac{\partial\theta}{\partial r}$	x	t $r=0$	—	—	Eq. (4.44)
$\frac{\partial\theta}{\partial r}$	x	t $r=r_s$	—	—	Eq. (4.45)

Table 4.3. Auxiliary relationships used for model testing with spherical product.

$$V = w/\rho_p$$

$$D = \left(\frac{6\ V}{\pi}\right)^{1/3}$$

$$A = \pi\ D^2$$

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

$$J_H = \frac{h}{c_b\ \rho_a\ v_a\ \varepsilon}\ (Pr)^{2/3} = \begin{cases} 0.91\ Re^{-0.51} & Re < 50 \\ 0.61\ Re^{-0.41} & Re > 50 \end{cases}$$

$$Re = \frac{\rho_a\ v_a\ \varepsilon}{a\ \mu_a}$$

$$J_D = \frac{h_D}{v_a}\ (Sc)^{2/3} = J_H$$

or, $h_D = 8.966 \times 10^{-4}\ h$ (at 10°C)

$$h_w' = 2.166 \times 10^{-3}\ h_D/T_A$$

$$F_1 = -\frac{h_w'\ D_{wa}}{r\delta h_D + D_{wa}}\ \gamma\ a\ (P_s - P_v)$$

$$F_2 = b_1\ T + b_2$$

the model will operate. Table 4.4 lists the properties taken at 10°C. Ranges for the product properties are condensed from Lutz and Hardenburg (1968) and are not representative of any specific product. A value near the midpoint of the range as given in Table 4.4 was used for testing the model. The range of values for $r\delta$ and γ for use in the moisture loss equation are unknown as this approach has been applied to only a few products (Fockens and Meffert, 1972; Villa, 1973).

Inspection of the model equations and initial and boundary conditions also reveals numerous nonlinear and nonhomogeneous terms. Therefore, an analytical solution cannot be obtained. Additional assumptions can be made to reduce the equations to forms solved analytically in the literature; these can be used to validate the numerical solutions.

Finite difference techniques can be applied to the equations in the form presented above. Either explicit or implicit difference equations can be written using forward differences on t and central differences on x.

For example, equation (4.41) can be written in explicit form as:

$$\frac{T_x^+ - T_x}{\Delta t} = - v_a \left(\frac{T_{x+\Delta x} - T_{x-\Delta x}}{2\Delta x}\right) - \frac{ha(T_x - \Theta_x)}{\rho_a \varepsilon (c_a + c_v H_x)} \qquad (4.46)$$

where the superscript "+" indicates a value at time t + Δt and the absence of the superscript implies time t. Forward or backward

Table 4.4. Thermal and physical properties of air and biological products.

Property	Units	Range or Value at 10 °C	Value used for Testing
b_1	J/h kg °C	2.5-150.	75.
b_2	J/h kg	~25.	25.
c_a	J/kg °C	1005.	
c_p	J/kg °C	2900.-4100.	3500.
c_v	J/kg °C	1884.	
c_w	J/kg °C	4187.	
D_{wa}	m^2/h	0.08454	
h_{fg}	J/kg	2,478,600.	
k_a	J/h m °C	89.1	
k_p	J/h m °C	1200.-3700.	2450.
Pr	—	0.7167	
$r\delta$	m		3.484×10^{-3}
Sc	—	0.605	
X	kg water/kg product	0.65-0.90	0.80
ϵ	m^3 void/m^3 bed	0.40-0.45	0.43
γ	—		0.3
ρ_a	kg/m^3	1.243	
ρ_p	kg/m^3	900.-1200.	1050.
ρ_w	kg/m^3	999.25	
μ_a	kg/m h	0.06354	

differences can be used on x at the bottom and top, respectively. If each of the equations pertaining to the particular model of interest are differenced in a manner similar to equation (4.46), each can be solved for its value of the dependent state variable at position x, time $t + \Delta t$ from information at time t. Each equation is then solved at each node throughout the depth of the bed, the time incremented, and the procedure repeated.

Similarly, equation (4.41) may be written in implicit form:

$$\frac{T_x^+ - T_x}{\Delta t} = - v_a \left[\frac{T_{x+\Delta x}^+ - T_{x-\Delta x}^+}{2\Delta x}\right] - \frac{ha(T_x^+ - \Theta_x^+)}{\rho_a \varepsilon (c_a + c_v H_x^+)} \qquad (4.47)$$

In this case each equation yields an expression for the dependent variable at time t based entirely on information at time $t + \Delta t$. If the equations are written for every depth node and the boundary conditions applied, a system of simultaneous equations which contains n unknowns results. Values of the dependent variables at all x and time $t + \Delta t$ are the unknowns. The system of simultaneous equations is solved and the procedure repeated at the next time level.

Due to the nature of the equations involved in the models, a nonlinear, multivariable search technique must be used to solve the system of simultaneous equations which result from the implicit form. The length of time required to achieve a solution under such circumstances is likely to be excessive, particularly since physical constraints such as the saturation point of air must be included. Therefore, no purely implicit solution was attempted.

Explicit techniques require restricted values of Δt and Δx in order to guarantee convergence to the solution. This is particularly true of several of the equations presented here. In particular, equation (4.41) is "ill-conditioned" in that $\frac{\partial T}{\partial t}$ becomes very small with respect to the terms on the right side of the equation. Many previous models of heat and mass transfer in beds of agricultural products have considered this term and $\frac{\partial H}{\partial t}$ to be negligible (Bakker-Arkema et al., 1967). The ill-conditioning of this equation requires the use of very small Δt and excessive amounts of computer time. The thermal equilibrium model, which does not contain equation (4.41), can be solved explicitly. However, the stability requirements on the equations still restrict the step sizes to very small values.

More complex methods of solution, such as alternating direction methods, generally suffer the undesirable characteristics already discussed when applied to these systems of equations. An attempt was made to apply a technique similar to the general "Hopscotch" algorithm outlined by Gourlay (1970) and expanded by Gourlay and McGuire (1971). The execution time of the resulting program was of the same order of magnitude as the time simulated. Considerable improvements would undoubtedly have resulted from continued development of the program. However, this approach was abandoned due to the very good agreement of the limited Hopscotch results with results from a less sophisticated, but faster solution technique.

4.3.1 Thermal Equilibrium Model

Equation (4.40) can be written in explicit difference form as:

$$T_x^+ = T_x + \{-\rho_a v_a \varepsilon \Delta t(c_a + c_v H_x)(T_{x+\Delta x} - T_{x-\Delta x})/2\Delta x$$

$$+ k_p(1-\varepsilon)(T_{x+\Delta x} - 2T_x + T_{x-\Delta x})/(\Delta x)^2$$

$$+ Q_x(1-\varepsilon)\rho_{px}\Delta t + \dot{m}_p \Delta t[T_x(c_v - c_w) + h_{fg}]\}$$

$$/\{\rho_a \varepsilon(c_a + c_v H_x) + \rho_{px} c_{px}(1-\varepsilon) + \rho_w c_w a \delta_{wx}\} \qquad (4.48)$$

Using this equation and the initial and boundary conditions, T_x^+ can be evaluated for all depth nodes. At the bottom, T_i is specified by the boundary condition. Initially, T_i is also specified by the initial product temperature. This inconsistency can be remedied and stability increased by defining the initial value of T_i as:

$$T_i^+ = \frac{\rho_a v_a \varepsilon c_a T_i \Delta t + \rho_{pi} c_{pi}(1-\varepsilon)\Theta_i \Delta x}{\rho_a v_a \varepsilon c_a \Delta t + \rho_{pi} c_{pi}(1-\varepsilon)\Delta x} \qquad (4.49)$$

At the top, $T_{n+1} = T_n$ while at the bottom $T_{1-\Delta x} = 2T_1 - T_{1+\Delta x}$ to satisfy the boundary condition.

After the temperature at any position is found by equation (4.48), the saturation humidity and then the maximum rate of mass transfer to the air can be evaluated using the psychrometric package and equation (4.37d) differenced as follows:

$$\dot{m}_p \geq - \left[\rho_a v_a \varepsilon \frac{H^+_{xsat} - H^+_{x-\Delta x}}{\Delta x} + \rho_a \varepsilon \frac{H^+_{xsat} - H_x}{\Delta t} \right] \tag{4.50}$$

This is basically an implicit form of equation (4.36) where the humidity at the new time corresponds to the saturation point at the temperature found using equation (4.48). If the mass loss rate used in equation (4.48) is greater than that given by equation (4.50), it and the temperature are accepted. Otherwise, a new temperature is computed using the result of equation (4.50). A limiting mass loss rate is again found using equation (4.50) and a further temperature calculation is necessary. The procedure is repeated until a mass loss rate and corresponding temperature are found which result in a physically feasible combination of T^+_x and H^+_x, H^+_x being given by equation (4.36) in the form:

$$H^+_x = \frac{\Delta x}{\Delta x + v_a \Delta t} \left[H_x + \frac{v_a \Delta t}{\Delta x} H^+_{x-\Delta x} - \frac{\dot{m}_p \Delta t}{\rho_a \varepsilon} \right] \tag{4.51}$$

Equation (4.37a), (4.37b), or (4.37c) is used to find ρ^+_{px} or δ^+_{wx} depending upon the conditions. The specific heat, c^+_{px}, is found using equation (4.38).

The solution procedure is shown schematically in Figure 4.3. The above steps are carried out at each depth node before moving on to the next time.

This solution technique proved to be more stable than a pure explicit procedure, although the precise stability and convergence criteria were not determined.

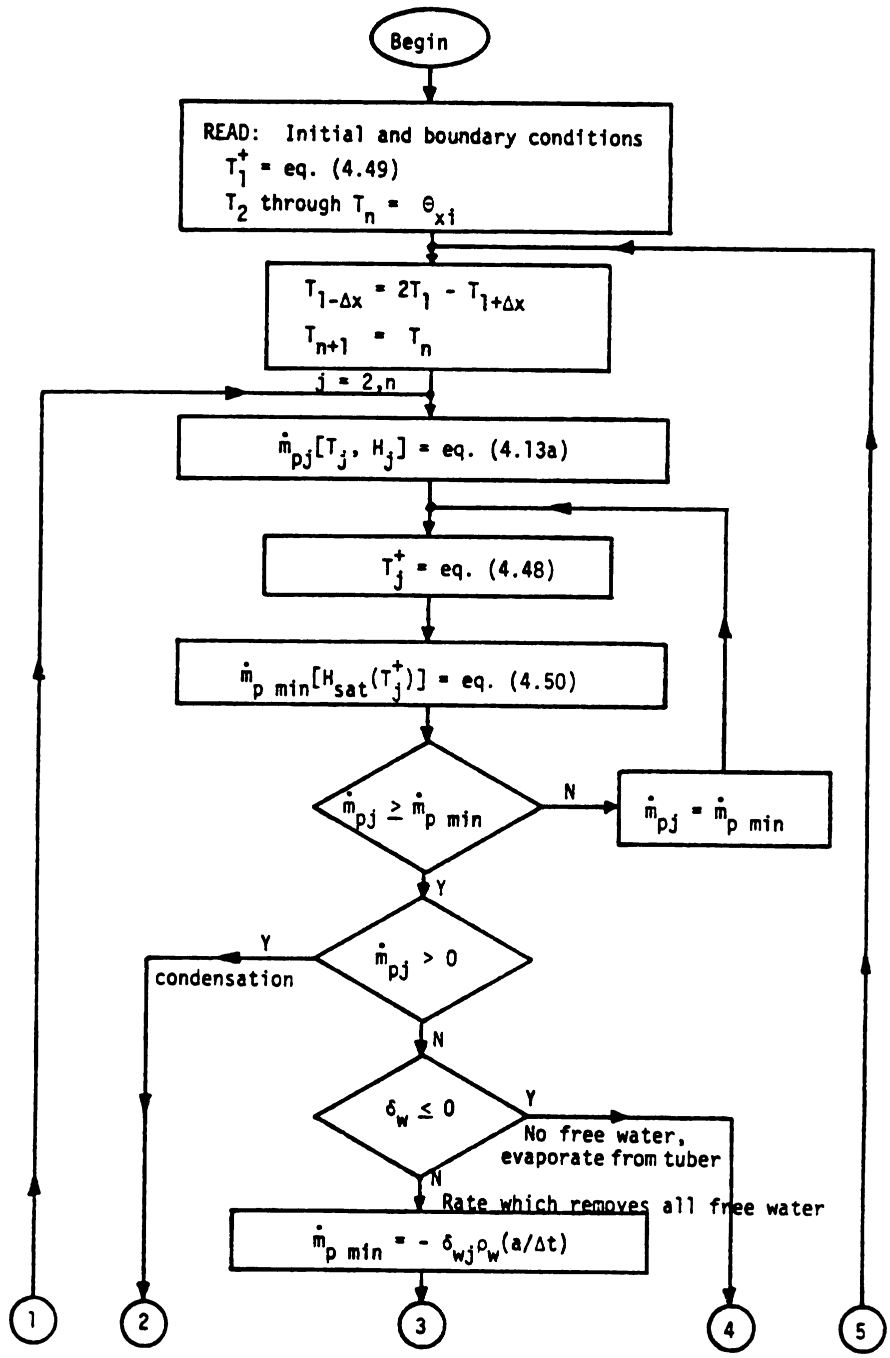


Figure 4.3. Flow chart of the thermal equilibrium model.

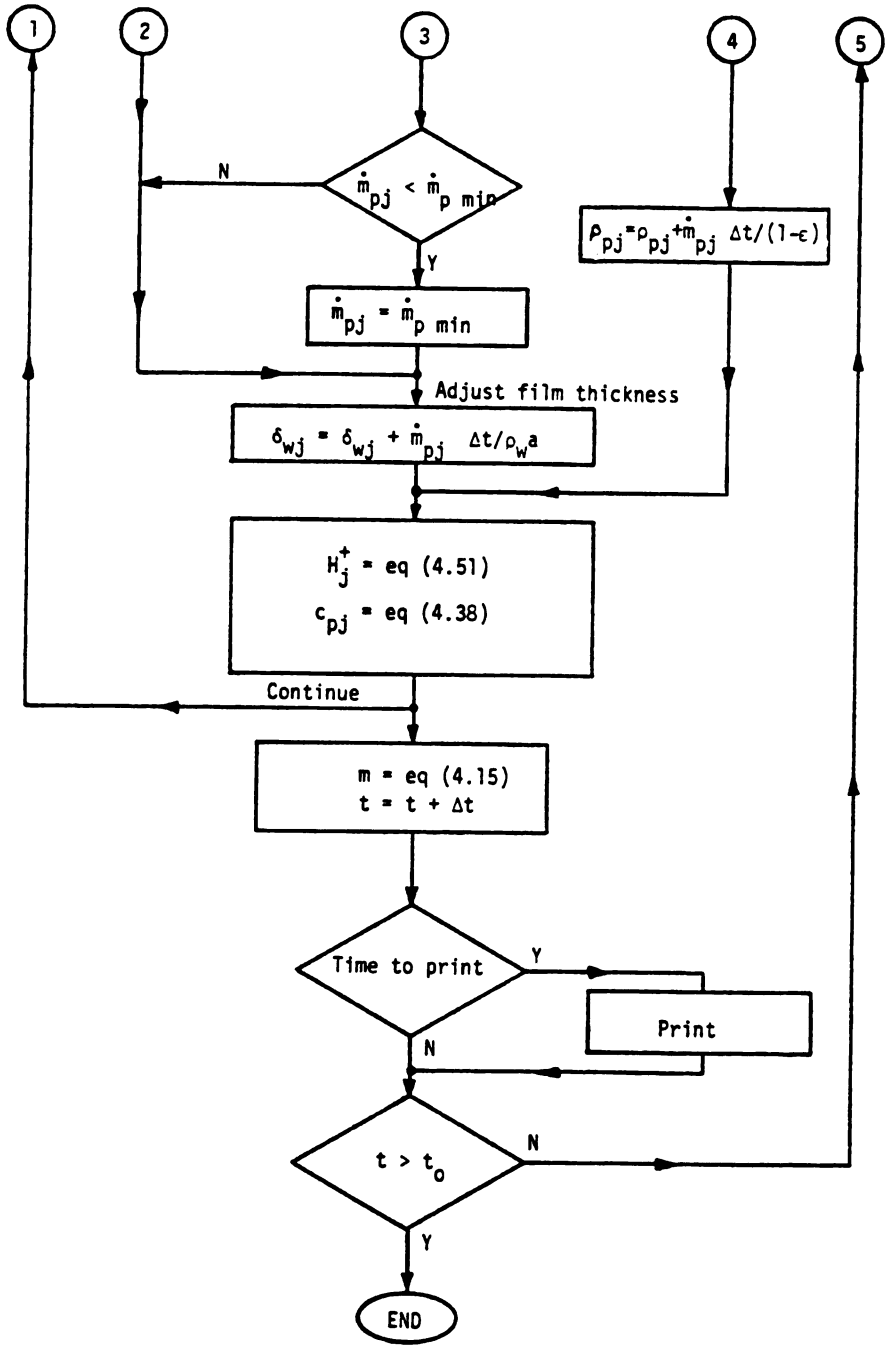


Figure 4.3. Continued.

4.3.2. Uniform Product Temperature Model

To overcome the ill-conditioning of equation (4.41), both the temperature and humidity equations are written in terms of the distance derivatives and differenced implicitly as:

$$T^+_{x+\Delta x} = T^+_x - \frac{\Delta x}{v_a \Delta t}(T^+_x - T_x) - \frac{ha\Delta x(T^+_x - \Theta^+_x)}{\rho_a v_a \varepsilon(c_a + c_v H^+_x)} \quad (4.52)$$

$$H^+_{x+\Delta x} = H_x - \frac{\Delta x}{v_a \Delta t}(H^+_x - H_x) - \frac{\Delta x \dot{m}^+_{px}}{\rho_a v_a \varepsilon} \quad (4.53)$$

Equation (4.42) is differenced explicitly as:

$$\Theta^+_x = \Theta_x + \{[k_p(1-\varepsilon)\Delta t \,/\, (\Delta x)^2](\Theta_{x+\Delta x} - 2\Theta_x + \Theta_{x-\Delta x})$$

$$+ ha\Delta t(T_x - \Theta_x) + \dot{m}_{px}\Delta t(c_v T_x - c_w \Theta_x + h_{fg})$$

$$+ Q_x \rho_{px}(1-\varepsilon)\Delta t\} \,/\, \{\rho_{px} c_{px}(1-\varepsilon) + \rho_w c_w a \delta_{wx}\} \quad (4.54)$$

The boundary and initial conditions provide sufficient information to solve for Θ at all depths for time Δt. However, the initial condition that $T = \Theta$ results in very little transfer. Therefore, only the value corresponding to the node at the inlet need be reevaluated using equation (4.54) with $\dot{m}_p$ based on the inlet conditions. To satisfy the conduction boundary condition, $\Theta_{1-\Delta x} = 2\Theta_1 - \Theta_{1+\Delta x}$ at the bottom and $\Theta_{n+\Delta x} = \Theta_n$ at the top.

With Θ_x^+ known for all x, and T_i^+ and H_i^+ given by the boundary condition, $T_{\Delta x}^+$ and $H_{\Delta x}^+$ can be found followed by $T_{\Delta x+\Delta x}^+$ and $H_{\Delta x+\Delta x}^+$ and so forth to the top of the bed. This in turn provides the information necessary for the calculation of Θ_x^{++} for all x.

Considerable savings in solution time are achieved if the calculation of Θ_x^{++} directly follows the calculation of $T_{x+\Delta x}^+$ and $H_{x+\Delta x}^+$ at each node. Using this approach, $\dot{m}_{px}^+$ needs to be evaluated only once for use in equations (4.53) for $H_{x+\Delta x}^+$ and (4.54) for Θ_x^{++}.

$T_{x+\Delta x}^+$ as given by equation (4.52) does not explicitly depend upon the rate of moisture transfer. Therefore, once $T_{x+\Delta x}^+$ has been found, the limiting value for the mass transfer rate is given by equation (4.37d) differenced as:

$$\dot{m}_p \geq -\left[\frac{\rho_a v_a \varepsilon}{\Delta x}\left(H_{x+\Delta x sat}^+ - H_x^+\right) + \frac{\rho_a \varepsilon}{\Delta t}\left(H_x^+ - H_x\right)\right] \qquad (4.55)$$

An iterative procedure to match the rate of transfer with the temperature as used in the equilibrium model is not needed here.

The actual moisture transfer rate is determined by equation (4.37a), (4.37b), or (4.37c) for loss from the product, evaporation of free water, or condensation, respectively. All of the conditions listed with equation (4.37) must be met.

The solution procedure is shown schematically in Figure 4.4.

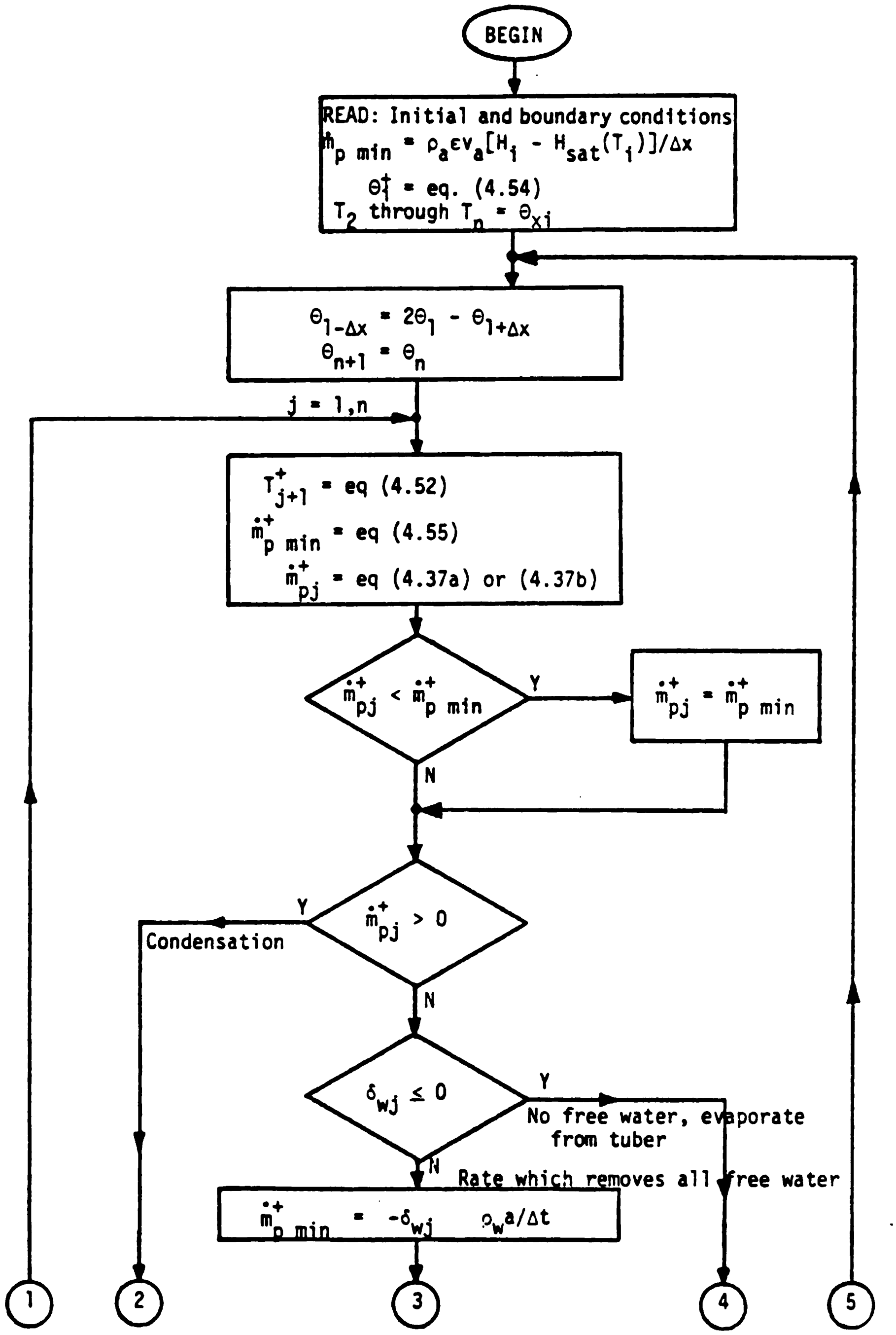


Figure 4.4. Flow chart of the uniform product temperature model.

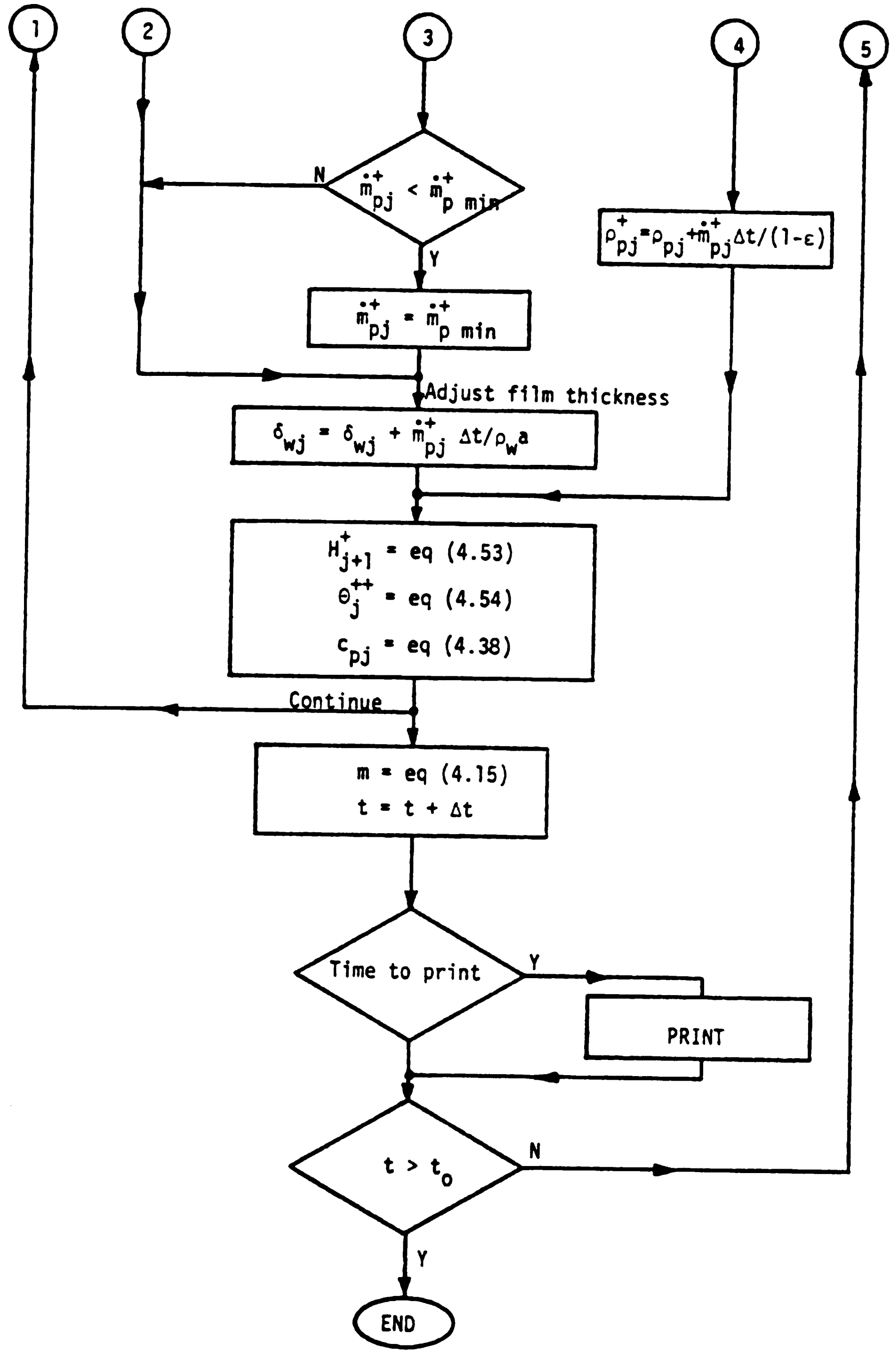


Figure 4.4. Continued.

Bakker-Arkema et al. (1974) showed that the necessary conditions for stability of a similar set of equations without mass transfer, heat generation or conduction are:

$$\Delta x \leq \frac{\rho_a v_a \varepsilon (c_a + c_v H)}{ha} \tag{4.56}$$

and,

$$\Delta t \leq \frac{\rho_p c_p (1 - \varepsilon)}{ha} \tag{4.57}$$

Unfortunately, addition of the mass transfer, heat generation and conduction terms complicate the analysis considerably. Using the above as a starting point, a trial-and-error approach was used to determine values of the step sizes for which the solution converged. It was found that adequate convergence resulted with step sizes expressed by:

$$\Delta x = \frac{\rho_a v_a \varepsilon c_a}{2ha} \tag{4.58}$$

and,

$$\Delta t = \frac{\rho_p c_p (1 - \varepsilon)}{4ha} \tag{4.59}$$

4.3.3. Internal Temperature Gradient Model

The solution of the model for predicting thermal gradients within the product is very similar to the solution of the uniform product temperature model outlined above. Equation (4.54) is replaced by equation (4.43); boundary conditions are given by equations (4.44) and (4.45). Where Θ appears in the other equations, Θ_s (the surface temperature) is used.

Equation (4.43) must be solved for each radial node, at each depth node, for every time step. To simplify the notation, only the radial position subscript and not the bed position subscript is shown on Θ. At the center, the equation reduces to:

$$\Theta_1^+ = \Theta_1 + \left[\frac{6k_p\Delta t}{(\Delta r)^2}(\Theta_2 - \Theta_1) + Q_1\rho_{px}\Delta t\right] / (\rho_{px}c_{px}) \qquad (4.60)$$

For interior nodes, equation (4.43) becomes:

$$\Theta_r^+ = \Theta_r + \left\{\frac{k_p\Delta t}{(\Delta r)^2}\left[\Theta_{r+\Delta r} - 2\Theta_r + \Theta_{r-\Delta r} + \frac{\Delta r}{r}(\Theta_{r+\Delta r} - \Theta_{r-\Delta r})\right] + \frac{c_w r}{6\Delta r}(\rho_{px}^+ - \rho_{px})(\Theta_{r+\Delta r} - \Theta_{r-\Delta r}) + Q_r\rho_{px}\Delta t\right\} / (\rho_{px}c_{px}) \qquad (4.61)$$

The surface temperature is given by:

$$\Theta_s^+ = \Theta_s + \Bigg\{-\frac{k_p\Delta t}{(\Delta r)^2}3(N - 1.5)^2(\Theta_s - \Theta_{s-1})$$

$$+ \frac{\dot{m}_p\Delta t}{1-\varepsilon}[(N - 1)^3(c_vT_x + h_{fg} - c_w\Theta_s]$$

$$+ (\rho_p^+ - \rho_p)(N - 1.5)^3c_w(\Theta_s - \Theta_{s-1})$$

$$+ \frac{h\Delta t}{\Delta r}3(N - 1)^2(T_x - \Theta_s) + Q_s\rho_{px}\{(N - 1)^3$$

$$- (N - 1.5)^3\}\Delta t\Big) \;/\; [\rho_{px}c_{px}\{(N - 1)^3 - (N - 1.5)^3\}$$

$$+ \rho_w c_w (N - 1)^2 \delta_{wx} \;/\; \Delta r] \qquad (4.62)$$

where N is the number of radial nodes.

At each depth node for each time step, equation (4.60) is solved for the center temperature, equation (4.61) for each interior node, and finally equation (4.62) for the surface temperature ($\Theta^{++}_{x,s}$) according to the solution procedure of the uniform product temperature model.

For the initialization of the inlet node, the equations can be greatly simplified if no internal gradient is assumed to exist. In this case, equations (4.60) and (4.61) reduce to:

$$\Theta^+_r = \Theta_r + \frac{Q_r \Delta t}{c_{px}} \qquad (4.63)$$

This change in Θ^+_r may be assumed negligible. The surface node equation becomes:

$$\Theta^+_s = \Theta_s + \Bigg(\frac{\dot{m}_p \Delta t}{1-\varepsilon} [(N-1)^3(c_v T_i + h_{fg} - c_w\Theta_s)]$$

$$+ (\rho^+_{p_1} - \rho_{pi})(N-1.5)^3 c_w(\Theta_s - \Theta_{s-1}) + h\,\frac{\Delta t}{\Delta r}\,3(N-1)^2(T_i - \Theta_s)$$

$$+ Q_s \rho_{pi}[(N - 1)^3 - (N - 1.5)^3]\Delta t\Bigg)$$

$$/ \ \{\rho_{pi} c_{pi} [(N - 1)^3 - (N - 1.5)^3]$$

$$+ \rho_w c_w (N - 1)^2 \delta_{wi} / \Delta r\} \tag{4.64}$$

In addition to the stability criteria given by equations (4.56) and (4.57), the temperature gradient model must satisfy the requirements of the spherical diffusion equation. Without mass loss or heat generation this requirement is given as:

$$\Delta t \leq \frac{(\Delta r)^2 \rho_p c_p}{2 k_p} \tag{4.65}$$

As the number of radial nodes increases additional calculations are needed and Δt decreases. The result is a rapidly increasing solution time requirement. All three step sizes Δx, Δt, Δr must be of a proper magnitude to insure convergence.

4.4 Validation and Testing of the Solutions

Since the models have not been solved analytically, a direct comparison of the numerical solutions is not possible. A simplified form of the uniform temperature model in which heat generation, mass transfer and conduction do not occur has been solved analytically and graphically. Although comparison of the simplified model to such solutions does not constitute validation of the full model, it can demonstrate the validity of a very important portion of the model. If the simplified model is derived by setting $\dot{m}_p$, Q, and k_p

to zero in the full model, this approach also serves as a check that null input results in null response for these terms.

The influence of the primary terms in the models can be determined by restoring them, one at a time, to the simplified model. The response of the solution as each term is restored should be consistent in direction and order of magnitude with reality. In addition, temperature time derivatives can be set to zero and an approximate steady state equation derived. This should also correspond to the solution if carried far enough in time.

The influence of variations in individual or groups of parameters can be tested for consistency with the differential equations and experience. In the case of design parameters, a knowledge of the relative influence of each is paramount to efficient design.

Finally, the response of the model to specific input variations can be tested. This information may be beneficial to the design of control systems as well as demonstrating the feasibility, if not the validity, of the solution.

Since all three models should show somewhat similar responses to identical inputs and initial conditions, only the uniform temperature model is used for the full series of comparisons. This model can be viewed as a compromise between total thermal equilibrium and existence of internal temperature gradients. Fortuitously, its solution time is considerably shorter than that required by the other models.

Unless otherwise specified, initial and boundary conditions are constant. Initial conditions are not functions of depth and boundary conditions are not functions of time. The bed is at a uniform temperature with uniform properties.

4.4.1 Comparison With the Classical Solutions

The uniform product temperature model has been solved for the simplified case of heat transfer only without heat generation or conduction within the bed. Schumann (1929) obtained analytical solutions for the cooling rates of solids under conditions of constant inlet cooling medium temperature and uniform initial solids temperature [equations (3.1) and (3.2)]. Furnas (1930) extended the solution to deeper beds and longer times using graphical integration. In both cases the results are presented as plots of dimensionless temperature $(\Theta-\Theta_i)/(T_i)$ or $(T-\Theta_i)/(T_i)$ versus a dimensionless term, Z, for constant term, Y, where:

$$Y = \frac{ha}{\rho_a \varepsilon c_a} \frac{x}{v_a} \tag{4.66}$$

$$Z = \frac{ha\ (t - x/v_a)}{\rho_p c_p (1 - \varepsilon)} \tag{4.67}$$

Figures 4.5 and 4.6 show the results of the numerical solution of the simplified uniform product temperature model as compared with the results of Furnas (1930). The model was simplified by

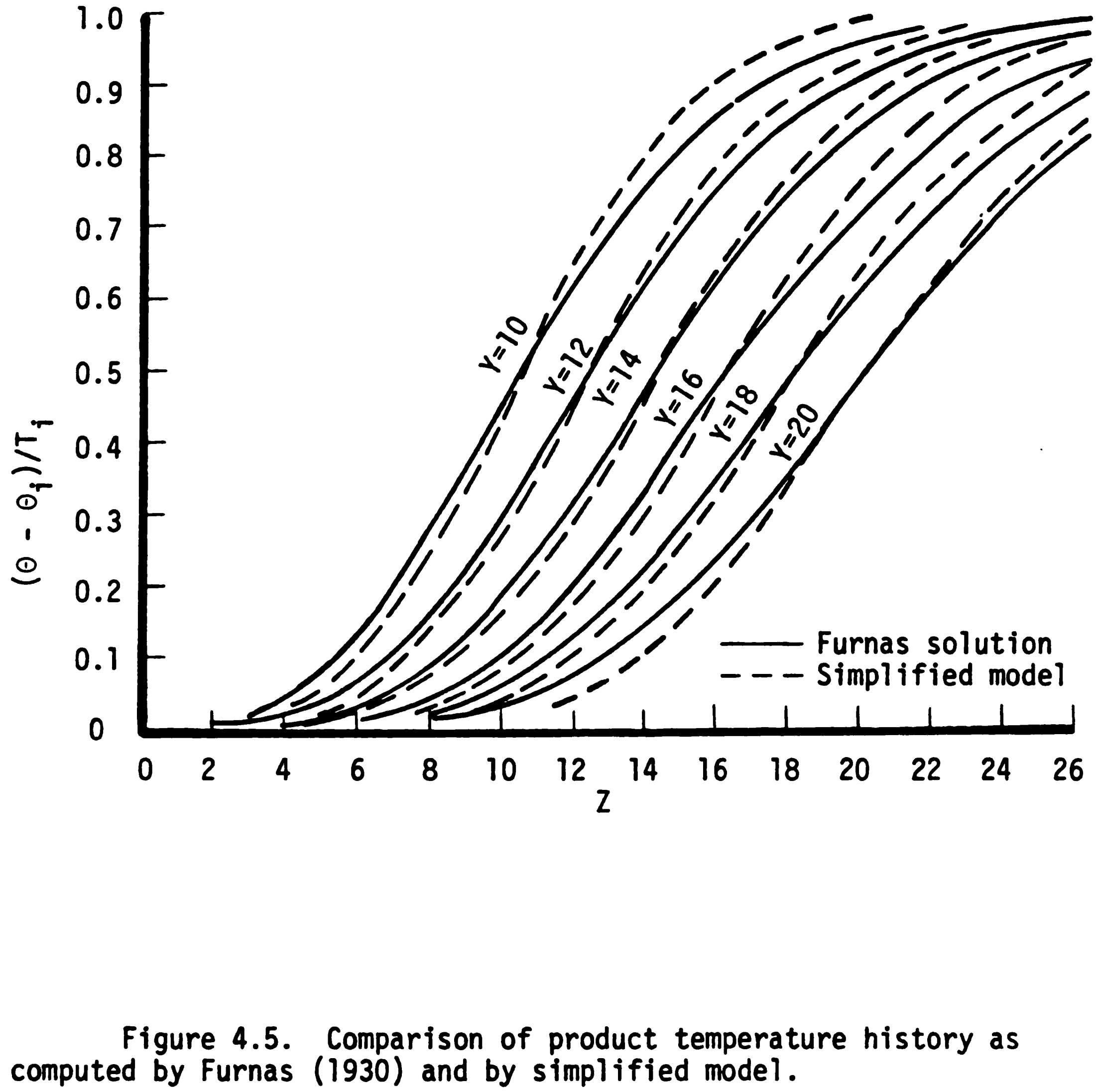


Figure 4.5. Comparison of product temperature history as computed by Furnas (1930) and by simplified model.

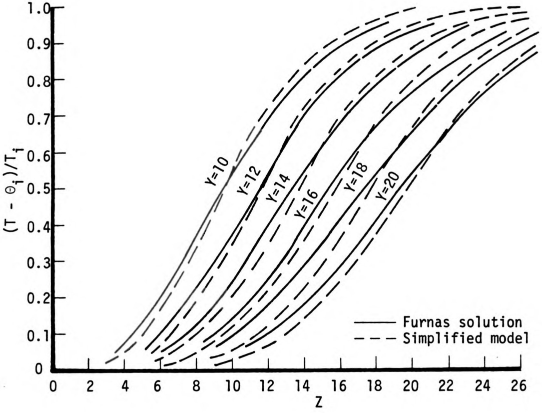


Figure 4.6. Comparison of air temperature history as computed by Furnas (1930) and by simplified model.

setting $k_p = \dot{m}_p = Q = 0$. The relationships presented in Table 4.3 and properties of Table 4.4 were used. Additional inputs are listed in Table 4.5.

Figures 4.5 and 4.6 reveal that agreement between the simplified model is less than perfect. The numerical solution tends to underpredict the normalized temperature for values less than 0.5 and overpredict for larger values. The difference is approximately the same for all depths (values of Y). The maximum deviation is on the order of 0.04 on the dimensionless temperature scale or 4%. It is presumed that this difference results from errors introduced by the numerical solution and by the graphical integration used by Furnas (1930).

Table 4.5. Inputs for the Furnas comparison.

T_i	=	20.0°C
Θ_i	=	0.0°C
H	=	0.003 kg water/kg dry air
L	=	2.0 m
v_a	=	300.0 m/h
w	=	275.0 g

4.4.2 Influence of Individual Terms on the Solution

Figure 4.7 shows the air temperature profile in a 2-meter bed of spherical product undergoing forced cooling at 3, 12, 24, and 36 hours as predicted by the simplified model. Tables 4.3 and 4.4 apply. Additional inputs are shown in Table 4.6. Figure 4.7 reveals that in the absence of heat generation, mass transfer and conduction, a distinct cooling front and zone pass through the bed. The top of the bed temperature remains constant at the initial temperature until the leading edge of the front arrives. Eventually, the entire bed reaches steady state at the inlet air temperature. With $\frac{\partial T}{\partial t} = 0$ and $\frac{\partial \Theta}{\partial t} = 0$, equation (3.1) shows $\frac{\partial T}{\partial x} = 0$ or $\frac{\Delta x}{\Delta T} = 0$.

Figure 4.8 compares the air temperature profile at 12 and 36 hours for the simplified model with $k_p = 0$ to a similar model with k_p as given in Table 4.4. With these inputs, k_p has very limited influence. Since this term of the equation involves the second derivative of temperature with respect to position, it is inactive where the profile is nearly linear.

Inspection of the model equations shows that the term $(k_p)/(\rho_p c_p)$ or thermal diffusivity appears. If k_p has a significant influence, it should occur when k_p is large with $\rho_p c_p$ small.

Figure 4.9 compares the air temperature profile at 12 hours for $k_p = 0$ and 3700 J/h m°C with $\rho_p = 900$ kg/m^3 and $c_p = 2900$ J/kg °C. These values are the extremes listed in Table 4.3. Again, the bed conduction term has very little influence.

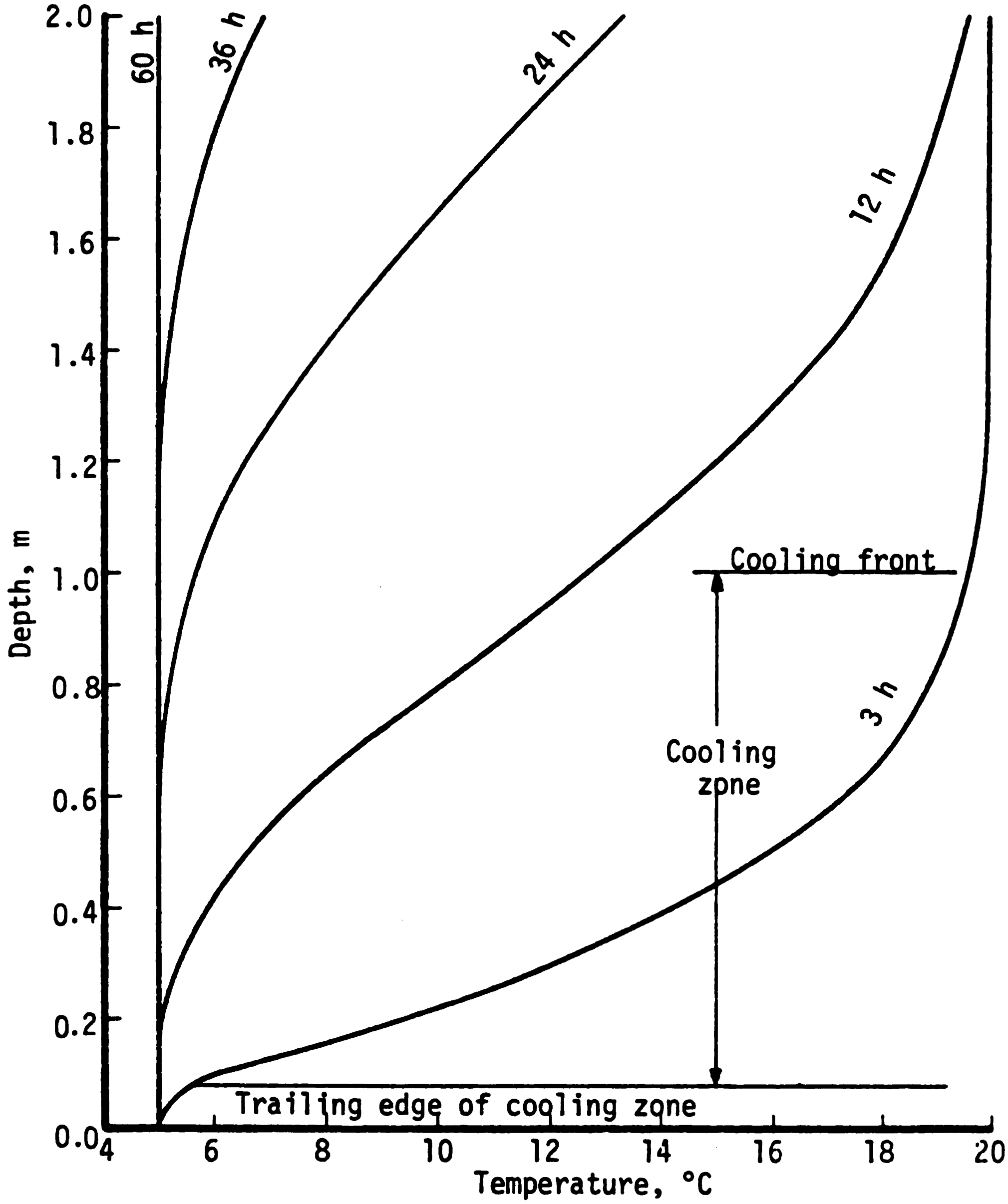


Figure 4.7. Temperature profile in a 2 m bed at various times as predicted by the simplified model ($k_p = \dot{m}_p = Q = 0$).

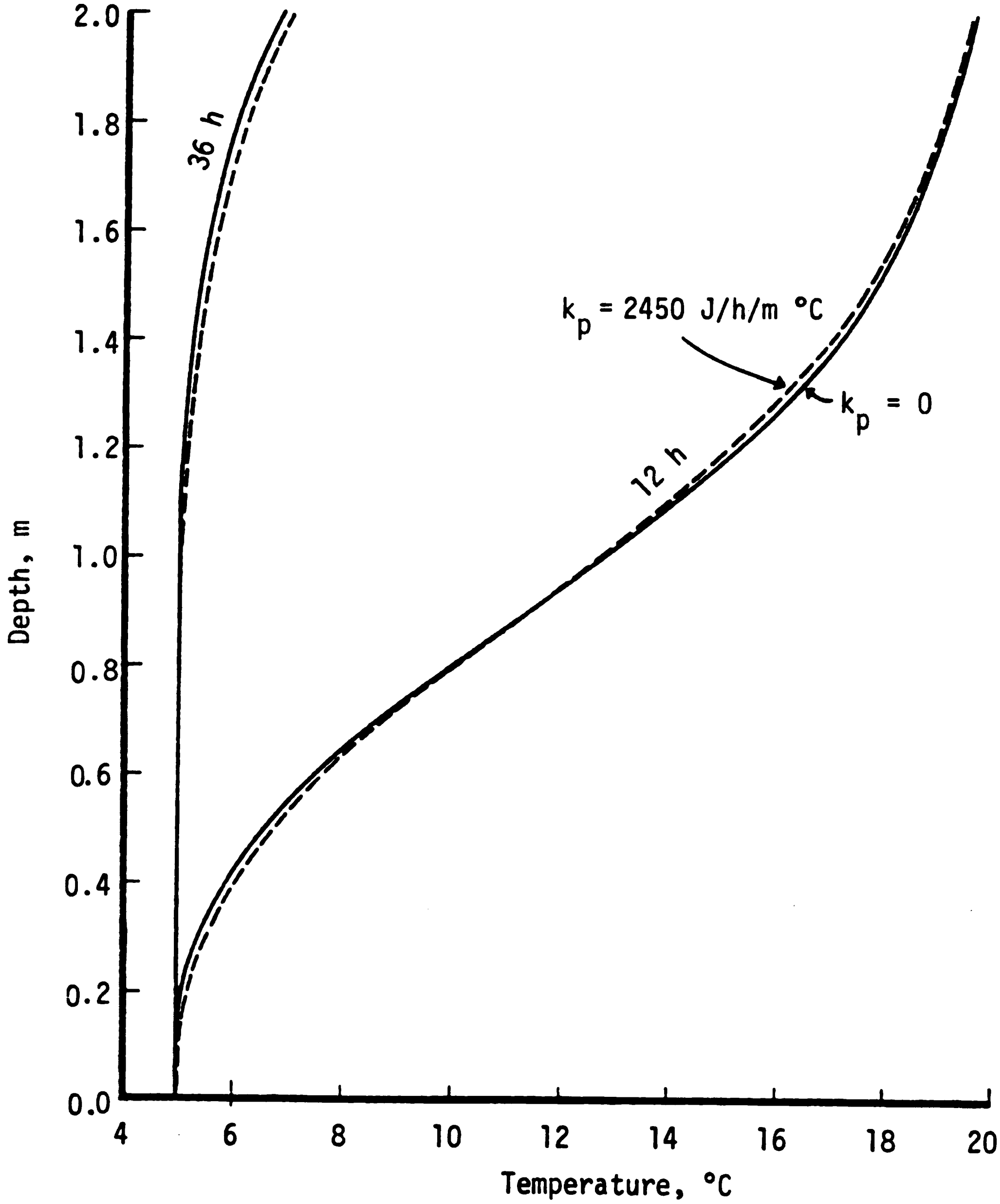


Figure 4.8. Comparison of temperature profile at 12 and 36 h for k_p = 0 and k_p = 2450 J/h m °C ($\dot{m}_p$ = Q = 0).

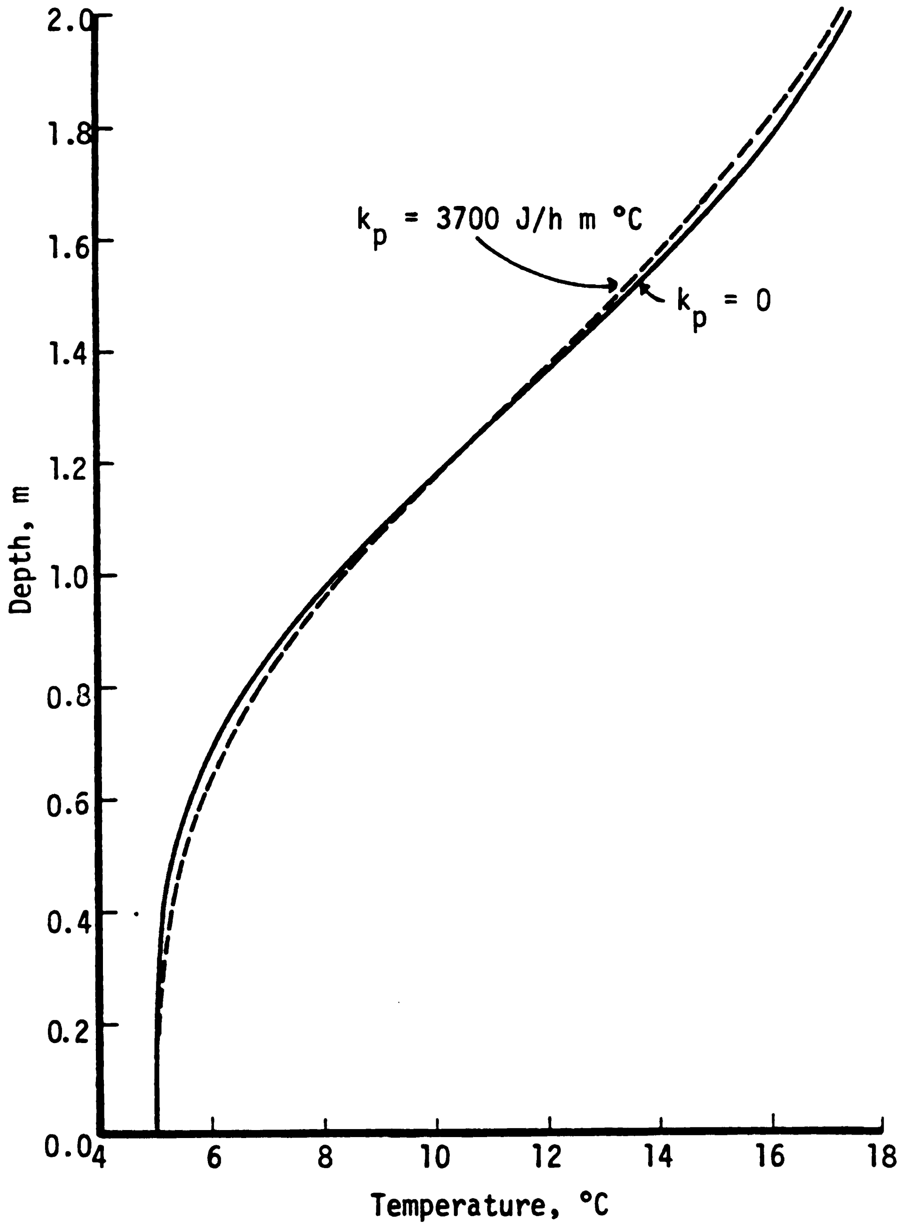


Figure 4.9. Comparison of the temperature profile at 12 h for $k_p = 0$ and k_p = 3700 J/h m °C with ρ_p = 900 kg/m^3 and c_p = 2900 J/kg °C ($\dot{m}_p$ = Q = 0).

The conduction term is not affected by air velocity. The remaining terms in the simplified model are decreased with decreasing velocity. Therefore, if the conduction term is of importance in any case, it should be significant with low velocities. Figure 4.10 compares the temperature profiles at 24 hours for an air velocity of 100 m/h for c_p = 2900 J/kg °C, ρ_p = 900 kg/m^3 and k_p = 3700 J/h m°C and 0. Heat generation and mass transfer are included in these results. At 24 hours with k_p = 3700 J/h m°C, the predicted weight loss is 13.01 kg/ton, while with k_p = 0, the weight loss is 13.07 kg/ton. Figure 4.10 again demonstrates the relative insignificance of the conduction term.

The simplified model is compared with a model including mass transfer in Figure 4.11 with inputs as listed in Table 4.6. Heat generation is still excluded. This figure illustrates the faster rate of cooling achieved by removing heat as latent heat of vaporization. The total moisture lost was 9.22, 11.72 and 12.44 kg/ton at 12, 36 and 60 hours, respectively. For the model including mass transfer, the steady state is approximated by setting time derivatives to zero resulting in:

$$\frac{\partial T}{\partial x} = \frac{\dot{m}_p(c_v T + h_{fg})}{\rho_a v_a \varepsilon (c_a + c_v H)} \tag{4.68}$$

Equation (4.68) gives a negative slope and gradual decrease in temperature with increasing x at the steady state. If the air reaches moisture equilibrium with the product as it passes through

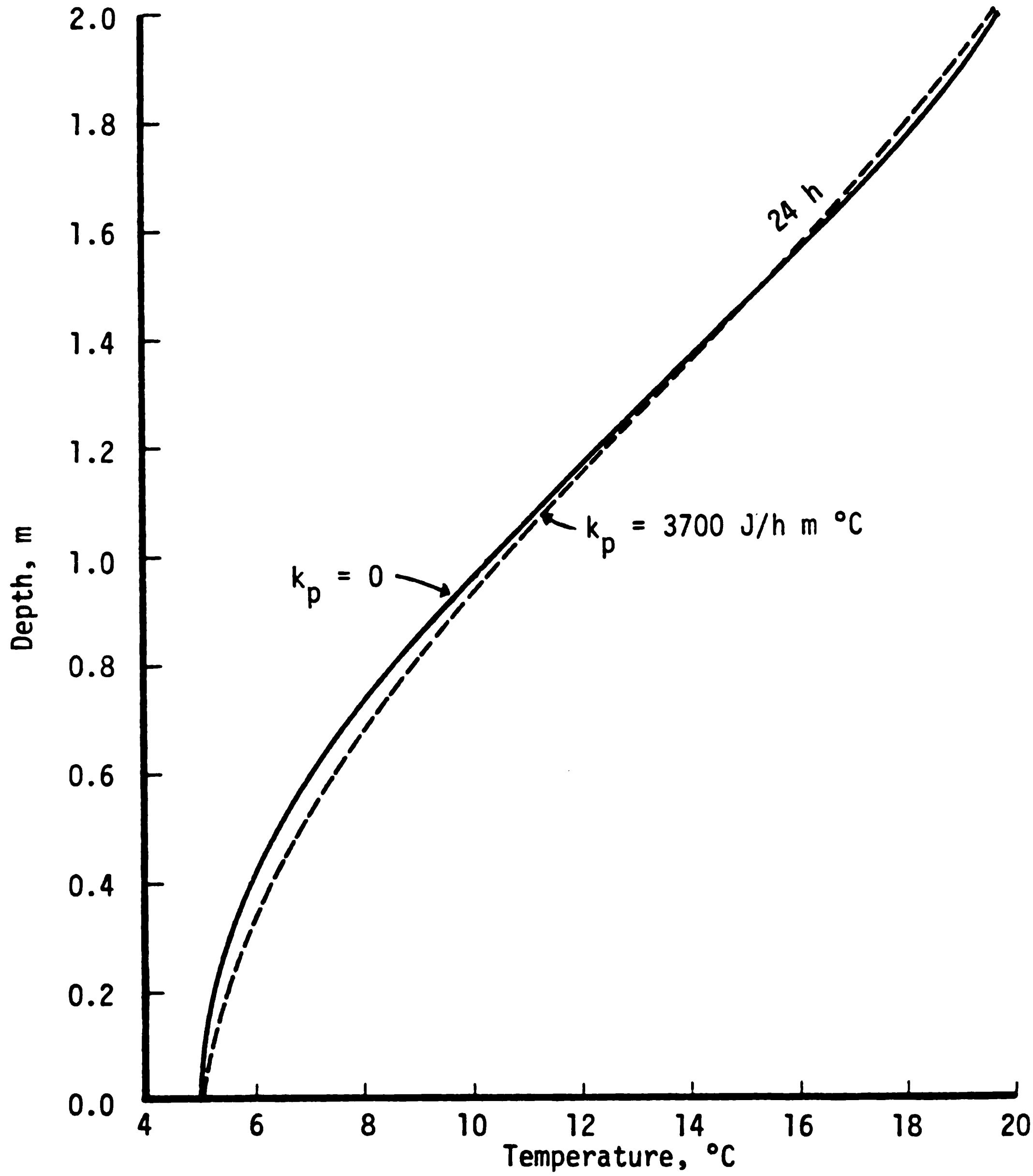


Figure 4.10. Comparison of the temperature profile at 24 h for $k_p = 0$ and $k_p = 3700$ J/h m °C with $\rho_p = 900$ kg/m^3 and $c_p = 2900$ J/kg °C.

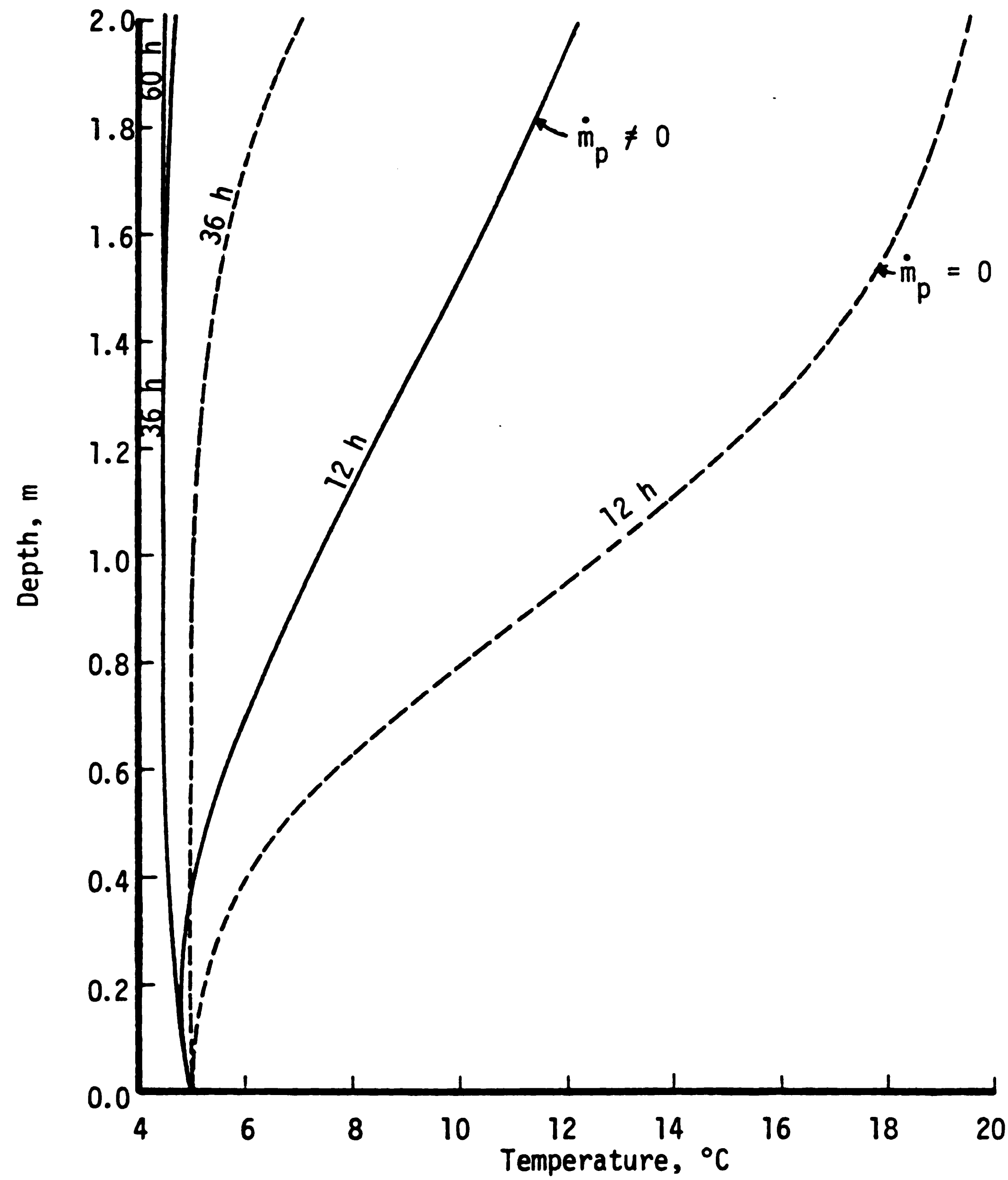


Figure 4.11. Comparison of the temperature profiles at 12 h and 36 h for the model with and without mass transfer (Q = 0).

Table 4.6. Inputs for comparison of the simplified model with models including heat generation, mass transfer, and conduction in the bed.

T_i	=	5.0°C
Θ_i	=	20.0°C
H	=	0.005 kg water/kg dry air
L	=	2.0 m
v_a	=	300.0 m/h
w	=	275.0 g

the bed, $\dot{m}_p = 0$ and the steady state temperature remains constant with depth.

The effects of heat generation without mass transfer as compared with the simplified model are shown in Figure 4.12. Heat generation slows the progression of the cooling front. The steady state has a positive slope approximated by:

$$\frac{\partial T}{\partial x} = \frac{\rho_p(1 - \varepsilon)Q}{\rho_a v_a \varepsilon(c_a + c_v H)} \qquad (4.69)$$

Figure 4.13 contains the air temperature profiles of the full model including mass transfer, heat generation, and conduction. Comparison with Figure 4.7 for the simplified model reveals the combined influence of the additional terms for the particular rates

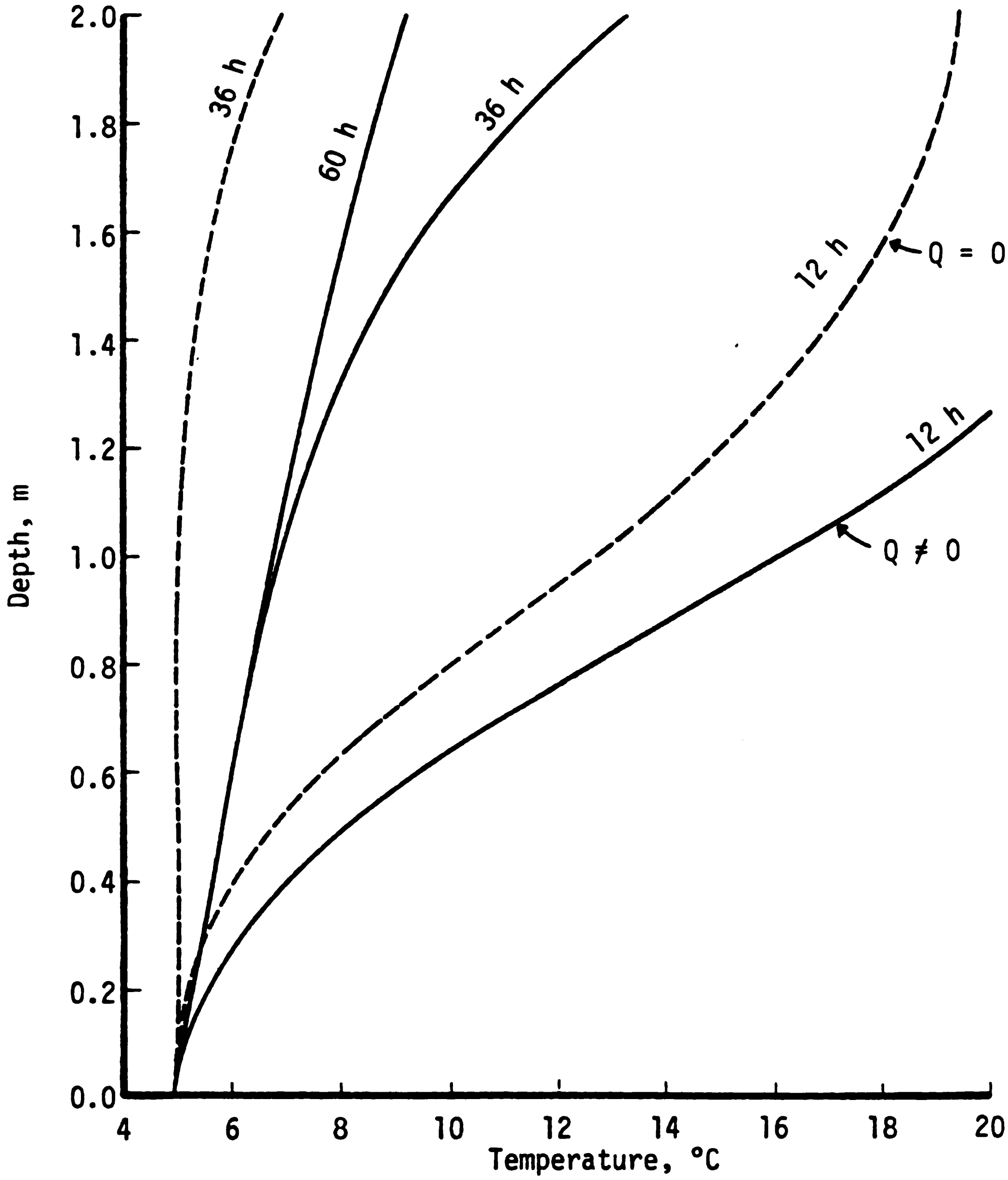


Figure 4.12. Comparison of the temperature profiles at 12 and 36 h for the model with and without heat generation ($\dot{m}_p = 0$).

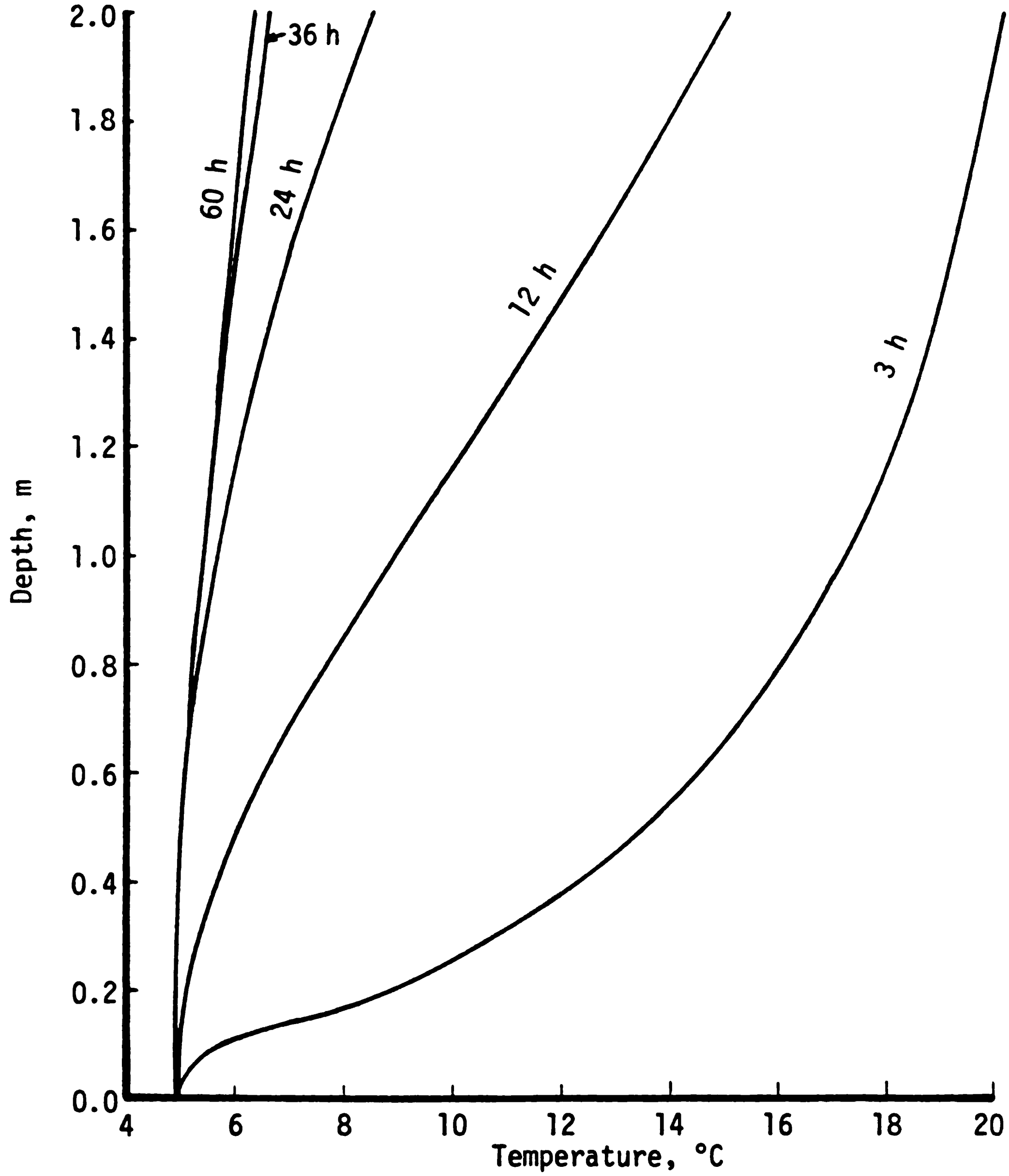


Figure 4.13. Temperature profiles from the full model at 3, 12, 24, 36, and 60 h.

used. Setting time derivatives to zero, the steady state is approximated by:

$$\frac{\partial T}{\partial x} = \frac{\dot{m}_p(c_v T + h_{fg}) + \rho_p(1 - \varepsilon)Q}{\rho_a v_a \varepsilon(c_a + c_v H)} \tag{4.70}$$

For inputs used here, a slight amount of evaporative cooling is evident at the bottom of the bed where the VPD is greatest, while heat generation keeps the top of the bed above the temperature of the inlet. The sign of the slope therefore changes from negative to positive. The amount of water lost was 10.94, 16.00, and 18.49 kg/ton at 12, 36 and 60 hours, respectively.

Equation (4.70) bears distinct resemblance to the steady state balance used by Hylmö et al. (1975a), equation (3.10).

Figure 4.14 depicts air temperature versus time at the 1 m level for the simplified model, mass loss without heat generation, heat generation without mass loss, and the full model. The model with heat generation and no mass loss exhibits the highest steady state temperature. The model with moisture loss and no heat generation shows the lowest steady state temperature. The positions of the simplified and full models with respect to each other depend upon the relative rates of heat transfer due to latent heat and heat generation. In this case, the full model has a higher steady state temperature indicating a greater rate of generation of heat versus heat use in vaporization.

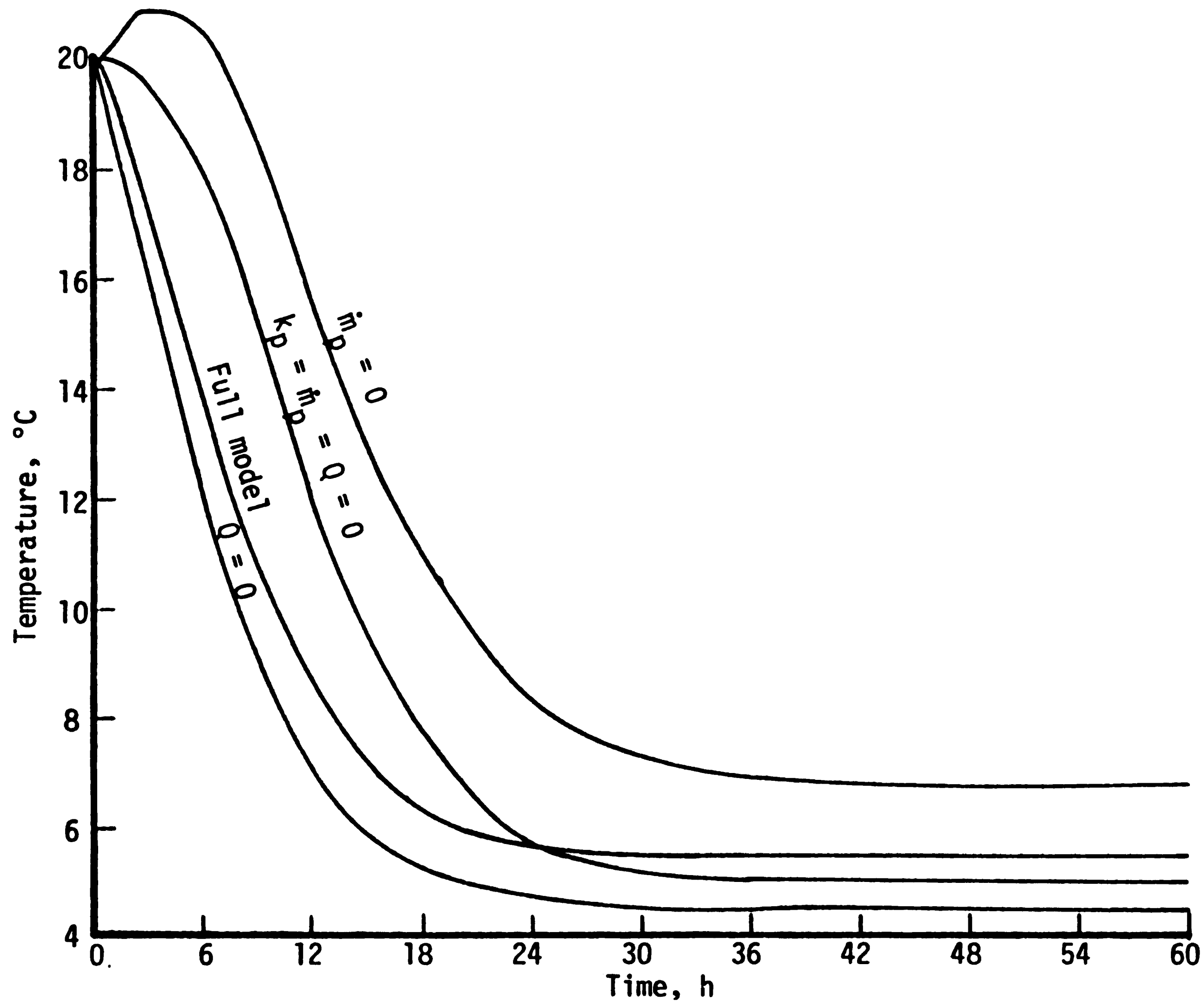


Figure 4.14. Temperature history at 1 m as predicted by the simplified model ($k_p = \dot{m}_p = Q = 0$), model without mass transfer ($\dot{m}_p = 0$), model without heat generation ($Q = 0$), and full model.

The models containing mass loss terms begin evaporative cooling immediately as shown by Figure 4.14. Conversely, the model containing heat generation without mass loss shows an initial increase in temperature until the cooling front reaches the 1 m level. The simplified model remains constant until the front arrives.

Figures 4.15 and 4.16 show the influence of the convective transfer coefficient, h, and hence the convective transfer term on the full model. The mass transfer coefficient was held constant. Figure 4.15 shows the temperature profile through the bed at 12 hours for the heat transfer coefficient as calculated by the Colburn J, twice this value and half of this value. Figure 4.16 shows the profiles for the same conditions at 24 hours.

As indicated by Figure 4.15, a lower rate of transfer causes the active transfer area to extend further into the bed initially. Thus, the top of the bed begins cooling sooner. Since the rate of transfer is less, the cooling zone is widened. Hence, the trailing edge of the cooling zone lags behind as in Figure 4.16.

The changes in the bed temperature, which result from changing h, also influence the amount of heat generated and weight lost. At higher temperatures, greater amounts of heat are generated. In order of decreasing h, the weight loss predicted at 12 hours was 11.40, 10.94, and 10.74 kg/ton.

If the heat transfer coefficient is increased sufficiently, the uniform temperature model should approximate the thermal

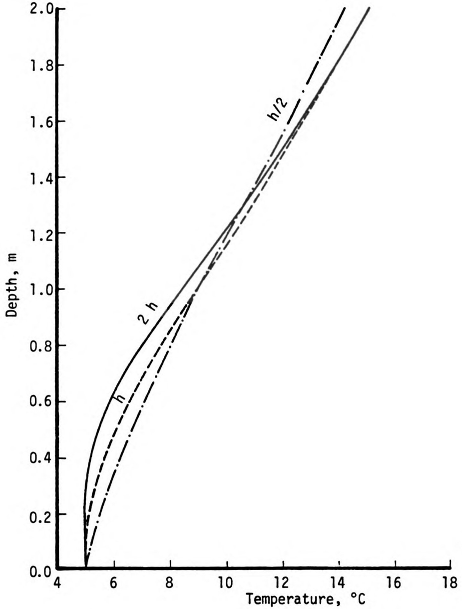


Figure 4.15. Influence of the convective heat transfer coefficient on the temperature profile at 12 h.

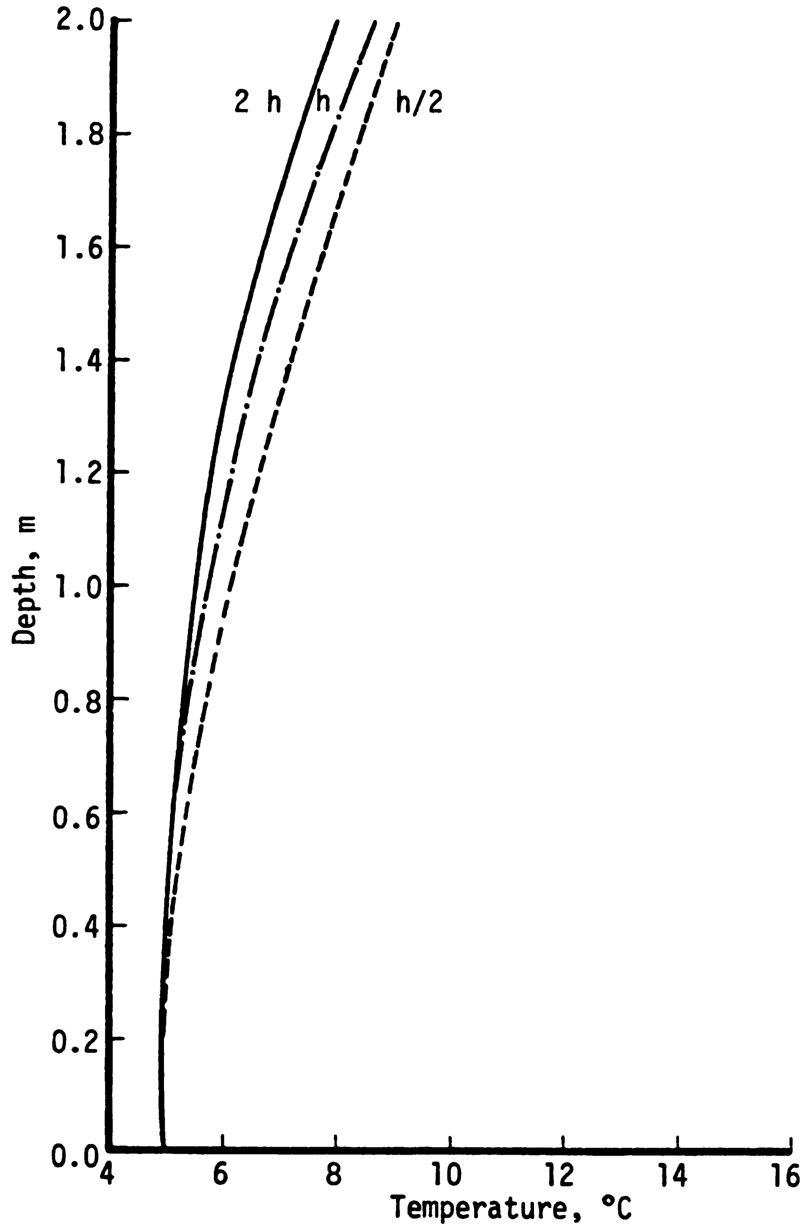


Figure 4.16. Influence of the convective heat transfer coefficient on the temperature profile at 24 h.

equilibrium model. As the transfer coefficient becomes larger, heat transfer becomes instantaneous. The thermal equilibrium model is based on assumptions of negligible surface and internal resistance to heat flow.

In this section each of the primary terms of the equations have been tested for their contributions to the solution. All of these results are consistent with the expected influence of the individual terms.

4.4.3 Influence of Parameters on the Solution

A number of the parameters in the model affect only one term of the equations. For example, γ, $r\delta$, and h_D are all part of the mass transfer term only. Hence, changes in these produce results similar to those previously discussed in regard to the influence of the mass transfer term. Increasing γ or h_D or decreasing $r\delta$ tends to increase the rate of moisture loss from the product.

The inlet absolute humidity also influences primarily the mass loss term. Lower humidities provide greater VPD and more rapid loss of moisture.

The terms b_1 and b_2 are contained in the heat generation term only. Increases in either b_1 or b_2 increase the amount of heat generated.

The product density and specific heat, ρ_p and c_p, occur in combination throughout the model as the volumetric heat capacity. These parameters are dependent upon X_w, the initial water fraction of the product by the definitions of c_d and ρ_d. In general, the specific heat and density of fresh fruits and vegetables are higher in those products containing greater percentages of water. Therefore, as ρ_p, c_p and X_w are increased with the product weight constant, the product diameter, surface area, and volume decrease. Hence, the specific surface area, a, as well as h and h_D, increase for a constant average air velocity.

Figure 4.17 illustrates the overall effect of c_p, ρ_p, and X_w on the temperature profile at 12 hours. The maximum and minimum values listed in Table 4.4 are used while the other properties and inputs are held constant at the values given in Tables 4.4 and 4.6. Decreasing the volumetric heat capacity of the product hastens movement of the cooling front and decreases the gradient within the bed. Weight losses at 12 hours are 11.49, 10.95, and 10.31 kg/ton for the maximum, standard, and minimum inputs, respectively.

Figure 4.18 depicts the influence of average product weight on the temperature profile at 12 hours. All other properties and inputs are held constant. Increasing the product weight without changing the density results in a larger diameter, surface area, and volume. Smaller specific surface area and transfer coefficients follow according to the relationships shown in Table 4.3. The same can be accomplished by decreasing the density while maintaining a constant weight.

Figure 4.18 shows the effect of increasing the weight on the temperature profile is not the same as decreasing the density.

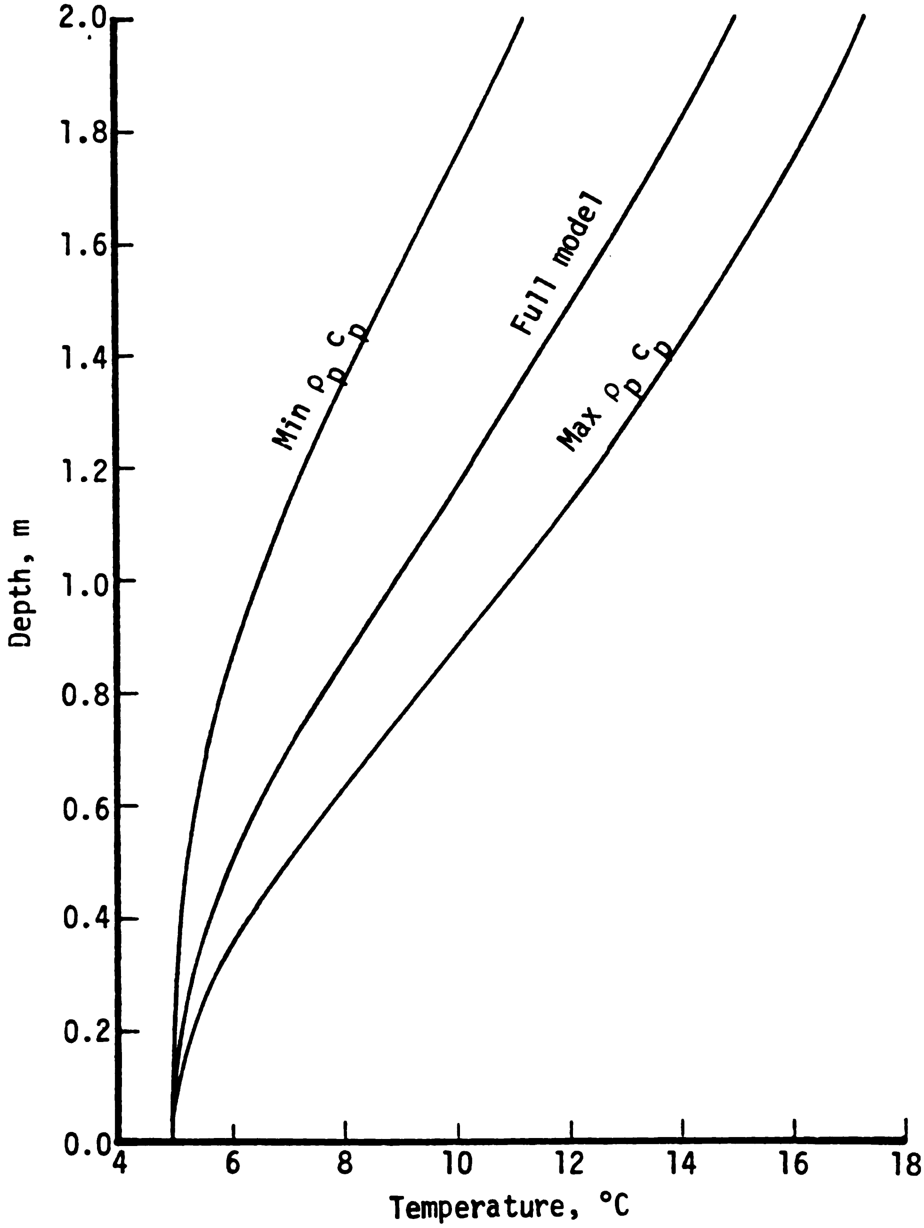


Figure 4.17. Influence of volumetric heat capacity on the temperature profile at 12 h.

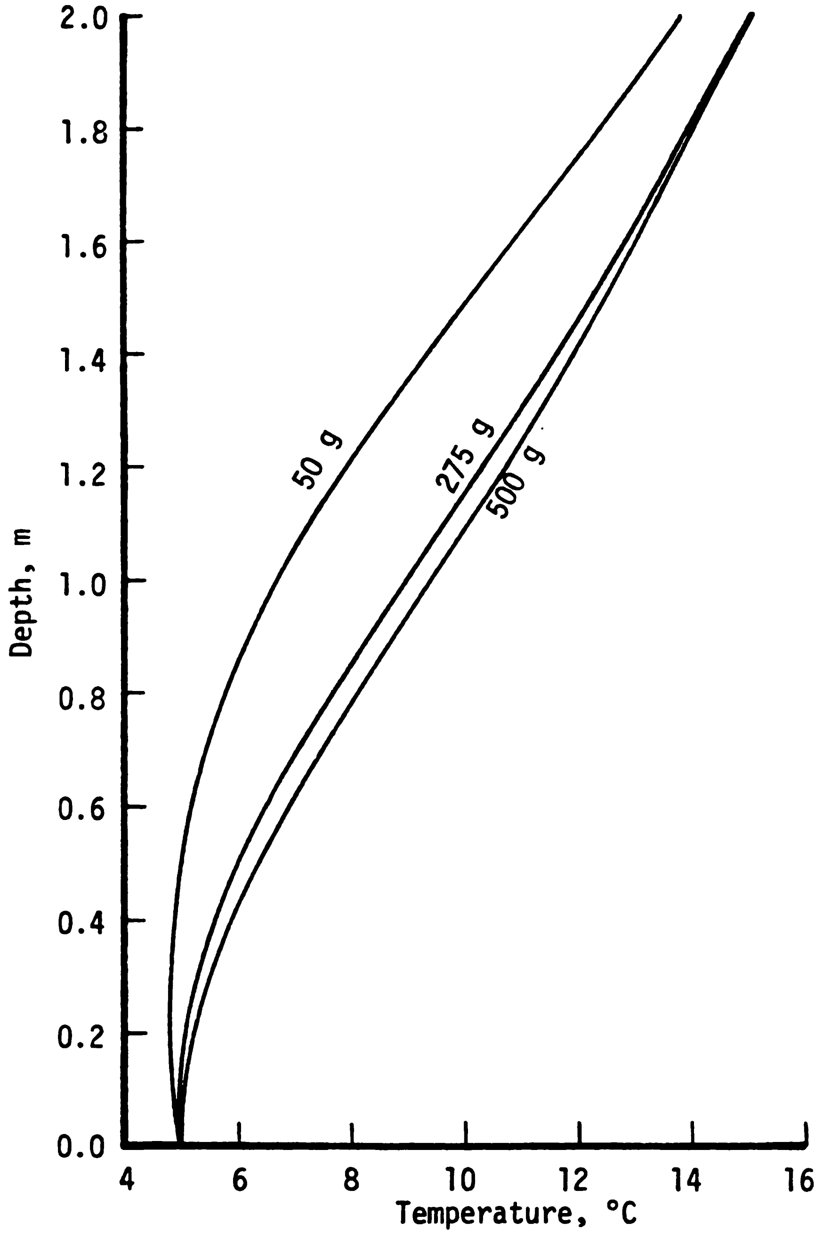


Figure 4.18. Influence of product weight (size) on the temperature profile at 12 h.

Changing the product weight does not change the volumetric heat capacity. Therefore, increasing the weight decreases the rate of movement of the cooling zone. Rearrangement of the equations in Table 4.3 reveals that a is related to $w^{-2/3}$. This, in combination with the influence of a upon h and h_D, results in the decreasing influence of increasing w at large values. Weight losses range from 12.95 kg/ton for the 50 g product to 10.41 kg/ton for the 500 g product.

Figure 4.19 shows the temperature change at 1 m during 60 hours of continuous ventilation at average velocities of 300 and 100 m/h. Other inputs and properties are the same as before. Lowering the ventilation rate widens the cooling zone and slows its movement through the bed. This is partially due to the influence of v_a on the transfer coefficients. As Figure 4.19 shows, at the lower rate the temperature at the 1 m level increases before the cooling front arrives. The lower rate of ventilation results in a higher steady state temperature and requires more than 60 hours to reach it.

Figure 4.20 shows the cumulative weight loss with time for average air velocities of 100 and 300 m/h. The lower air velocity results in a lower rate of weight loss initially and greater rate after 28 hours as evidenced by the slope of the curve. The mass transfer coefficients are 12 and 20.7 m/h for the velocities of 100 and 300 m/h, respectively. With the high airflow rate, the bed has reached a thermal steady state before 60 hours. At 60 hours, the

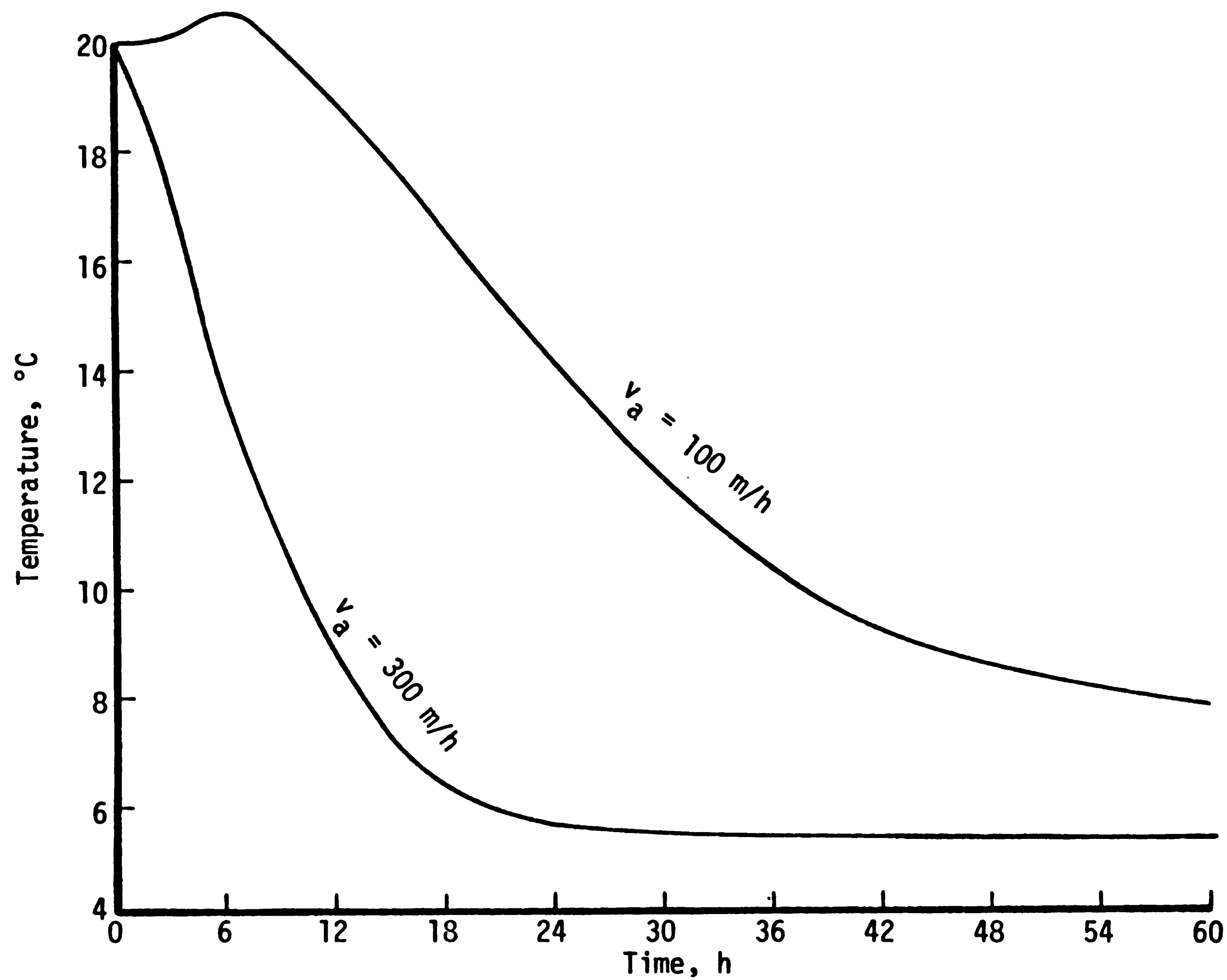


Figure 4.19. Temperature history at 1 m for v_a = 100 m/h and v_a = 300 m/h.

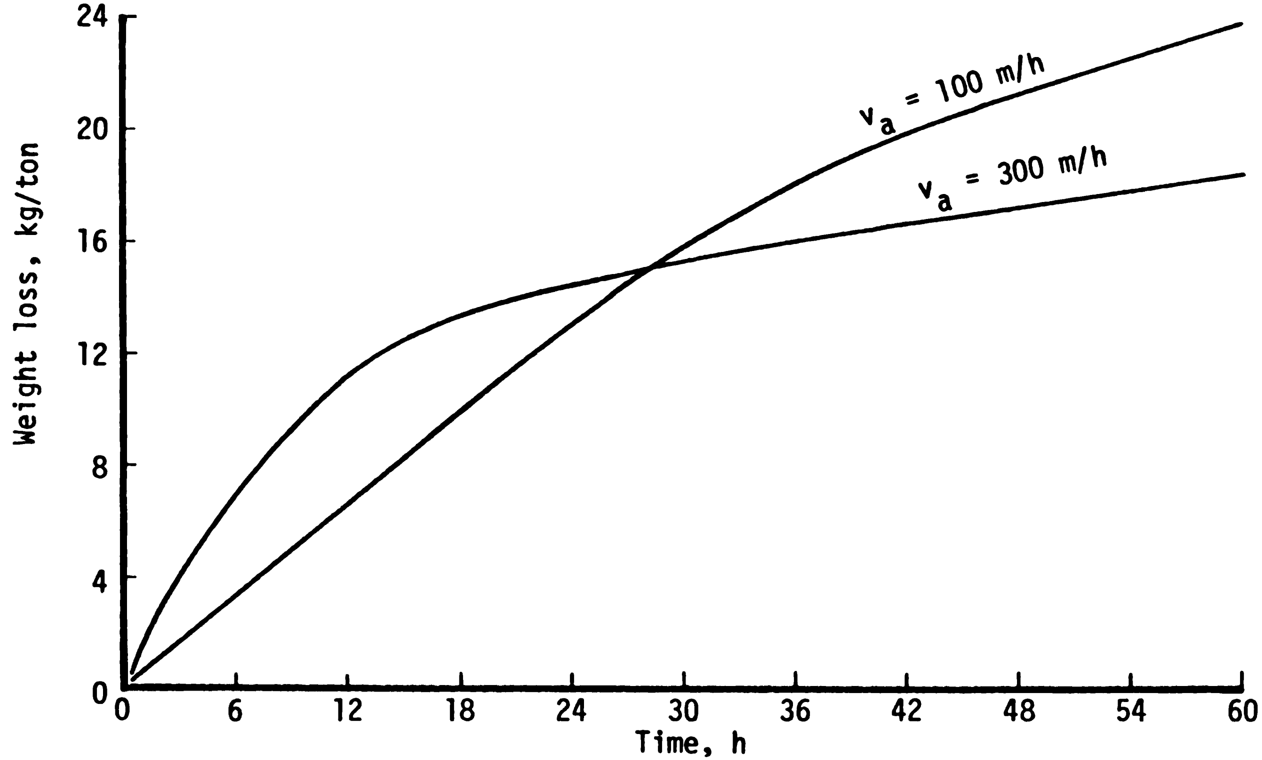


Figure 4.20. Cumulative weight loss predicted for v_a = 100 m/h and v_a = 300 m/h.

air leaves the bed at 6.35°C, 96.81% relative humidity (.0058 kg water/kg dry air). With the low airflow rate, the bed has not reached steady state at 60 hours. The temperature and humidity of the air leaving the pile are 14.57°C and 86.84% (.0090 kg/kg). In this case, the higher airflow cools faster, produces a smaller VPD, and causes less weight loss.

Based on these results, the fastest cooling occurs with a minimum combination of $\rho_p c_p$ and X_w, low weight, low heat generation rate, high water loss rate, and high velocity. For the hypothetical product which has the properties listed in Table 4.3, minimum weight loss is favored by a minimum combination of $\rho_p c_p$ and X_w, large size and high velocity.

4.4.4 Nonconstant Inlet Conditions

The response of the model to varying input conditions is shown in Figure 4.21. The temperature and humidity boundary conditions are:

$$T_i(t) = 4 \sin \left(\frac{2\Pi}{24} t\right) + 5 \qquad (4.71)$$

and:

$$H_i(t) = 0.0019 \sin \left(\frac{2\Pi}{24} t\right) + 0.005 \qquad (4.72)$$

These represent sine wave signals with a 24-hour period. The temperature varies from 1° to 9°C while the humidity ranges from 0.0031 to 0.0069 kg/kg.

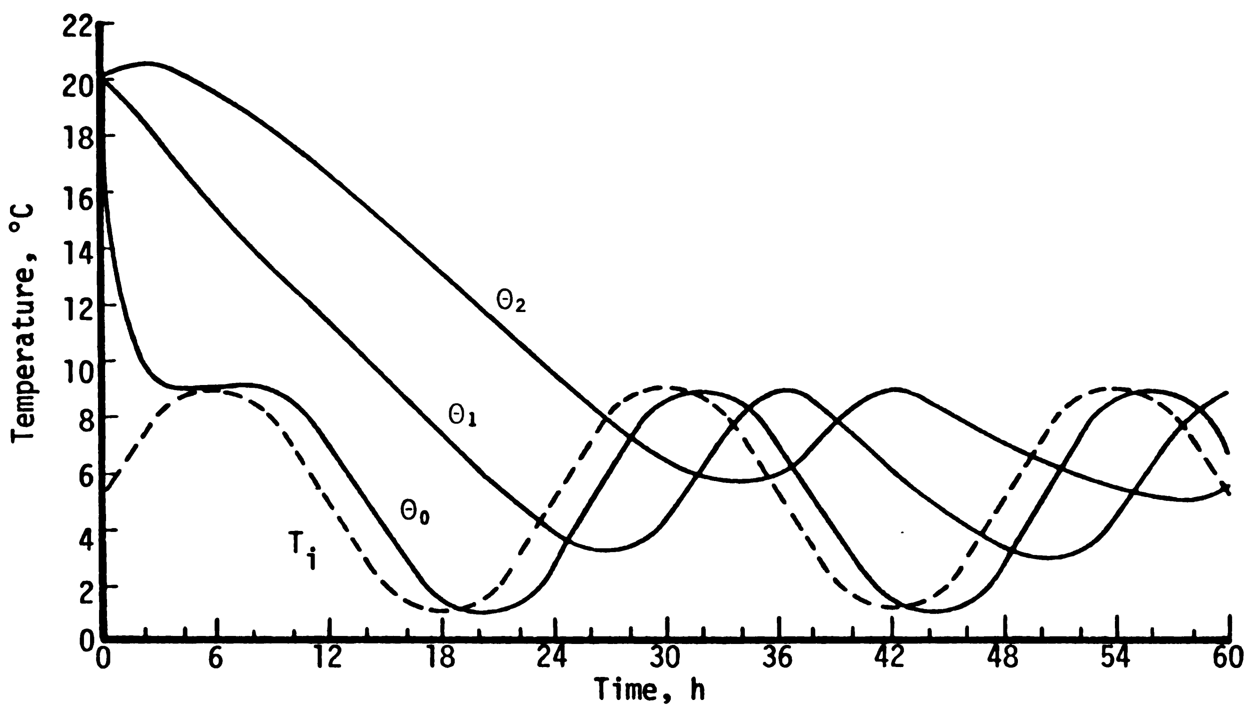


Figure 4.21. Product temperature response at 0, 1, and 2 m and sine wave temperature input.

At the bottom of the pile, the product quickly cools to a value near that of the air at 6 hours. The product temperature then follows the sine wave pattern lagging behind the air by about 3.6 hours. Evaporative cooling causes the minimum temperature of the product to be slightly less than that of the air.

At the 1 m level, the product is only slightly affected at the end of the first 24-hour temperature cycle. It then lags behind the bottom temperature by nearly 6 hours. That portion of the wave form which has a negative slope begins to show some distortion. While the maximum temperature of the 1 m cycle is near that of the air inlet and bottom product, the minimum is more than 2°C higher.

At the top of the pile, the influence of the sine wave input is dampened considerably. The temperature difference between the maximum and minimum of the cycle is only 3.3°C, less than half of the 8°C variation of the inlet air.

Figure 4.21 shows that in the neighborhood of 36 hours and again at 60 hours the maximum temperature occurs in the middle of the bed and the minimum at the top. Due to the temperature inversions and high input humidities, condensation and evaporation of free water occur. This contributes to the distortion and dampening of the sine wave pattern.

4.5 Comparison of the Models

Except for the product temperature equation, the three models are identical in formulation. The equilibrium model assumes that the product and air are in continuous thermal equilibrium and hence are at the same temperature. The uniform product model assumes that the product and air are at different temperatures but that there is no thermal gradient within the product. The gradient model accounts for radial thermal gradients within the product.

Results presented thus far in this section have been from the uniform product temperature model. In heat transfer calculations it is usually assumed that internal gradients are negligible if $Bi = (hD)/(2k_p) < 0.1$. For the hypothetical product used in testing, k_p is 2450 J/h m°C. An average weight of 225 g and density of 1050 kg/m^3 correspond to a sphere of 0.079 m diameter. With an average velocity of 300 m/h, the convective heat transfer coefficient is 23,134 J/h m^2°C by the formulae of Table 4.3, and with a velocity of 100 m/h it is 13,407 J/h m^2°C. This results in Biot numbers of 0.38 and 0.21, respectively, for the high and low airflow rates. Thus, on the basis of convective heat transfer alone, use of the uniform temperature model is marginally justifiable.

Figures 4.22 and 4.23 show the air temperature profiles predicted by the models at 12 hours for v_a = 300 m/h and at 24 hours for v_a = 100 m/h, respectively. In both cases, the uniform and gradient models are quite similar. The equilibrium model, however, exhibits a distinctly different pattern. The trailing edge of the cooling zone is further advanced in the bed and better defined. This results from assumption of instantaneous equilibrium and the lack of consideration of the time necessary for the transfer.

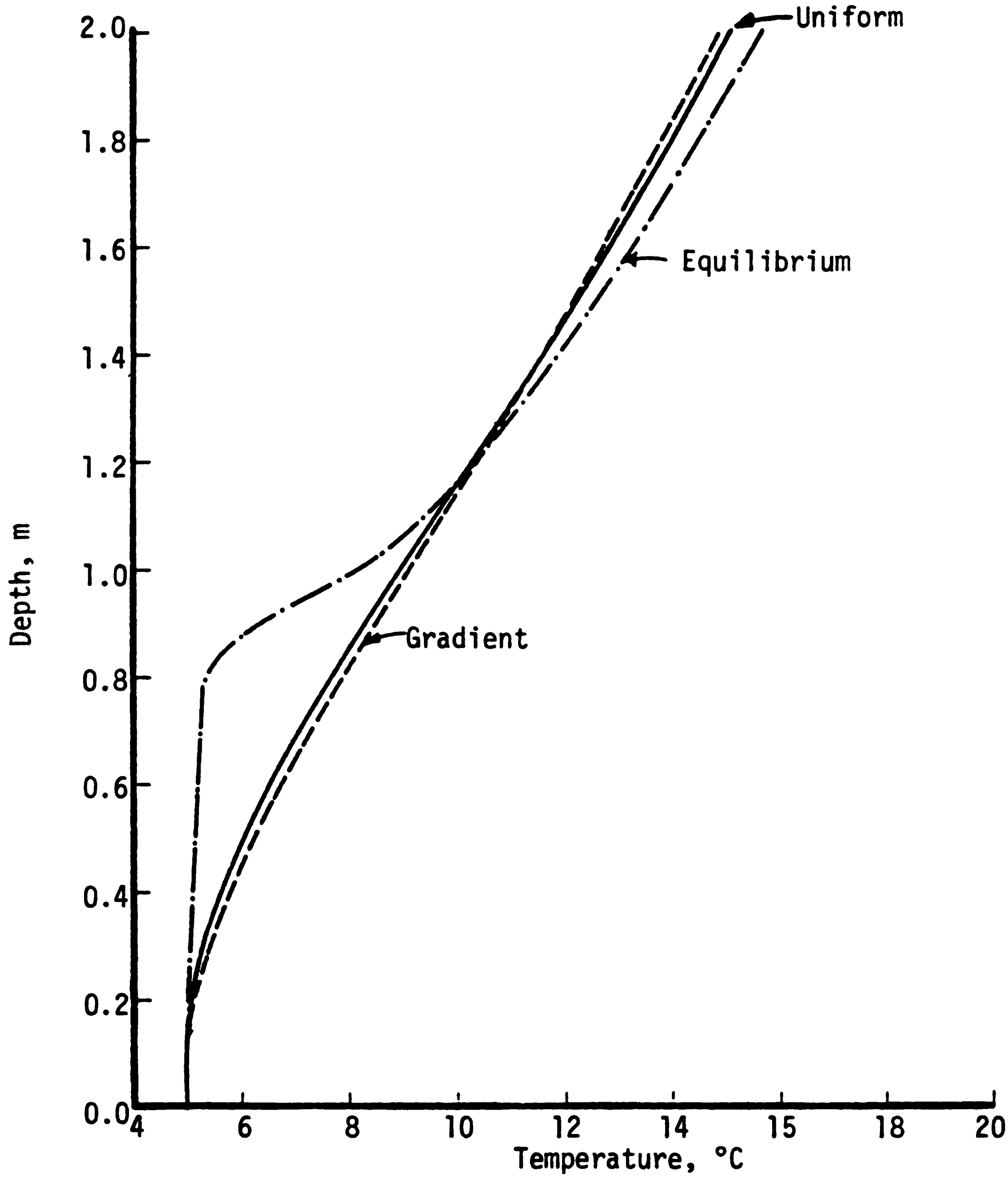


Figure 4.22. Temperature profiles at 12 h as predicted by the three models (v_a = 300 m/h).

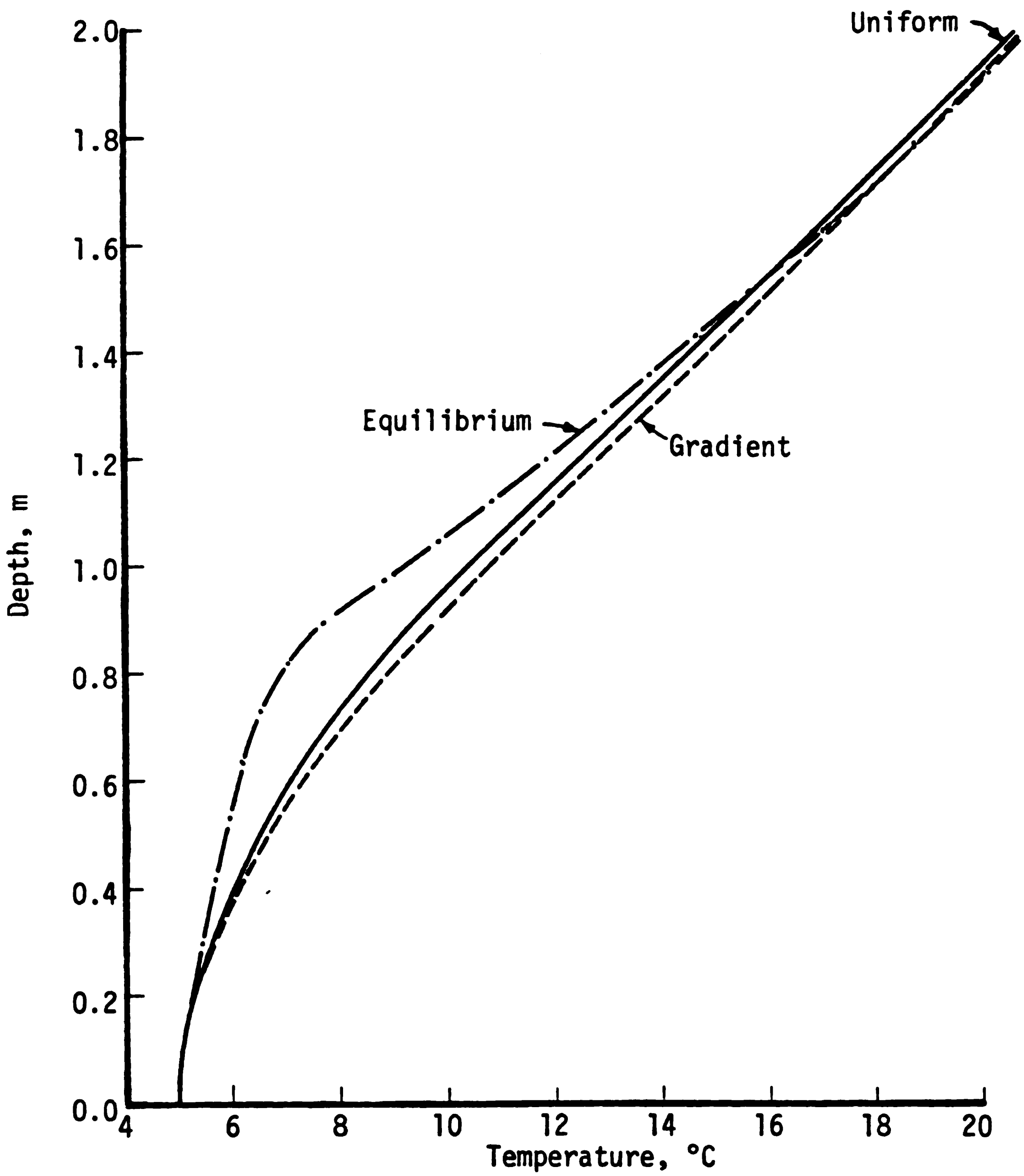


Figure 4.23. Temperature profiles at 36 h as predicted by the three models (v_a = 100 m/h).

As mentioned previously, the same curve should result if h is increased sufficiently in the uniform model (see Figure 4.15).

Figures 4.24 and 4.25 illustrate the air temperature history at the 1 m bed depth for air velocities of 300 m/h and 100 m/h, respectively. Again, the uniform and gradient models are very close. The gradient model temperature is initially less than the uniform model temperature and the uniform model temperature is less than the equilibrium model temperature. Then, as the cooling zone passes the 1 m level, the gradient temperature becomes higher and the equilibrium temperature lower than the uniform model prediction. Eventually all three models predict the same steady state temperature.

In the gradient model, the rate of heat transfer is limited by a surface convection term and an internal conduction term. Thus, initially less heat is transferred to the air and the air temperature remains lower. Later, heat still remains to be removed and the gradient model then predicts slightly higher temperatures.

The instantaneous heat transfer of the equilibrium model similarly accounts for the position of this curve relative to the others.

The uniform temperature model may be considered a limiting case of the internal gradient model with respect to the numerical solution. That is, the case where only one node is used. The number of internal nodes or size of Δr influences the solution. Table 4.7 compares the air temperature predicted by the model using

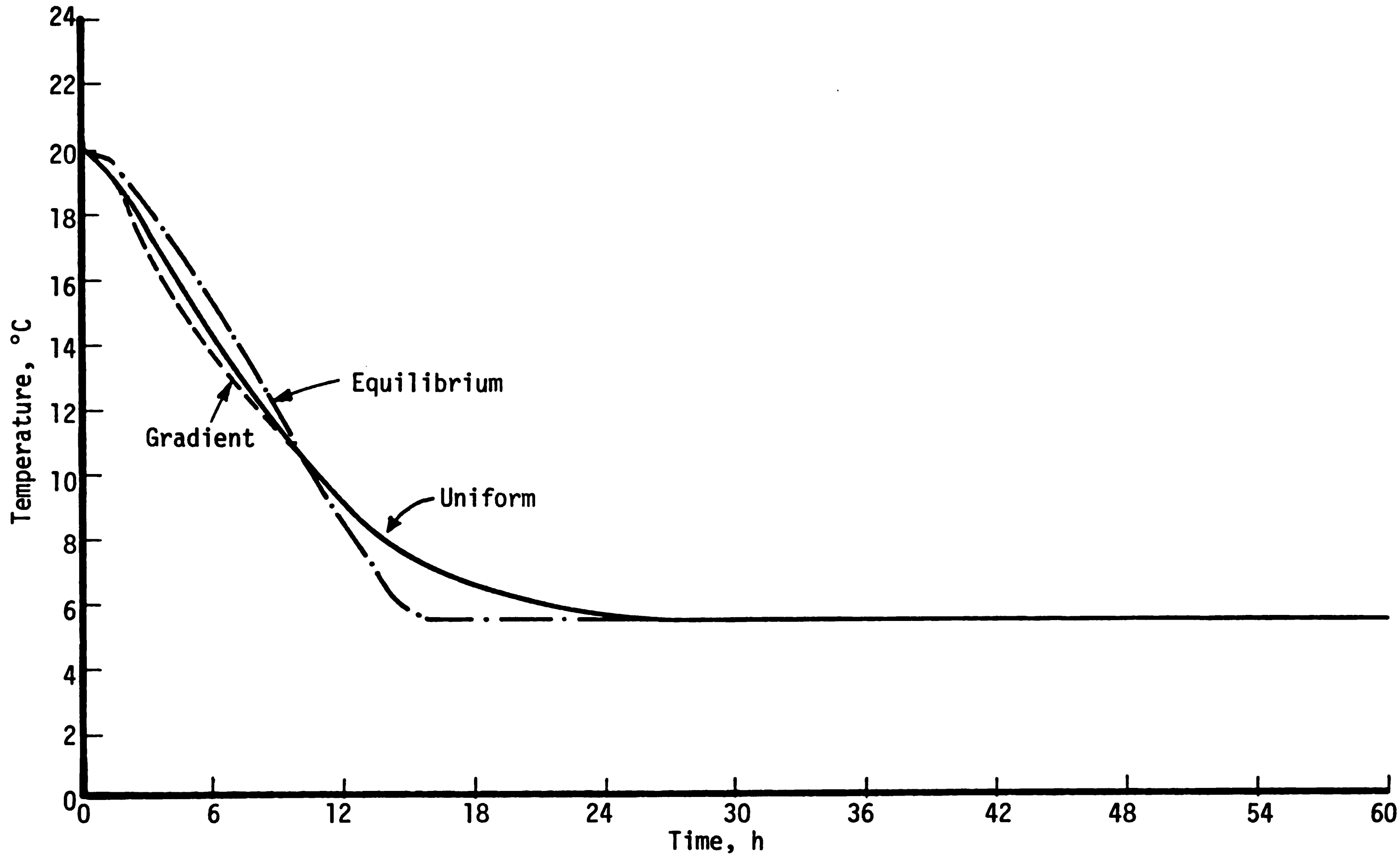


Figure 4.24. Air temperature history at 1 m as predicted by the three models (v_a = 300 m/h).

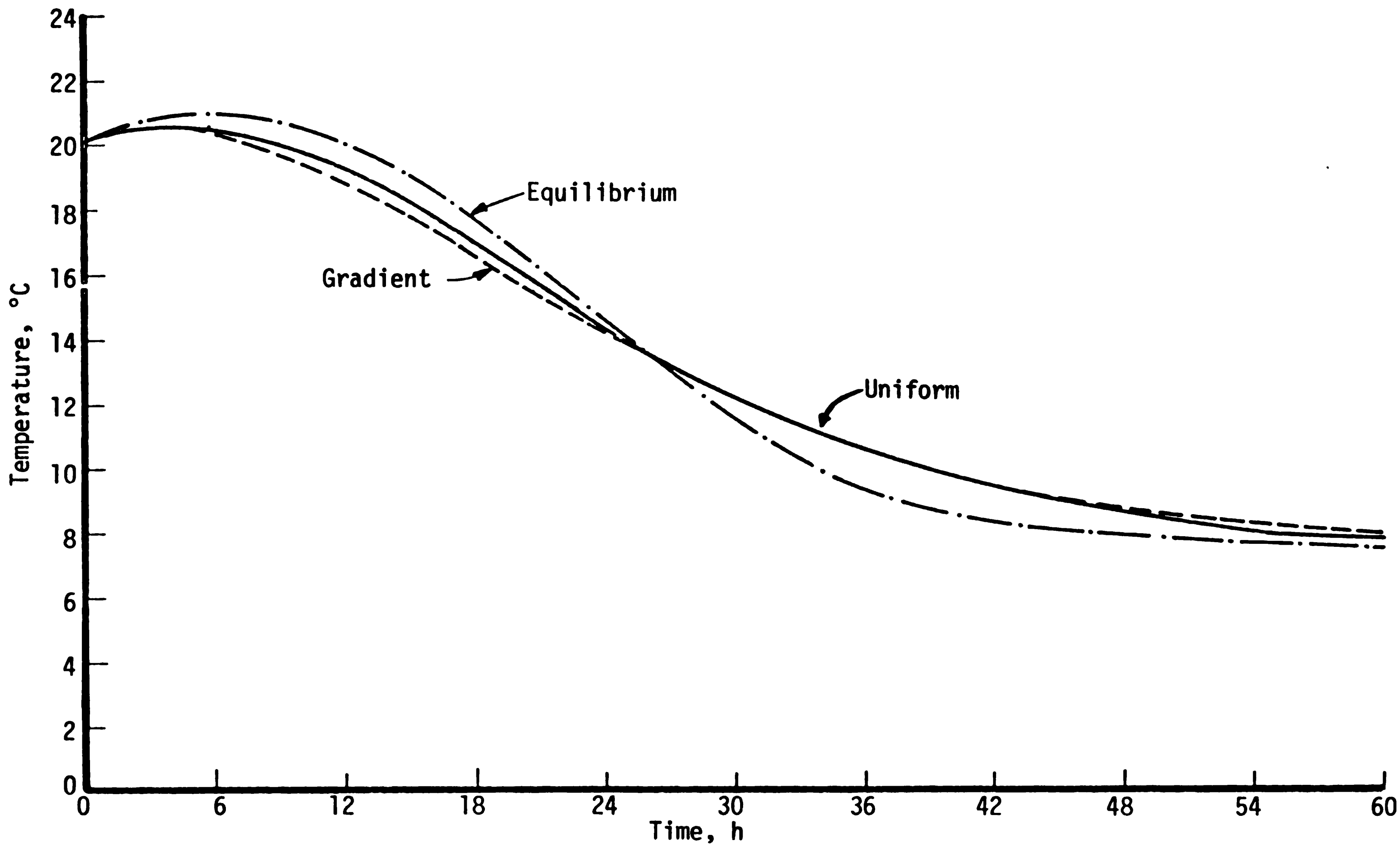


Figure 4.25. Air temperature history at 1 m as predicted by the three models (v_a = 100 m/h).

Table 4.7. Air temperatures within the bed at 12 hours predicted by the uniform model and the gradient model using three and six nodes (v_a = 100 m/h).

Depth	Uniform Model	Gradient Model	
		Three Nodes	Six Nodes
0.0	5.00°C	5.00°C	5.00°C
0.2	7.51	7.97	8.02
0.4	11.24	11.59	11.63
0.6	14.41	14.56	14.60
0.8	16.94	16.94	16.96
1.0	18.96	18.85	18.86
1.2	20.56	20.38	20.38
1.4	21.83	21.61	21.60
1.6	22.83	22.58	22.58
1.8	23.61	23.36	23.35
2.0	24.40	23.97	23.96

three and six nodes. For these conditions very little difference is shown. A great difference does exist, however, in the computer time since Δt must satisfy the stability requirement for the thermal diffusion equation. At 300 m/h air velocity, the three node run used Δt = 0.0732 hours, the six node, Δt = 0.0118 hours, and the uniform model, Δt = 0.5 hours.

Tables 4.8 and 4.9 show the cumulative weight loss predicted by three models at 12-hour intervals for air velocities of 300 m/h and 100 m/h, respectively. The differences are attributable to the influence of temperature on VPD.

Table 4.8. Weight loss predicted by the models (v_a = 300 m/h).

Time	Equilibrium Model	Uniform Model	Gradient Model
12	11.6 kg/ton	11.0 kg/ton	10.8 kg/ton
24	14.8	14.4	14.4
36	16.1	16.0	16.0
48	17.3	17.2	17.3
60	18.5	18.4	18.6

Table 4.9. Weight loss predicted by the models (v_a = 100 m/h).

Time	Equilibrium Model	Uniform Model	Gradient Model
12	6.3 kg/ton	6.6 kg/ton	6.2 kg/ton
24	13.2	13.1	12.6
36	18.5	18.0	17.6
48	21.9	21.4	21.2
60	24.0	23.9	23.7

5. DEVELOPMENT OF THE MODEL FOR SIMULTANEOUS HEAT AND MASS TRANSFER IN BULK STORED POTATOES

In the preceding section, models were developed and solved for simultaneous transfer of heat and mass in beds of biological products during forced convection. Models resulted for the three cases of (1) continuous thermal equilibrium between the air and product, (2) uniform product temperature with convective heat transfer at the surface, and (3) thermal gradients within the product with convective heat transfer at the surface. All models included the generation of heat and evaporation of water.

In addition to establishing the most appropriate representation of the product temperature, a number of assumptions made in the formulation of the model must be satisfied. Although acceptability of a model's results may serve as justification for all assumptions, justification based on experimental data specific to the product is desirable. Assumptions thus justified are less suspect of introducing errors and are maintained in further development of the model. Assumptions not justified may limit the applicability of the models.

Further assumptions and simplification of the models may be made based on comparisons of results of the model, with and without the term in question. Terms which complicate the solution without significantly contributing to the accuracy of the results should be discarded.

As indicated in the previous section, a number of auxiliary relationships, and thermal and physical properties which are product dependent are required by the models before they can be applied to any specific product. These relationships and properties in association with the range of conditions to be considered, determine the applicability of the three methods of product temperature description which distinguish the models.

This section attempts to justify the assumptions and establishes the appropriate relationships and properties necessary to the establishment of a model specifically for potatoes. Alternatives for the simulation of the storage during nonventilated periods are considered. Finally, comparisons are made of the model predictions with experimental data from commercial and laboratory scale storages.

5.1 Discussion of the Assumptions

The first set of assumptions which reduces the number of dimensions considered by the models requires uniformity of the product and airflow throughout the storage. It has been shown (Schaper et al., 1976) that uniformity of air distribution does not often exist. However, uniformity is a primary objective of design and storage loading (Cargill, 1976). Cloud (1976a) discussed the design criteria for the air handling system and Cloud and Morey

(1977) presented various means of solving the problem of obtaining uniform air discharge from ventilation ducts. Hylmö and Johansson (1976b) showed example calculations to determine dimensions of the air distribution system. Proper design of the air distribution system and good management practices during storage loading are paramount to the success of the model.

Wall effects are considered negligible due to the size of modern storage bins and the relatively small percentage of total volume which resides near a wall. Proper insulation guarantees adiabatic conditions.

The assumption of uniform spacial characteristics with negligible settling and volumetric shrinkage is difficult to justify. This is particularly true if the potatoes have a large amount of adhering soil when placed into storage or if excessive weight loss is experienced. These assumptions must serve as limitations to the applicability of the model. Hylmö et al. (1978) reported settling rates of 13 to 16 mm/month/m of pile height for low ventilation rates and 19-28 mm/month/m for high ventilation rates.

Consideration of conductive and convective heat transfer only is based on the small temperature differences which exist. Conduction within the air stream is negligible due to the low thermal conductivity of air.

Assumptions regarding the incompressibility of, constant properties of, and negligible conduction within dry air and thermal equilibrium with the water vapor are easily justified based on the small temperature change and low velocities encountered in potato storages. The convective heat transfer coefficient is assumed constant for computational simplicity.

Oxygen and carbon dioxide are transferred to and from potato tubers as a result of normal respiratory processes. Although some time lag may occur, on the average, O_2 and CO_2 are exchanged in equal volumes (Burton, 1963b, 1974b). Thus, the net exchange of mass and energy associated with dry gases is very small.

In addition to CO_2, Meigh et al. (1973) reported that 20 to 30 substances are produced by potatoes at rates on the order of 10^{-9} g/kg/h at 10°C. In comparison to the minimum rate of moisture loss of 7.5×10^{-5} g/kg/h per N/m^2 VPD (Burton, 1966), these are negligible.

In general, total weight loss of components other than water amounts to less than 1% even after prolonged storage (Singh and Mathus, 1938; Burton, 1966). Although it may be of interest to compute an estimate of these losses, their effects on the energy and mass balance equations are negligible. Hence, the assumptions of no generation or transfer of gases other than water vapor and constant dry matter density are accepted.

The models consider the product to consist of a homogeneous mixture of dry matter and liquid water. All resistance to water flow and change of phase are assumed to occur at the surface. In fact, potatoes are far from microscopically homogeneous. They are composed of individual cells grouped into specific tissues and interconnected by vascular tissues and intercellular spaces. The intercellular spaces connect with the outside through the lenticels and account for about 1% of the tuber volume (Davis, 1962).

Wigginton (1973) found that O_2 is supplied to the tuber for respiration entirely through the lenticels. He found rates to vary from 2.37×10^{-7} to 2.92×10^{-6} cm^3/h N/m^2 of partial pressure difference. The lenticels have also been implicated as the primary site of CO_2 release to the atmosphere (Burton, 1972). It seems likely that they also play a major role in the evaporation and transport of water vapor (Hayward, 1974). Adams (1975a,b) studied the development and structure of lenticels. His findings indicate a relationship between the soil moisture conditions and the anatomy of lenticels.

As previously discussed, the site of vaporization is only important in the temperature gradient model. Vaporization probably occurs within the lenticels and not necessarily at the surface. Therefore, the assumption that evaporation occurs at the product surface is suspect. Nevertheless, since no experimental evidence exists to support any other specific site or distribution of latent heat of vaporization, this assumption is maintained.

Burton and Wigginton (1970) studied the effect of a film of water upon the oxygen status of a potato. They found that the thickness of the water film retained by a wet tuber is slightly less than 5×10^{-2} mm. Furthermore, after 6.5 h at 10°C or 2.5 h at 29°C, a film of 3×10^{-2} mm thickness resulted in anaerobic conditions which may be favorable to initiation of lenticel proliferation and invasion by pectolytic bacteria. Lund and Kelman (1977) reported water film thicknesses of $9.03 \pm 0.24 \times 10^{-2}$ mm immediately after moistening, $8.80 \pm 0.23 \times 10^{-2}$ mm after four hours in a mist chamber, and $10.39 \pm 0.26 \times 10^{-2}$ mm after five days in a mist chamber.

If a free water film exceeds 5×10^{-2} mm thickness, surface flow and drip are imminent and the model fails. Due to the associated high risk of rotting, this is not a severe limitation on the model. Furthermore, an indication of the time during which the free water film has been greater than that leading to anaerobiosis may be helpful in assessing the risk associated with a particular management strategy.

A free water film 5×10^{-2} mm thick residing on the surface of all the tubers in a 1 m^3 volume will occupy less than 0.007 m^3. This is based on a specific surface area of 140 m^2/m^3, a large value for potatoes. This represents a change of less than 2% of normal void space (.43 m^3/m^3).

The remaining assumptions of uniform homogeneous spheres with negligible particle-to-particle conduction are applied to the internal temperature gradient model only. These assumptions seem valid and are made in the interest of computational ease; no attempt is made to justify them on a theoretical or physical basis.

5.2 Thermal and Physical Properties of Potatoes

The models require initial values for density, moisture content, and specific heat and constant values for bed void fraction, specific surface area, thermal conductivity, and convective heat transfer coefficient. To maximize the usefulness of the models, all inputs should be in the most conveniently measured form. Therefore, all physical dimensions are evaluated at the initial weight and specific gravity of an average tuber.

The initial weight of an average tuber, w, may be determined by weighing a representative sample and dividing this number by the number of tubers. The specific gravity, S_g, is determined by weighing the tubers in air and in water. Specific gravity is calculated as the weight in air divided by the difference between weight in air and weight in water. Ideally, the air, water, and tubers should be at the same temperature and the temperature should be reported.

The density of the tubers is the product of specific gravity and the density of water at the same temperature.

Density is a function of dry matter and water content as indicated by equation (4.14). Burton (1966) reported the following relationship:

$$\%\ \text{dry matter} = 24.182 + 211.04\,(S_g - 1.0988) \qquad (5.1)$$

with variation of the constants 24.182 ± 0.035 and 211.04 ± 3.33. Simmonds (1977) performed linear regression analysis on specific gravity-dry matter content data from published sources. Mean regression yielded:

$$\%\ \text{dry matter} = 4.13 + 204\ (S_g - 1.0) \qquad (5.2)$$

The initial moisture content (wet basis) can be determined by subtracting the percentage of dry matter from 100. Dry matter density results from a rearrangement of equation (4.14).

Bulk density, $\rho_p(1 - \varepsilon)$, rather than tissue density, is usually reported in the literature. Table 5.1 summarizes bulk density and void fraction values measured or applied by several researchers.

Table 5.1. Potato bulk density values.

Source	Bulk Density (kg/m^3)	Void Fraction	Comment
Burton (1966)	625-667	0.38-0.47	
Burton (1972)	714	--	Kidney-shaped tubers
Burton et al. (1955)	593	--	
Ophuis (1957)	700	0.33	Mean diameter 0.04 m
Rice (1974)	623	0.43	
Rao et al. (1975)	597-603	0.426 (assumed)	Five varieties
Shirokov (1968)	650-700	0.40-0.45	

With knowledge of the average tuber weight and the density, the average potato volume can be calculated (see Table 4.3).

In Table 4.3, surface area is evaluated from the formula for a sphere whose diameter provides the proper volume. Since some varieties of potatoes deviate significantly from a spherical shape and since surface area is relatively important to the transfer terms, an alternative approach should be used for nonspherical varieties.

Maurer and Eaton (1970) applied the following modified form of the equation for the area of a prolate spheroid to potatoes:

$$A = \pi(\beta_1 + \beta_2)[(\beta_1 + \beta_2)e + 2\beta_3 \sin^{-1} e]/8e \tag{5.3}$$

where β_1, β_2, and β_3 are the width, thickness, and length, respectively; eccentricity, e, is defined by:

$$e = \frac{\sqrt{\beta_3^2 - [(\beta_1 + \beta_2)/2]^2}}{\beta_3} \tag{5.4}$$

They found good agreement with experimentally determined areas of a number of varieties with different characteristic shapes. The disadvantage is the need to determine three dimensions which represent the average tuber. Van den Berg and Lentz (1971) expressed the surface area as:

$$A = 3.6 \times 10^{-4} W^{.713} \tag{5.5}$$

Equation (5.5) represents an average for five varieties.

Villa (1973) found the prolate spheroid relationship inadequate to describe the surface area of Monona potatoes. He proposed:

$$A = 4.833 \times 10^{-4} w^{0.6638} \tag{5.6}$$

For a density of 1001 kg/m^3 this is essentially equivalent to the formula for a sphere with $w^{2/3}$.

Specific surface area is calculated by (Schumann, 1929):

$$a = \frac{A}{V}(1 - \varepsilon) \tag{5.7}$$

For the thermal gradient model, the equivalent diameter can be calculated from the surface area or from the volume. Diameter is used to determine the length of the conduction path, the volume and hence heat capacity associated with each node, and the mutual area of transfer between adjacent nodes. The model presented here calculates the diameter on the basis of equivalent surface area. The error thus introduced is negligible for nearly spherical tubers where equation (5.6) describes the surface area but may be significant for oblong varieties.

Yamada (1970) measured the variation of specific heat with moisture content. His results showed that the variation was adequately described by two linear equations: one for moisture contents greater than 50% and one for moisture contents between 20% and 50%. Since dehydration should be prevented during normal storage, only the former is needed for the models:

$$c_p = 904.3 + 3265.7\, X_w \qquad X_w > 0.50 \tag{5.8}$$

Equation (5.8) was used by Misener and Shove (1976a).

Figure 5.1 shows a plot of equation (5.8) and values of c_p at various moistures as reported in the literature. It should be noted that equation (5.8) is identical to equation (4.20) if c_d = 904.3 J/kg °C and c_w = 4170 J/kg °C. Table 4.4 gives c_w as 4187 J/kg °C at 10°C.

Yamada (1970) also determined thermal conductivity. Although a general trend of decreasing conductivity with decreasing moisture content was observed, no correlation was found. Rao et al. (1975) suggested that thermal conductivity varies with both moisture content and density. Table 5.2 summarizes thermal conductivity values of potatoes from the literature.

Many expressions for convective heat transfer coefficients for potatoes or packed beds have been proposed. Hunter (1976) developed an expression for the convective heat transfer coefficient for beds of potatoes based on work by Malling and Thodos (1967) for beds of spheres. With properties evaluated at 10°C, it takes the form:

$$h = \frac{140.5}{D}\, Re_p^{.563} \tag{5.9}$$

with $Re_p = \dfrac{D\rho_a v_a \varepsilon}{\mu}$.

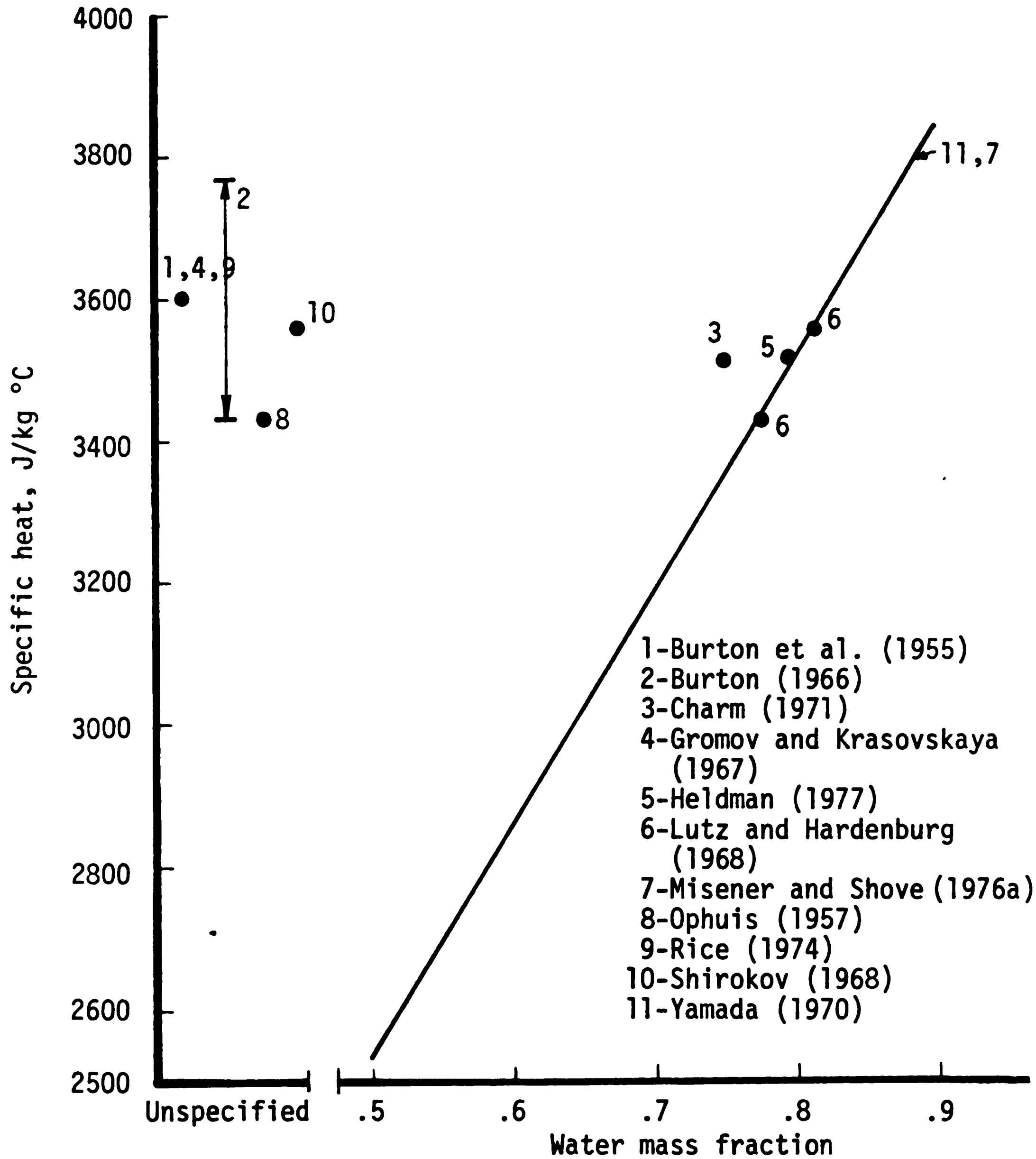


Figure 5.1. Specific heat of potato tissue as predicted by equation (5.8) and values from the literature.

Table 5.2. Potato thermal conductivity values.

Source	Thermal Conductivity, J/hm °C	Moisture, %
Burton (1966)	2093	--
Gromov and Krasovskaya (1967)	2135-2261	--
Heldman (1977)	1994	81.5
Rao et al. (1975)	1919-2056	81.2-83.6
Yamada (1970)	1746	76

The formula for packed columns presented by Bird et al. (1960) listed in Table 4.3 with properties at 10°C becomes:

$$h = v_a \varepsilon \begin{cases} 1420.4 \quad Re^{-0.51} & Re < 50 \\ 952.1 \quad Re^{-0.41} & Re > 50 \end{cases} \qquad (5.10)$$

with $Re = \dfrac{\rho_a v_a \varepsilon}{\mu a}$.

Ophuis (1957), in applying Businger's (1954) model, used

$$h = 20934 + 3.95\, v_a \qquad (5.11)$$

The value predicted was claimed to give good agreement with an experimental bed. Since Businger's model does not include moisture loss (latent heat) or heat generation, this value of the convective heat transfer coefficient must compensate for these effects. Also, the strict linear dependence on velocity is unusual for heat transfer coefficients.

Watson and Staley (1963) experimented with the heating and cooling of a laboratory bin of potatoes. They analyzed the data using the Furnas charts to determine the heat transfer coefficient. The result was:

$$h = \frac{8183.2}{a} v_a^{.96} \qquad (5.12)$$

Again the model did not account for latent heat and heat generation. Watson and Staley pointed out that this apparent heat transfer coefficient includes contributions of heat conduction through the laminar surface film, internal resistance to heat flow, and the latent heat of evaporation of water. Equation (5.12) indicates only a slight deviation from linear dependence on velocity.

Figure 5.2 shows the heat transfer coefficients calculated by equations (5.9) through (5.12) for velocities ranging from 70 m/h to 1400 m/h. A diameter of 0.061 m, void fraction of 0.43, and specific surface area of 56.2 m^2/m^3 were used to produce this figure.

The comparison between the coefficient predicted by Bird et al. (1960) and by Hunter (1976) is of particular interest since both of these represent acceptable forms for the models developed here. Figure 5.2 shows that Hunter's value is approximately 50% greater than that predicted by the Colburn J_H.

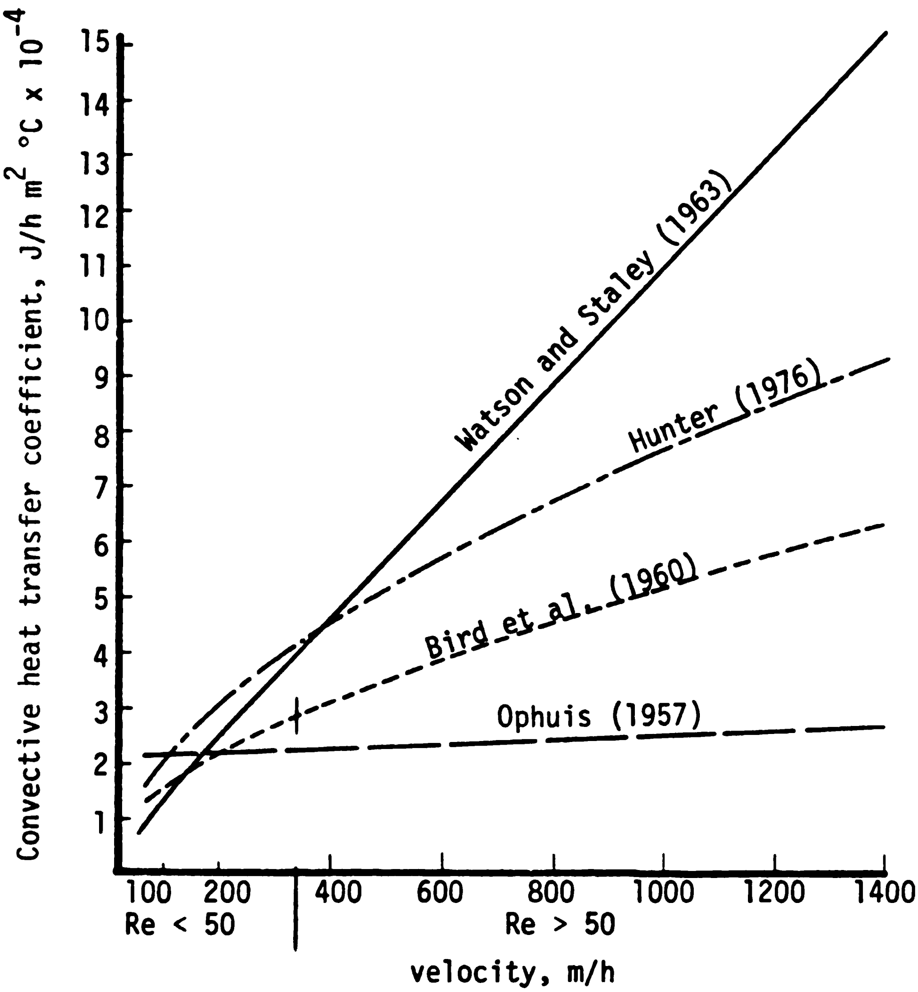


Figure 5.2. Heat transfer coefficients as predicted by equations (5.9) through (5.12) as influenced by velocity ($D = 0.061$ m, $\varepsilon = 0.43$, $a = 56.2\ m^2/m^3$).

5.3 Auxiliary Relationships

Section 4.4.2 discussed the influence of the water evaporation and heat generation rates on the temperature profiles and weight loss predicted by the models. Accurate rate expressions are essential for the model to mimic reality.

Dependence of moisture loss and heat generation rates of potatoes upon previous treatment, variety, and other factors was discussed in Sections 1.2 and 1.3. The rates for a particular lot of potatoes in a particular storage at a particular time are not easily determined.

This section reviews general rate expressions which have been proposed, specific rate expressions which have resulted from particular experimental trials, and data which indicate the form or dependence of the rate upon other measurable quantities.

In addition to the rates of evaporation and heat generation, a relationship for the rot potential or likelihood should be included in the model. The model should be capable of detecting and reporting situations which impart a high risk of failure due to rotting.

5.3.1 Water Evaporation Rate

Although a great number of researchers have measured the weight loss of potatoes under various conditions, few of these have attempted to express the results in the form of equations. In most cases, insufficient data was available to permit formulation of an equation. Those equations which have been published are often independent of time or apply only to well-suberized tubers. The few equations which are time dependent have resulted from statistical correlations which do not include all of the relevant parameters. Since the mechanism of transfer is not fully understood, those factors which limit the rate are not clearly defined. Nevertheless, the time dependent expressions do identify general patterns of response even though they cannot be applied with certainty to any lot of potatoes other than the one which was used to develop the equation.

Ophuis (1957) proposed the following relationship for cumulative weight loss:

$$m = K_D A(VPD)t \qquad (5.13)$$

He did not evaluate K_D, the water vapor transmission coefficient (kg/m^2 h unit VPD), or indicate its dependence on time.

Burton (1963a) expressed the percent weight loss per week for well-healed tubers as:

$$m = (0.2 + 0.1s)\ VPD\ (mm\ Hg) \qquad (5.14)$$

where s is the percent by weight of sprouts. He found the rate of weight loss to be independent of velocity at high rates.

Schippers (1971d) found a linear relationship between cumulative percent weight loss and the product of VPD and time in weeks after the initial storage period (i.e., after suberization).

The slope was dependent on maturity, variety, and several other factors. The average value after the initial storage period was 0.125% per week per mm Hg VPD.

Van den Berg and Lentz (1971) experimentally determined the coefficient of transpiration (rate of moisture loss per unit weight per unit VPD) for five varieties of cured and uncured potatoes. Table 5.3 shows the results. They reported ± 50% variations for a given size and variety and stated that the coefficient for an individual potato was not related to its size or surface area. These values are approximately twice as large as rates reported by Burton and Schippers.

Table 5.3. Coefficient of transpiration (mg/kg h mm Hg) for five varieties of cured and uncured potatoes (from Van den Berg and Lentz, 1971).[1]

Variety	Uncured	Cured
Kennebec	82	29
Katahdin	20	12
Sebago	76	18
Warba	27	15
Netted Gem	--	16

[1]Coefficients adjusted on the basis of surface area to compare with 200 g weight.

Fockens and Meffert (1971) proposed a model for moisture loss from biological products which considered the surface to consist of an impermeable area, free water area (γ'), and permeable membrane area (γ). The model was discussed in terms of three resistances to movement of water vapor in parallel by Villa and Bakker-Arkema (1974a). The resistance of impermeable areas is infinite. Resistance of free water areas was expressed as the resistance associated with convection:

$$R_{\text{free water}} = \frac{1}{h_D \gamma' a} \qquad (5.15)$$

Permeable membranes were represented as resistance of the membrane in series with resistance of convection:

$$R_{\text{membrane}} = \frac{r\delta}{D_{wa}\gamma a} + \frac{1}{h_D \gamma a} \qquad (5.16)$$

The rate of moisture loss was expressed as:

$$-\dot{m}_p = \left(\frac{1}{R_{\text{free water}}} + \frac{1}{R_{\text{membrane}}}\right) \frac{m}{R_o T_A} \text{VPD}$$

$$= \left(h_D \gamma' + \frac{\gamma}{\frac{\delta r}{D_{wa}} + \frac{1}{h_D}}\right) a \frac{m}{R_o T_A} \text{VPD} \qquad (5.17)$$

Villa and Bakker-Arkema (1974) applied the model to potatoes and found negligible free water areas. The resulting equation is also presented in Table 4.3:

$$\dot{m}_p = - \frac{h'_w D_{wa}}{r\delta h_D + D_{wa}} \gamma a(VPD) \tag{5.18}$$

with:

$$h'_w = 2.166 \times 10^{-3} h_D/T_A \tag{5.19}$$

The coefficient of convective mass transfer, h_D, can be evaluated using the analogy to heat transfer and the Colburn J factor which, at 10°C, results in equation (5.10) or

$$h_D = 8.96 \times 10^{-4} h \tag{5.20}$$

Villa and Bakker-Arkema (1974) also found that $r\delta$ was a function of VPD for potatoes:

$$r\delta = 4.94 \times 10^{-4} + 3.31 \times 10^{-6} \text{ VPD} \tag{5.21}$$

The average value for $r\delta$ was 0.003484 m corresponding to a VPD of 903 N/m^2 while the area fraction, which behaved as a membrane, γ, was 0.0089.

Equation (5.18) contains the velocity dependent mass transfer coefficient in both numerator and denominator. The general form of the equation after substitution of equations (5.10), (5.19), and (5.20) into equation (5.18) is:

$$\dot{m}_p = \frac{b_1 \gamma}{r\delta + (b_2/v_a)^{b_3}} \text{ VPD} \tag{5.22}$$

where b_2 and b_3 are dependent upon Re.

At low velocities, the term $b_2/v_a^{b_3}$ becomes much larger than $r\delta$. Equation (5.22) can then be reduced to:

$$\dot{m}_p \doteq \frac{b_1}{b_2} \gamma v_a^{b_3} \, \text{VPD} \quad \text{for} \quad b_2/v_a^{b_3} >> r\delta \qquad (5.23)$$

Hence, at low velocities, the rate of evaporation is dependent upon the skin parameter, γ, and air velocity, v_a.

At high velocities, the term $b_2/v_a^{b_3}$ becomes less than $r\delta$. Equation (5.22) can then be approximated by:

$$\dot{m}_p \doteq b_1 \frac{\gamma}{r\delta} \, \text{VPD} \quad \text{for} \quad b_2/v_a^{b_3} << r\delta \qquad (5.24)$$

Thus, at high velocities, the rate of evaporation is independent of velocity and asymptotically approaches the result of equation (5.24).

The above velocity influence is consistent with the results of Burton (1963a, 1966) who believed that the air becomes saturated at low velocities and that weight loss under those conditions is controlled by the quantity of air; also that at higher velocities skin permeability limits vapor transfer. Equation (5.22) shows that weight loss is controlled by the convective transfer process at low velocities and by the membrane permeability at high velocities. The critical ventilation rate of individual tubers has been defined by Burton as the rate above which air velocity has little or no effect on rate of weight loss. He found critical velocities on the order of 190 and 55 m/h for freshly harvested and well-suberized unsprouted potatoes, respectively.

Analysis of Burton's data results in $\gamma = 0.256$ with $r\delta = 0.0449$ m for freshly harvested potatoes and $\gamma = 0.134$ with $r\delta = 0.0827$ m for potatoes stored for some weeks. Figure 5.3 shows the weight loss rate versus velocity as predicted by equation (5.22) and data points from Burton (1966).

It must be noted that Burton's data does not adequately cover low velocities. At high velocities, equation (5.24) can be used to determine the ratio $\gamma/r\delta$. Accurate determination of γ and $r\delta$ requires additional data at low velocities. Villa's (1973) data was taken at velocities greater than 900 m/h. This may explain the large deviation between values of γ and $r\delta$ reported by Villa and those given above for Burton's data. The ratio $\gamma/r\delta$ is 2.55/m using the average value of $r\delta$ reported by Villa, 9.52/m using equation (5.21) for $r\delta$ with 1 mm Hg VPD, and 18.02/m with no VPD. The values determined for Burton's data result in ratios of 5.7/m and 1.62/m for freshly harvested and well-suberized tubers, respectively.

Figure 5.4 illustrates the influence of $r\delta$ on equation (5.18) with $\gamma = 0.024$. As $r\delta$ increases, the asymptotic weight loss decreases and the bend in the curve becomes more abrupt. The critical velocity depends upon the relative magnitude of $r\delta$ and $b_2/v_a^{b_3}$ and hence decreases as $r\delta$ increases.

Equation (5.21) which relates $r\delta$ to VPD implies a physiological response in that the resistance to flow of evaporated water increases as the potential for evaporation (VPD) increases.

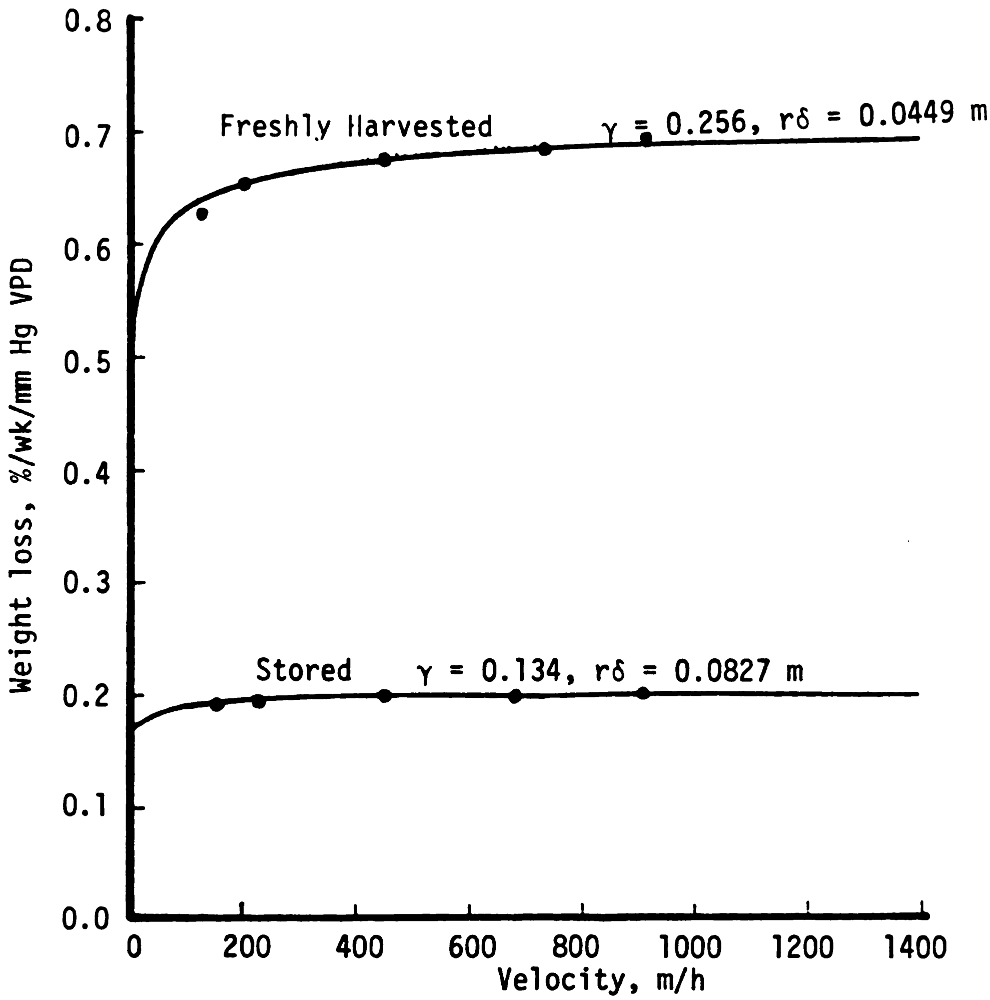


Figure 5.3. Weight loss predicted by equation (5.22) versus velocity and data from Burton (1966) for freshly harvested and stored potatoes.

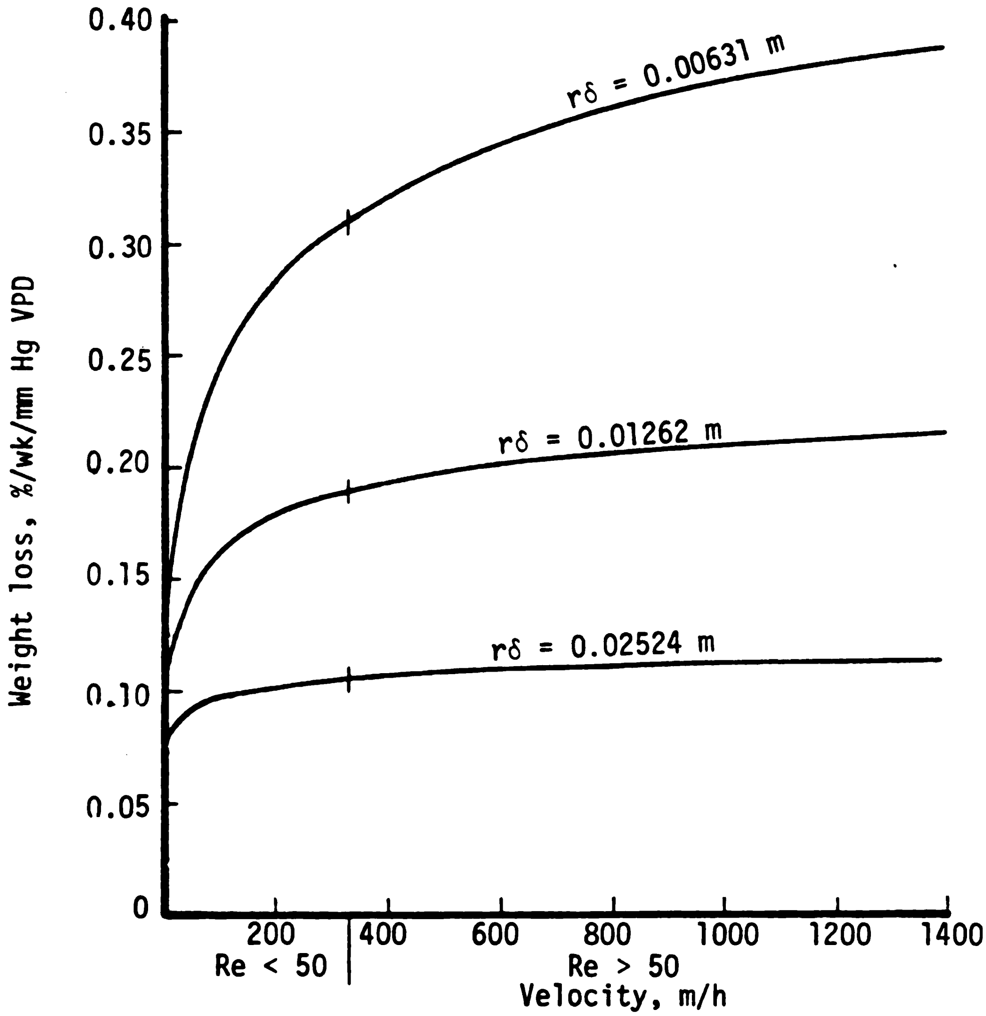


Figure 5.4. Weight loss predicted by equation (5.18) for $\gamma = 0.024$ and three values of $r\delta$. Other properties are the same as in Figure 5.2.

This nonlinear response of weight loss rate to VPD is inconsistent with results reported by Burton (1963a), Schippers (1971d), and others but has been reported by Hunter (1977) and Grähs et al. (1978). Use of equation (5.21) for $r\delta$ in equation (5.18) will result in weight loss rates which asymptotically approach a limiting value as VPD increases. This maximum rate is approached as $(b_4 + b_2/v_a^{b_3})/\text{VPD}$ becomes much smaller than b_5 where b_4 and b_5 are the intercept and slope of equation (5.21), respectively. Thus, at higher velocities, the maximum rate is achieved at lower VPD (higher relative humidity of the air).

Kolattukudy and Dean (1974) and Dean and Kolattukudy (1977) found that resistance to water loss by tissues slices and cylinders was directly proportional to the quantity of suberin acids (18-hydroxyoctadec-9-enoic and octadec-9-ene-18-dioc) present. Figure 5.5 shows the change in resistance over time for two varieties of potatoes. Tissue thickness (wound response) is known to affect the rate of metabolic changes and may account for much of the variation between the curves in Figure 5.5 (Dean and Kolattukudy, 1977).

Although Figure 5.5 shows results based on tissue slices and cylinders rather than whole tubers, it seems reasonable to assume that the change of resistance with respect to time for freshly harvested tubers follows the same pattern. Thus, damaged areas will be characterized by low resistance for several days until synthesis of suberin acids begins. The resistance will then increase rapidly to some final value.

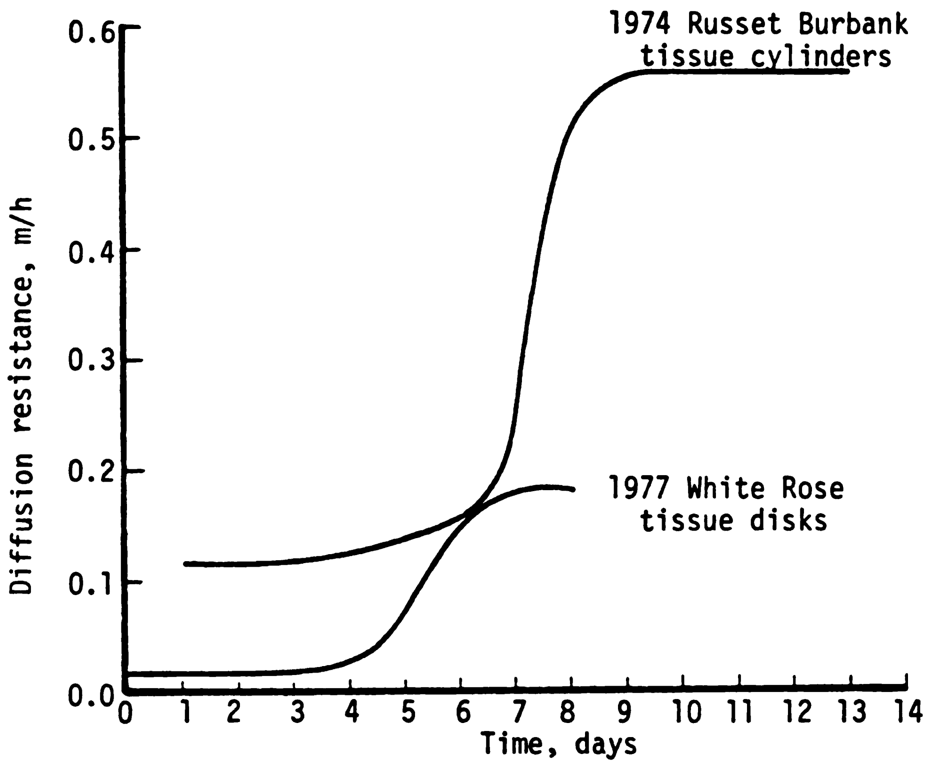


Figure 5.5. Resistance to water loss during suberization of potato tissue for two varieties (from Kolattukudy and Dean, 1974; Dean and Kolattukudy, 1977).

A large portion of the surface of fresh tissue slices should behave as a free water surface. Thus, equation (5.17) is expected to apply. Unfortunately, the data is not adequate to permit determination of γ', γ, and $r\delta$ individually. However, an exponentially decreasing γ' and exponentially increasing $r\delta$ (to some limiting level) results in the general shape of Figure 5.5.

Larsson (1973) reported cumulative weight losses of potatoes from harvest through seven to nine months of storage. Air humidity, temperature, degree of mechanical damage, type of damage, and tuber size were controlled. The pattern of weight loss during suberization is not evident from this data since measurements were taken at two-week intervals. Larsson did not attempt to express the rate of weight loss mathematically.

Butchbaker et al. (1973) performed a regression analysis on weight loss data for three varieties of potatoes. Resulting equations are shown in Table 5.4. They concluded that these equations would overpredict the weight loss since a greater surface area was exposed than would be the case in a commercial storage. The average weight loss of all tests was on the order of 0.25% per week.

Misener and Shove (1976b) measured weight losses of individual suberized Kennebec potatoes in controlled humidity chambers. Temperatures of 4.5°, 15.5°, and 28.4°C with relative humidities ranging from 11.9% to 98.4% were used. Humidity was maintained with saturated salt solutions; forced airflow was not provided.

Table 5.4. Prediction equations for weight loss by Butchbaker et al. (1973).

KENNEBEC

$$\%WL = 2.046978 + .0465739\ (DAY) - .000178\ (RH)^2 - .000057\ (DAY)^2 + .142572\ (VEL)^2 + .000163\ (TEMP)^2 - .000002\ (PWT)^2 - .026382\ (RH) - .218780$$

RED PONTIAC

$$\%WL = 0.142250 + .085763\ (DAY) - .000405\ (RH)^2 + .440875\ (VEL) - .000201\ (DAY)^2 + .000589\ (TEMP)^2 - .003181\ (PWT)$$

NORGOLD RUSSET

$$\%WL = 13.913711 + .060779\ (DAY) - .000098\ (DAY)^2 + .436951\ (TEMP) - .001332\ (RH)^2 + .095461\ (RH) - .003635\ (TEMP)^2$$

Where:

%WL = percent weight loss of tuber based on initial weight

DAY = day from date tubers placed in storage

RH = relative humidity

TEMP = temperature, °F

PWT = tuber weight, g

VEL = air velocity, ft per min

The data was analyzed using a regression program and resulted in the following expression:

$$\frac{-\dot{m}_p}{(1 - \varepsilon)\rho_p} = 1.896 \times 10^{-5} \, (VPD)^{0.59} \, t^{-0.35} \tag{5.25}$$

Hunter (1976a) used the following relationship to predict weight loss:

$$K_D A(P_s - P_v) = \frac{A}{r\delta} (P_i - P_s) \tag{5.26}$$

where $P_s - P_v$ is the VPD across the air boundary layer and $P_i - P_s$ across the tuber skin. This is a simple balance which requires that the air receives all of the moisture removed.

Hunter evaluated the mass transfer coefficients by:

$$K_D = \frac{h}{c \; M \; P} \left(\frac{0.72}{Sc}\right)^{0.67} \tag{5.27}$$

and:

$$\frac{1}{r\delta} = \frac{b_1}{(VPD)^{b_2}} \tag{5.28}$$

The value of b_2 was reported as 0.5 for 3.3° and 7.2°C and 0.8 for 12.8°C.

Hunter (1976a, 1976b) collected weight loss data for Kennebec and Russet Burbank potatoes during two seasons. The data followed a general pattern of exponential rise and decay and was fitted to curves of the type:

$$\% \text{ loss/week} = b_1 e^{b_2 t} + b_3 \quad (5.29)$$

Values for b_1, b_2, and b_3 were reported for each treatment (Hunter, 1976b, 1977). Hunter found the parameters to differ somewhat from season to season and concluded they were not suitable for general use.

5.3.2 Heat Generation Rate

Although few studies have been conducted which measure heat generation rate directly, a conversion from rate of CO_2 produced (12.1 mg CO_2/kg h = 1 J/kg h) has been found acceptable (Van den Berg and Lentz, 1972). There is no shortage of published data on evolution of CO_2.

Only a few attempts have been made to mathematically express the heat generation rate. This is due partially to the difficult shape of the respiration rate curve as shown in Figure 1.4, partially to the unsettling influence of various treatments as shown in Figures 1.5 through 1.7, and partially to the number of factors which have been implicated as contributing to the rate.

Figure 5.6 shows the range of heat generation rates compiled by Grähs et al. (1978). Burton (1966) gave values of 41.9 J/h kg for normal storage conditions, 167.5 J/h kg for freshly harvested mature tubers, and 251.2 J/h kg for freshly harvested immature tubers. Lutz and Hardenburg (1968) listed a broad range for respiration rates of mature and immature potatoes.

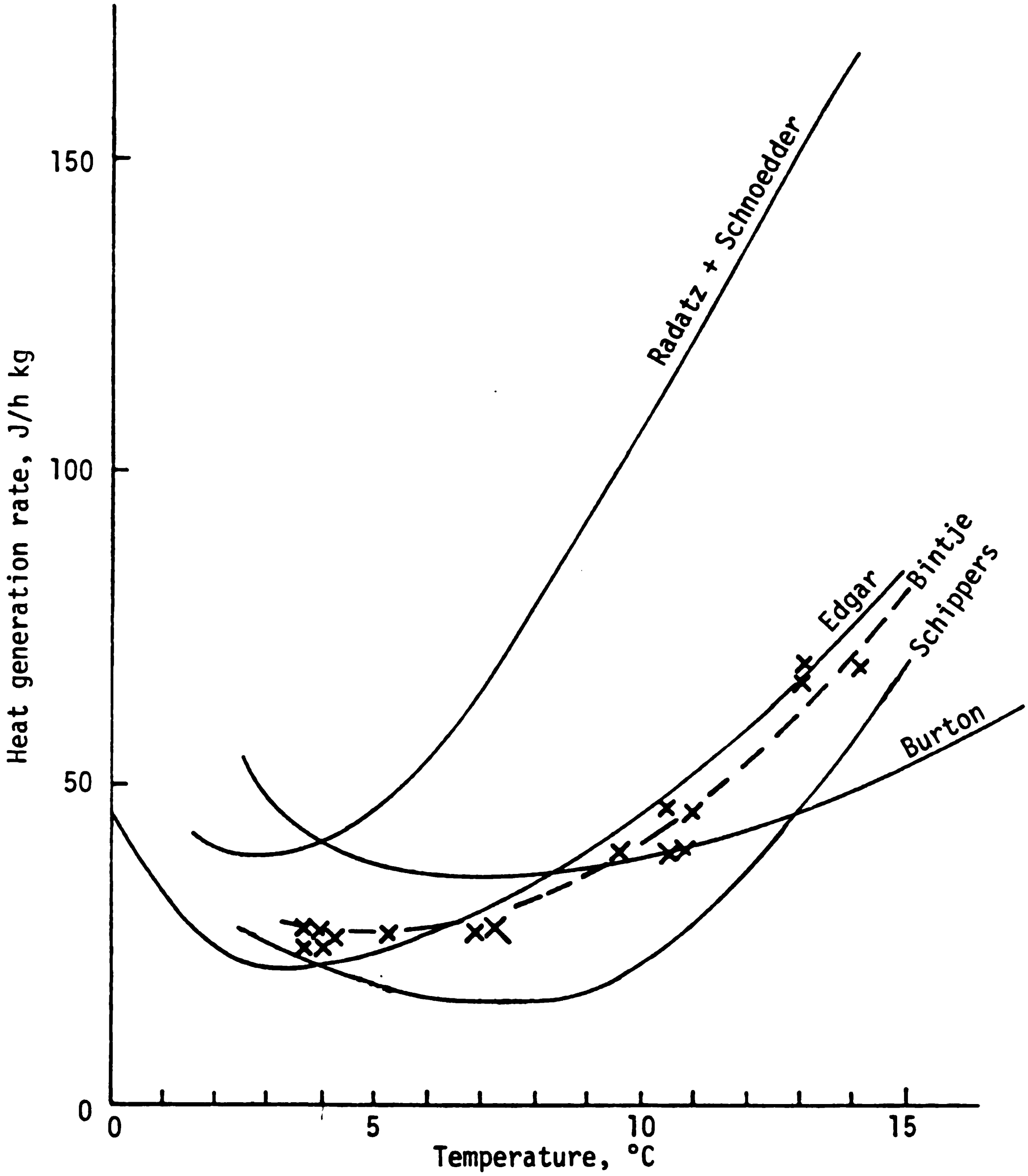


Figure 5.6. Heat generation rates for potatoes compiled by Grähs et al. (1978).

Meinl (1967) found that respiration rates of individual tubers were best expressed in terms of $\sqrt{Aw}$. No specific formula was presented.

Boe et al. (1974) measured respiration rates of Russet Burbank potatoes at five temperatures during several months of storage. Regression polynomials of degree five were calculated for each temperature condition to give CO_2 evolved as a function of time in storage. Only the resulting curves and not the polynomial coefficients were published.

Misener and Shove (1976a) used a linear regression of the Edgar data shown in Figure 5.6. The resulting equation for the temperature range 4.5°-21 °C was:

$$Q = 6.99\Theta - 17.7 \qquad (5.30)$$

The influence of temperature on respiration rate shown in Figure 5.6 may be misleading. Most of the data at high temperatures were taken shortly after harvest when suberization and wound periderm formation may not have been complete. The data at lower temperatures were collected from potatoes after some time in storage.

Hunter (1976b) developed equations for the respiration rates of Kennebec and Russet Burbank under various conditions and treatments. These take the form:

$$\text{rate}\left(\frac{mgCO_2}{kg\ hr}\right) = b_1\, e^{b_2 t} + b_3 \qquad (5.31)$$

Values for b_1, b_2, and b_3 were determined for each treatment.

Hylmö (1977) determined respiration rates from temperature distributions in commercial storages as previously discussed. Figure 5.6 shows results for the variety Bintje based on data from three storage seasons. These data indicate a nearly constant rate from 4° to 7°C and nearly linear increase from 7° to 14°C. The slope is slightly less than that given in equation (5.30).

5.3.3 Rot Index

Only one notable attempt has been made to quantify the potential for development of bacterial soft rot. Kendrick et al. (1959) presented a linear equation for the incidence of infection based on the percent relative humidity hours above 90% and degree temperature hours above 4.4°C. Unfortunately, Hendrick's equation applies only to the tubers and conditions used in their experiment.

Sections 1.3.5 and 5.1 discussed the importance of free water films leading to anaerobic conditions which favor the development of bacterial soft rots. Since the development of rots depends upon the depletion of O_2, the time at which anaerobic conditions prevail is a function of the rate of O_2 diffusion through the water film thickness and rate of O_2 depletion within the tuber by respiration. The influence of decreasing O_2 concentrations on respiration rate and degree of anaerobiosis required are not well defined. Hence, it is not possible to precisely predict the time when pectolytic bacteria become active in the lenticels.

Maintaining a record of amount of time that the surface is covered by any free water film is a simple matter for a computer model. It might be expected that rot initiation is related to the product of time and water film thickness such that anaerobic conditions prevail after long times with small water films or after short times with greater film thicknesses. Data from Burton and Wigginton (1970) suggest a film thickness-time product of 1.95×10^{-4} h-m at 10°C or 7.5×10^{-5} h-m at 21°C will result in initiation of rot. If the influence of temperature on both O_2 diffusion and respiration is assumed to be linear, a critical water film-time combination at any particular temperature can be determined by linear interpolation or extrapolation from the two values given above. Hence, the rot index (RI) is defined as:

$$RI = \begin{cases} \sum_t \delta_w \, \Delta t & \text{when} \quad \delta_w > 0 \\ 0 & \text{when} \quad \delta_w = 0 \end{cases} \tag{5.32}$$

The limiting or critical value at any temperature is:

$$RI_{critical} = -1.1 \times 10^{-5} \, T + 3.04 \times 10^{-4} \tag{5.33}$$

Although equations (5.32) and (5.33) are at best a crude approximation, they should serve as a basis of comparison between results predicted by the model for various storage management policies or control systems.

5.4 Nonventilated Period Model

Free convection occurs in bulk stored potatoes if the ventilation fans are turned off for prolonged periods. Burton (1963) estimated the volumetric flow rate of convective currents as $0.015/\sqrt{L}$ m^3 air/h/kg of potatoes. This results in an average interstitial velocity of 39 m/h for a 3 m bed and 60 m/h for a 7 m bed. Hylmö et al. (1976) reported velocities of 9 to 15 m/h for a 4 m bed.

It is possible to use the above expression to determine an average velocity and proceed with the same model as is used for forced convection. However, such low velocities require correspondingly small depth increments [equation (4.58)] and high computer costs. Besides, the velocities will not be uniform so the validity of the results obtained is in doubt.

Accurate modeling of free convection is a three-dimensional problem. When forced ventilation ends, there is usually a temperature increase from the bottom of the pile to the top. Thus, air currents rise through the bulk of the pile. If the ambient temperature is less than the storage temperature, the wall surfaces are cooler than the potatoes and air currents fall along the edges of the pile due to density differences.

Air currents also become active in the space above the pile. The exact pattern is largely determined by the construction of the ceiling and distance between the ceiling and the pile. Air currents above the pile often result in cooling of the top layer. Air which is rising through the pile will be saturated and free water will condense on the cooler top layer (Hylmö et al., 1976). The same phenomenon occurs in stored grain.

Potato piles which are not ventilated by forced convection should be covered by a 0.5 m layer of straw. The straw then forms the top layer and adsorbs the condensate. The zone of maximum temperature is usually 0.2 to 0.5 m below the top surface (Burton, 1963) in nonventilated piles.

In modern storages, built for forced ventilation, nonventilated periods should be short enough to avoid condensation in the top layers. This implies that free convection currents are not fully developed.

A simplified approach to heat and moisture transfer during nonventilated periods must be used with the one-dimensional forced convection models. If the fans are off for a sufficient length of time, the air and tuber temperatures will approach equilibrium at each level of the bed. In addition, the relative humidity will approach saturation. The model assumes that both of these phenomena occur instantaneously when forced convection ends. Thus, temperature is given by:

$$T_x^+ = \Theta_x^+ = \frac{\rho_a \varepsilon (c_a + c_v H_x) T_x + \rho_p (1 - \varepsilon) c_p \Theta_x}{\rho_a \varepsilon (c_a + c_v H_x) + \rho_p (1 - \varepsilon) c_p} \qquad (5.34)$$

The humidity is computed from psychrometric relationships such that:

$$H_x^+ = H_{sat}\,(T_x^+) \qquad (5.35)$$

It is assumed that no bulk flow of air occurs. Heat transfer occurs only as conduction through parallel paths of still air and potato tissue. Under these conditions an energy balance yields:

$$[\rho_a \varepsilon (c_a + c_v H) + \rho_p (1-\varepsilon) c_p] \frac{\partial T}{\partial t} = -\rho_a \varepsilon (c_v T + h_{fg}) \frac{\partial H}{\partial t} + Q\rho_p (1-\varepsilon) + [k_a \varepsilon + k_p (1-\varepsilon)] \frac{\partial^2 T}{\partial x^2} \qquad (5.36)$$

The left side of equation (5.36) accounts for the accumulation or change in sensible heat of the air and potatoes. The terms on the right side express the latent heat, generated heat and conducted heat, respectively.

Equation (5.36) is written in finite difference form as:

$$T_x^+ = T_x + \{-\rho_a \varepsilon (c_v T + h_{fg})(H_x - H_x^-) + Q\rho_p (1 - \varepsilon)\Delta t + [k_a \varepsilon + k_p (1 - \varepsilon)] \frac{\Delta t}{(\Delta x)^2} (T_{x+\Delta x} - 2T_x + T_{x-\Delta x})\} / [\rho_a \varepsilon (c_a + c_v H) + \rho_p c_p (1 - \varepsilon)] \qquad (5.37)$$

where a backward time difference is used for $\frac{\partial H}{\partial t}$. At the top and bottom, $\frac{\partial T}{\partial x} = 0$.

In spite of the gross simplifications, this approach to nonventilated periods should be adequate provided the nonventilated time interval is neither too long (so that convective currents become fully developed) nor too short (so that thermal equilibrium and saturation are not attained).

5.5 Validation of the Potato Model

The previous section presented a number of alternatives for values of thermal and physical properties of potatoes and equations to calculate additional parameters, weight loss and metabolic heat generation rates. Unless otherwise specified, the properties listed in Table 5.5 are used in this and subsequent sections for testing along with equations (5.1) for initial water fraction, (5.5) for surface area, (5.10) for convective heat transfer coefficient, (5.18) through (5.20) for evaporation rate, and (5.30) for heat generation rate.

Section 4.4 discussed validation of the forced convection models with respect to the influence of individual terms and

Table 5.5. Property values used for testing the potato storage model.

Property	Value	Units
c_d	904.3	J/kg °C
k_p	2000.	J/h m °C
S_g	1.09	--
w	170.	g
ε	0.426	m^3/m^3
γ	0.07	--
$r\delta$	0.035	m

parameters. The numerical solution of a simplified model (no heat generation, moisture loss, or conduction) was compared with analytical solutions showing that the shape of the resulting temperature profiles was similar even though exact aggreement was not achieved (Figures 4.5 and 4.6). The influence of the heat conduction term in the thermal equilibrium and uniform temperature gradient models was shown to be negligible even for conditions of large k_p and small $\rho_p c_p$ (Figures 4.9 and 4.10).

Comparison of the three models in section 4.5 revealed that the uniform product temperature and internal temperature gradient models produced similar temperature profiles while those predicted by the thermal equilibrium model possessed a distinctly different shape (Figures 4.22 and 4.23). The sharply defined trailing edge of the cooling zone predicted by the thermal equilibrium model is not evident in potato storages. With the small temperature differences normally encountered (usually less than 2°C between the inlet air and warmest spot in the pile during cooling), the thermal equilibrium profile will be very similar to the uniform and gradient profiles. However, a wider range of applicability is desirable and since the uniform model is numerically solved in less time than the equilibrium model using the techniques presented here, the equilibrium model will not be discussed further.

The significance of internal temperature gradients needs further consideration. The uniform product temperature model assumes that the effects of latent heat of vaporization and convective heat transfer at the surface are instantaneously reflected in the uniform temperature. The temperature gradient model predicts a temperature distribution from surface to center such that the center temperature lags behind in response to stimuli of heat convection and evaporation at the surface. Since the respiration rate equation is a linear function of temperature and the uniform product temperature represents the mass average temperature of any imposed gradient, no difference in heat generation rate between these two models is expected. On the other hand, evaporation rate (free water or moisture from the tuber) and condensation rate are functions of the difference between the partial pressure of water vapor in the air and the saturated vapor pressure at the surface or uniform product temperature depending upon the model used. Hence the temperature difference might give rise to a difference in moisture transfer and quantity of latent heat.

One measure of the significance or magnitude of internal temperature gradients is given by the Biot number. For heat transfer without mass transfer or heat generation, a Biot number of 0.1 results in a ratio of normalized surface temperature to normalized center temperature $[(\Theta_s - T)/(\Theta_c - T)]$ of 0.95 while a Biot number of 1.0 results in a ratio of 0.66 (Myers, 1971). If the recommended maximum temperature difference of 2°C exists between the tuber surface and the air, then the maximum difference between the tuber center and air temperature will be less than 3.0°C for $Bi \leq 1.0$.

Figure 5.7 shows the range of the Biot number for potatoes based on equation (5.10) for h, and ranges of 1700 to 2400 J/h m °C and 0.05 to 0.10 m for k_p and D, respectively. An interstitial velocity of 700 m/h is nearly equivalent to 370 $kg/h/m^2$ or 100 m^3 $air/h/m^3$ of potatoes in a three-meter bed. Since rate of evaporation is constant or increases with velocity due to the convective mass transfer coefficient, differences between the uniform and gradient models should be greatest at high velocities.

Figures 5.8 and 5.9 show the air temperature profiles at 6 and 48 hours as predicted by the uniform and gradient models for a three-meter bed ventilated with an air velocity of 700 m/h. Figure 5.8 is based on values listed in Table 5.5 while Figure 5.9 is based on $\gamma = 0.21$. Figure 5.10 shows the uniform and surface potato temperature at the 2 m level corresponding to the profiles in Figure 5.8.

Figures 5.11 and 5.12 show the potato temperature response at three levels as predicted by the uniform and gradient models, respectively. Properties listed in Table 5.5 and sinusoidal inlet temperatures and humidities given by equation (4.71) and (4.72) apply to Figures 5.11 and 5.12.

In all cases, the uniform product temperature and surface temperature are almost identical. The sine wave temperature and humidity inputs are a particularly stringent test as condensation occurs throughout the bed during periods when the air temperature and humidity increase. Both the temperatures and mass transfer

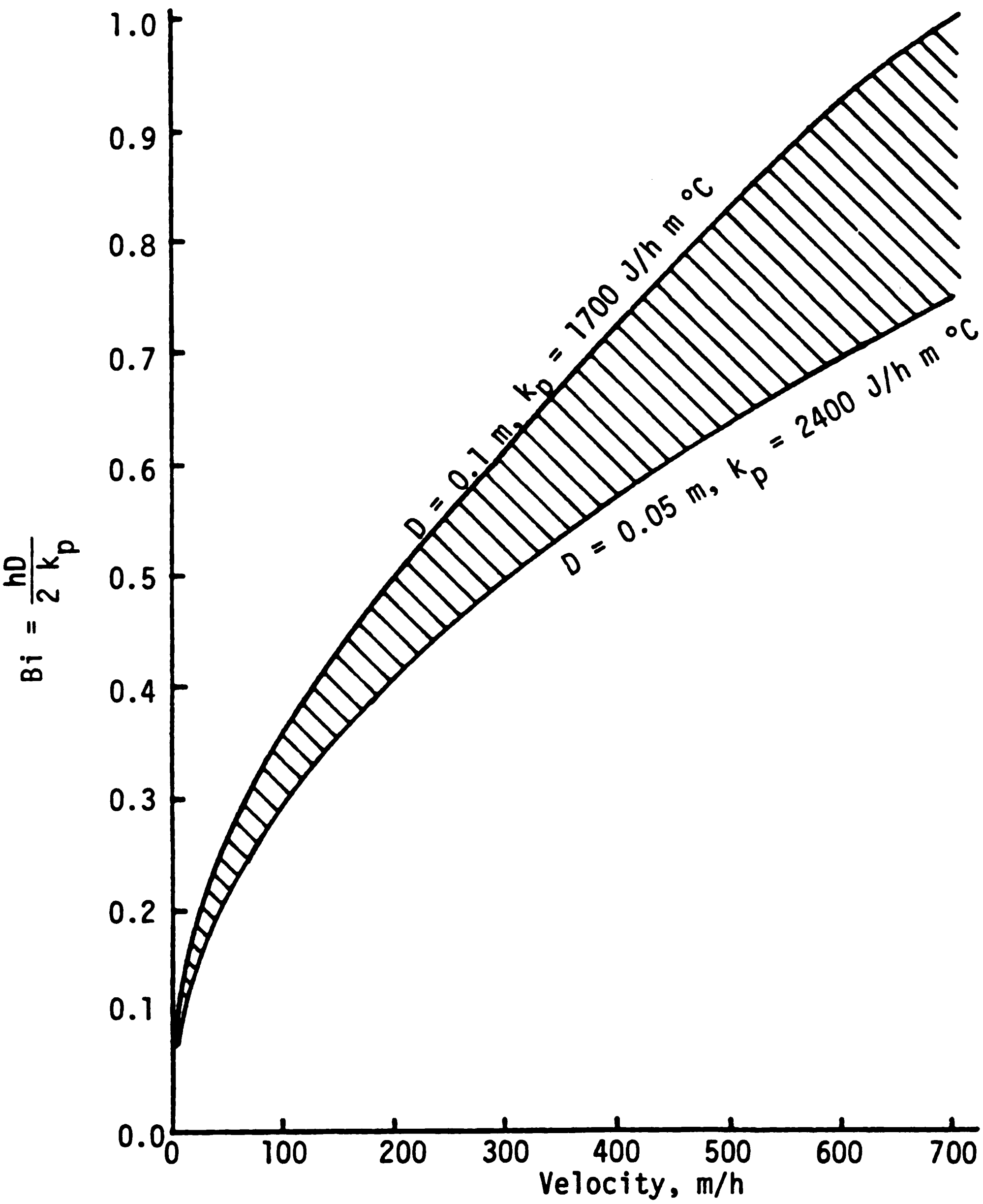


Figure 5.7. Range of Biot number for potatoes for velocities from 0 to 700 m/h.

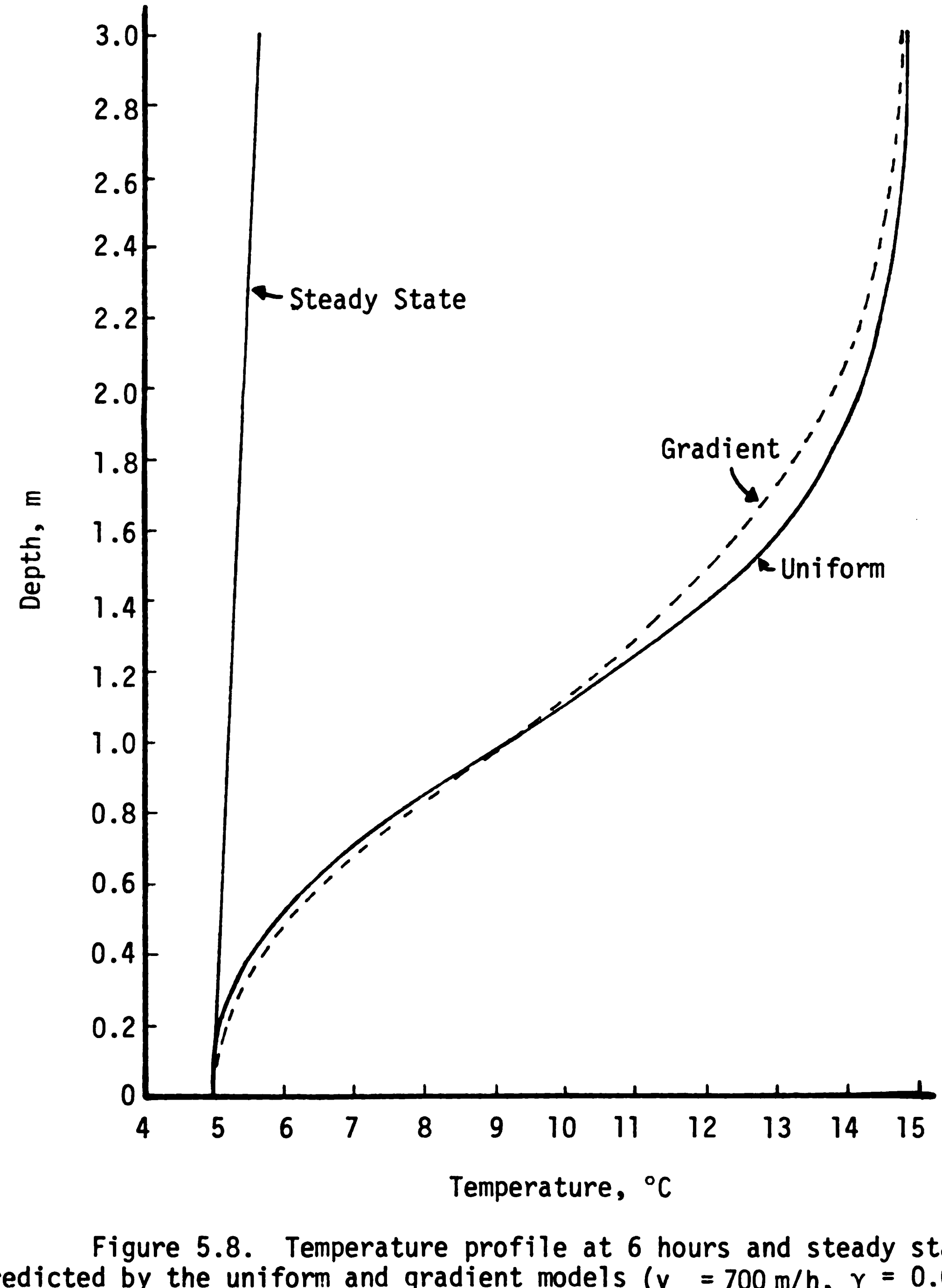


Figure 5.8. Temperature profile at 6 hours and steady state predicted by the uniform and gradient models (v_a = 700 m/h, γ = 0.07).

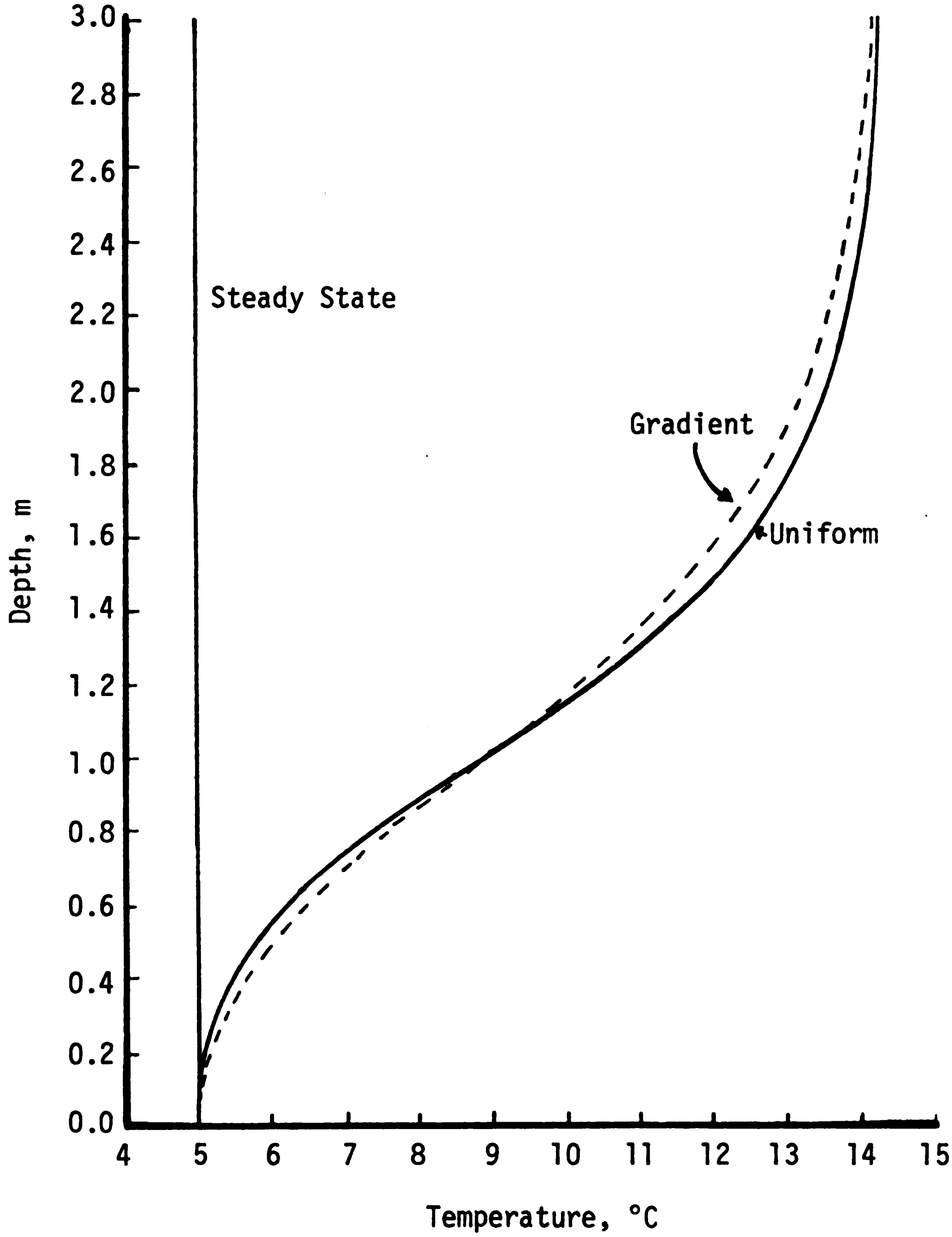


Figure 5.9. Temperature profile at 6 hours and steady state predicted by the uniform and gradient models (v_a = 700 m/h γ = 0.21).

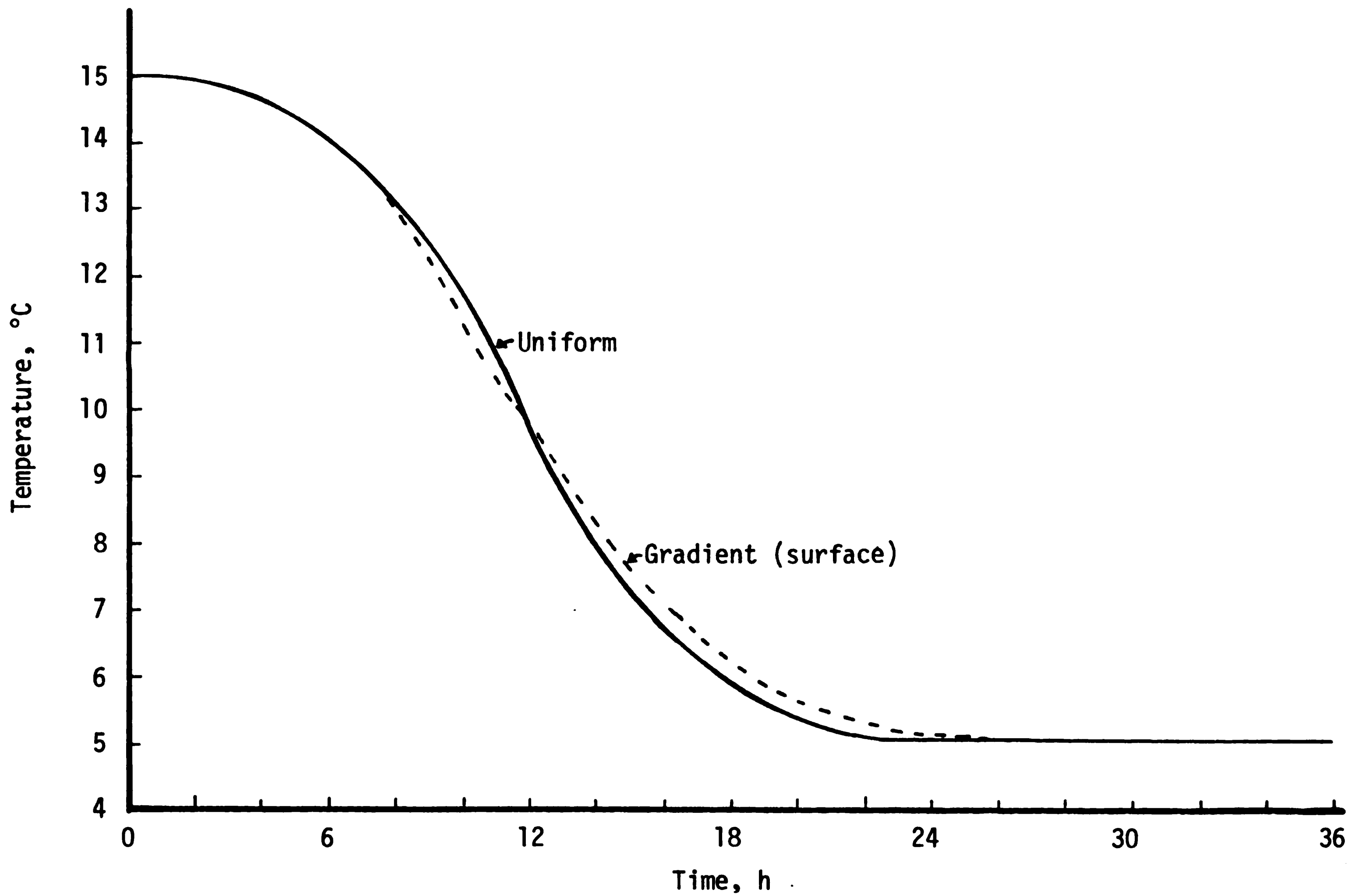


Figure 5.10. Potato temperature history at 2 m as predicted by the uniform and gradient models (v_a = 700 m/h, γ = 0.07).

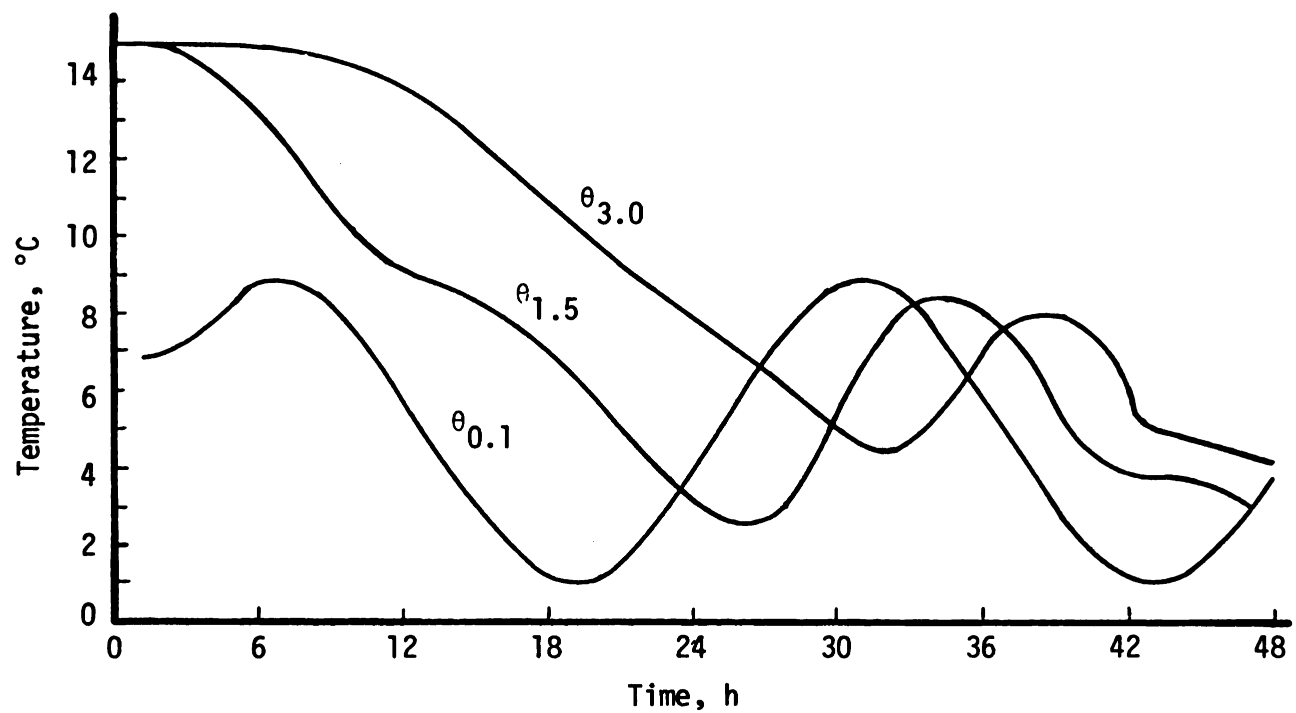


Figure 5.11. Potato temperature history predicted by the uniform model at three levels in a 3 m bed with sinusoidal inlet temperature and humidity (v_a = 700 m/h, γ = 0.07).

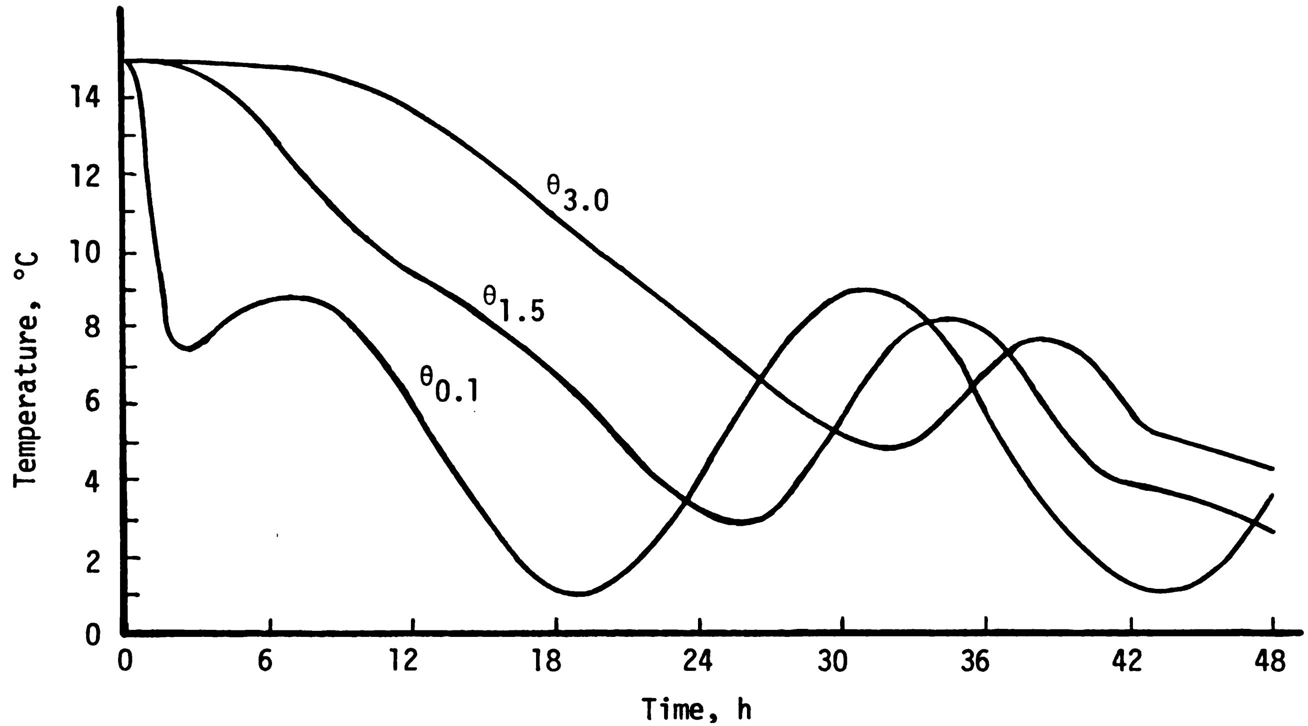


Figure 5.12. Potato temperature history predicted by the gradient model at three levels in a 3 m bed with sinusoidal inlet temperature and humidity (v_a = 700 m/h, γ = 0.07).

rates (weight loss and free water film thickness) are nearly identical and well within limits of practical measurement errors.

Temperature differences between surface and center are significant during the first hour and a half when a 10°C difference between the air temperature and initial product temperature exists --a situation not likely to occur in commercial practice. After the first two hours, the maximum difference between center and surface temperature is less than 0.5°C in spite of the high velocity, fluctuating inputs, evaporation, and condensation.

Based on above and previous results, it is concluded that the uniform product temperature model is suitable for the simulation of temperatures and weight loss of bulk stored potatoes. It remains to be shown that this model adequately predicts the time course of change of temperatures, humidity and weight loss at all levels within the bed. The uniform temperature model is hereinafter referred to as the MSU potato storage model.

5.5.1 Comparison With Misener Data

Misener (1973) obtained data for cooling potatoes from a laboratory scale bed 0.7 m diameter by 2.4 m high. Kennebec potatoes were mechanically harvested and suberized at 15.5°C for 11 days before the cooling test. The column was then ventilated at 24 $m^3/h/m^2$ with air at 6.7°C and 60% relative humidity. The column contained 360 kg of potatoes, which, based on the dimensions of the column, represented a bulk density of only 390 kg/m^3.

Individual tubers, apparently from the same lot, were suspended over saturated salt solutions and the weight loss measured with time. Equation (5.25) resulted from a regression analysis of this data. Misener and Shove (1976b) measured an average length of 95 mm and diameter of 51 mm for these tubers. Equation (5.3) with width and thickness equal to diameter gives a surface area of 0.013 m^2/tuber. Equation (5.5) predicts the same area for an average tuber weight of 155 g. Data on the specific gravity, initial moisture content, or tuber density was not reported.

Misener simulated the cooling of potatoes using algebraic heat and mass balances on thin layers with the outlet conditions of each successive layer serving as inputs to the adjacent layer. Thermal equilibrium between the air and tubers was assumed. Results of the simulation and experiment are shown in Figures 5.13 and 5.14 for 24 and 92 hours, respectively. Misener used equation (5.25) to predict weight loss and equation (5.30) for heat generation. Whereas the former was developed for potatoes with similar origin and treatment to those used in the cooling test, equation (5.30) was developed from data from other sources.

Figures 5.13 and 5.14 also show the temperature profiles predicted by the MSU potato storage model using equations (5.25) and (5.30) for weight loss and heat generation rate, respectively. A specific gravity of 1.05 was assumed (X_{wi} = 86%, ρ_p = 1049 kg/m^3). From the bulk density previously calculated, it follows that ε = 0.62. This high void fraction implies that the column was loosely

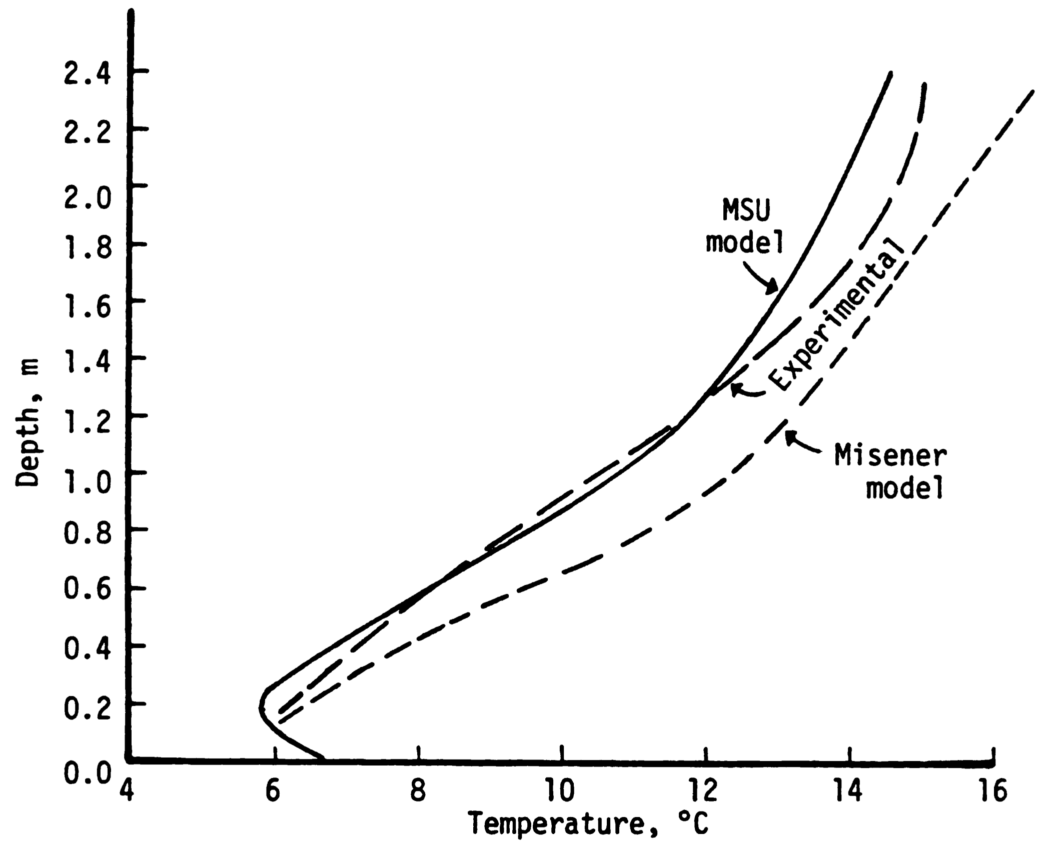


Figure 5.13. Comparison of Misener's experimental and predicted temperature profiles at 24 hours and profile predicted by the MSU model using equation (5.30) for heat generation rate.

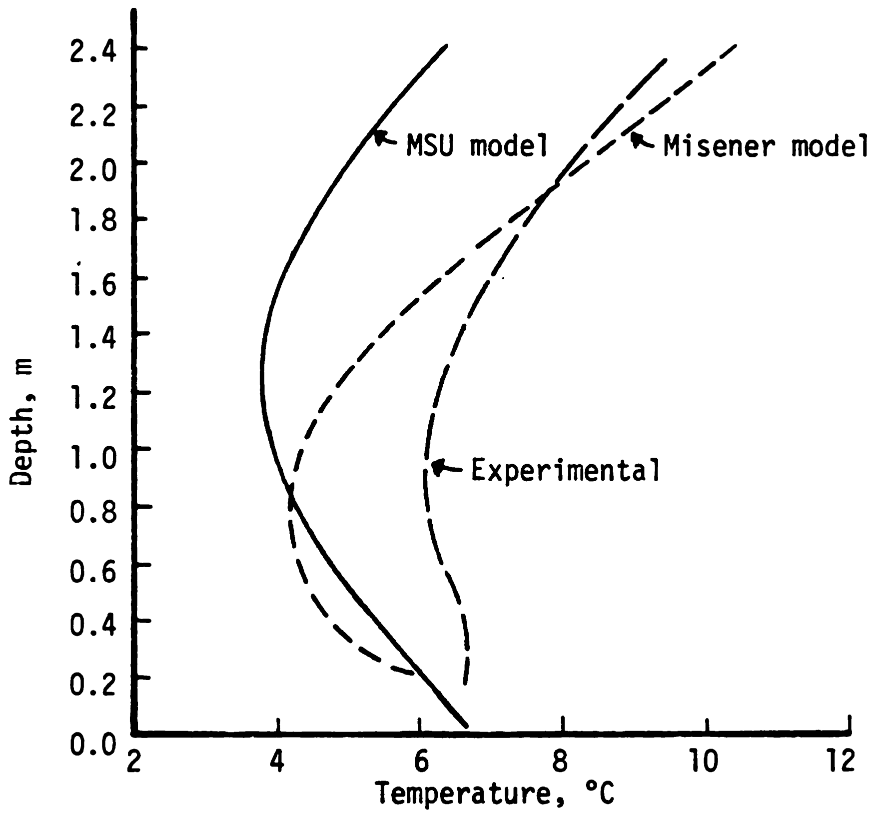


Figure 5.14. Comparison of Misener's experimental and predicted temperature profiles at 92 hours and profile predicted by the MSU model using equation (5.30) for heat generation rate.

filled rather than packed. Although a number of factors are involved, the shape of the curves predicted by the MSU model would compare better with Misener's model if a greater potato volumetric heat capacity was used, i.e., larger ρ_p or w (see Figures 4.17 and 4.18).

Figure 5.14 shows that after 92 hours of cooling the lower portion of the experimental bed is approaching a steady state quite different from that approached by the models. Equation (4.70) expresses the steady state slope for the MSU potato storage model. This equation shows a balance between the sensible heat of the air, latent heat of vaporization, and heat generation. Misener experimentally determined the sensible heat of the air and latent heat of vaporization but not the rate of heat generation. Analysis of the experimental data reveals that a linear heat generation rate with an intercept of 125 J/kg h, rather than -17.7 J/kg h as given by equation (5.30), would result in a better fit of the data. The resulting heat generation rates are still within the range given by Lutz and Hardenburg (1968) for immature tubers. The strong dependence of weight loss rate on time as evidenced by equation (5.25) indicates that suberization was not complete at the beginning of Misener's tests.

Figures (5.15), (5.16), (5.17) and (5.18) show the Misener experimental and the simulated temperature profiles at 24, 48, 72, and 92 hours, respectively, using the revised heat generation rate

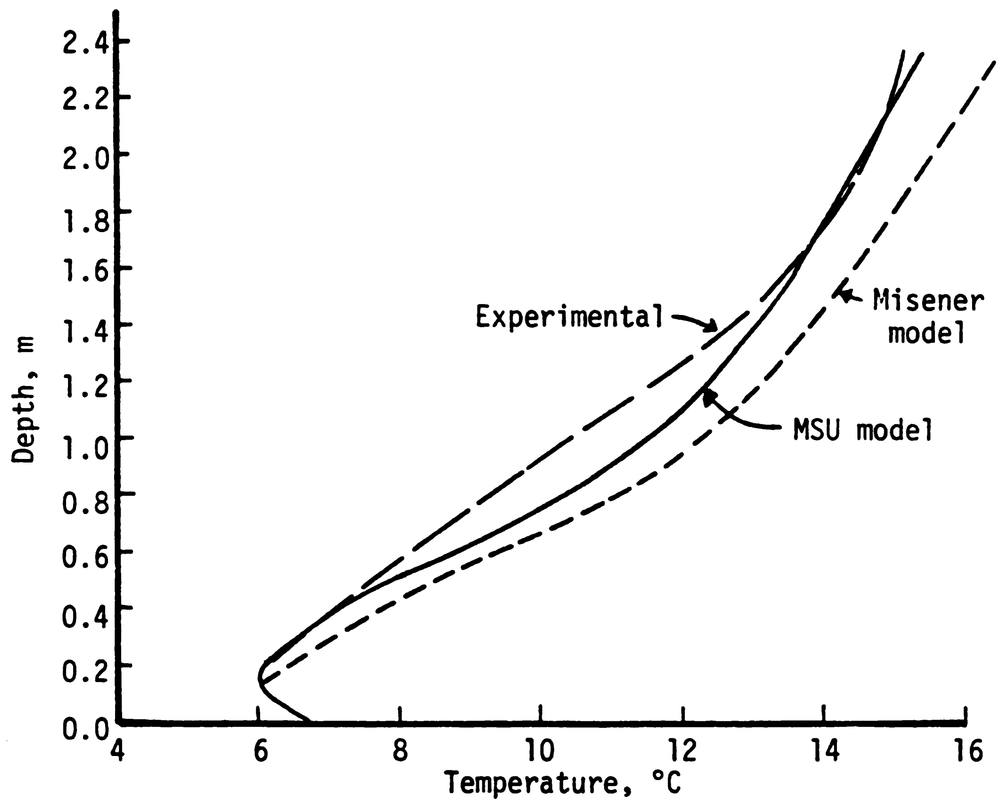


Figure 5.15. Comparison of Misener's experimental and predicted temperature profiles at 24 hours and profile predicted by the MSU model using revised equation (5.30) for heat generation rate.

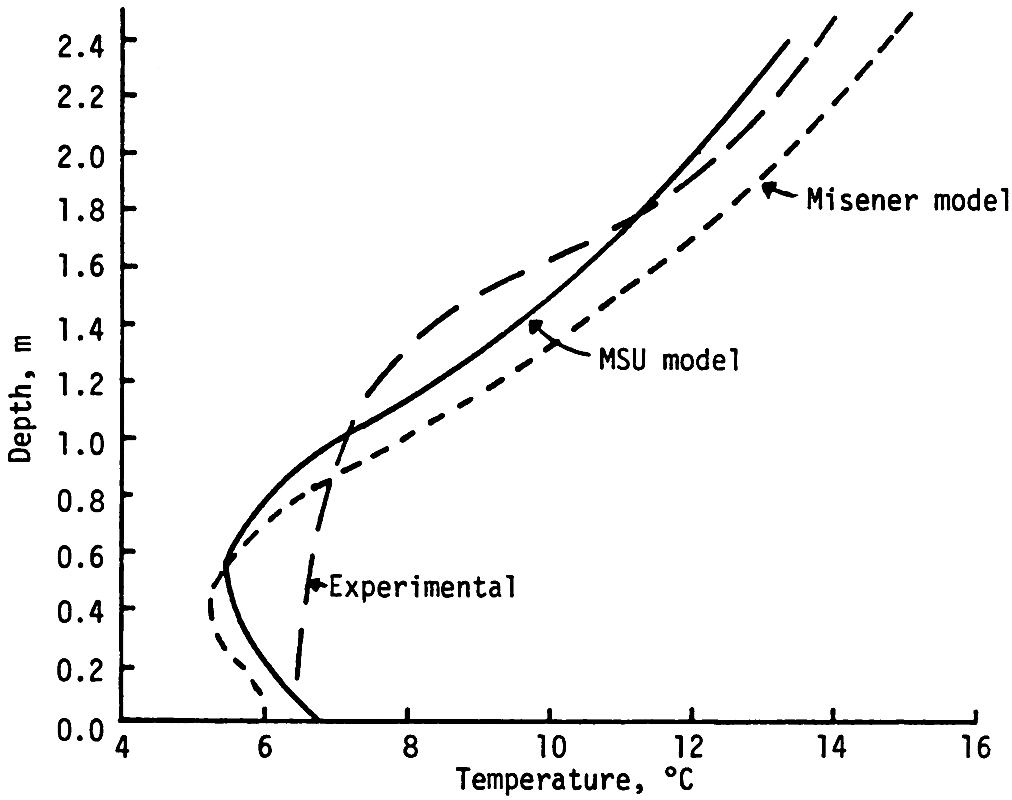


Figure 5.16. Comparison of Misener's experimental and predicted temperature profiles at 48 hours and profile predicted by the MSU model using revised equation (5.30) for heat generation rate.

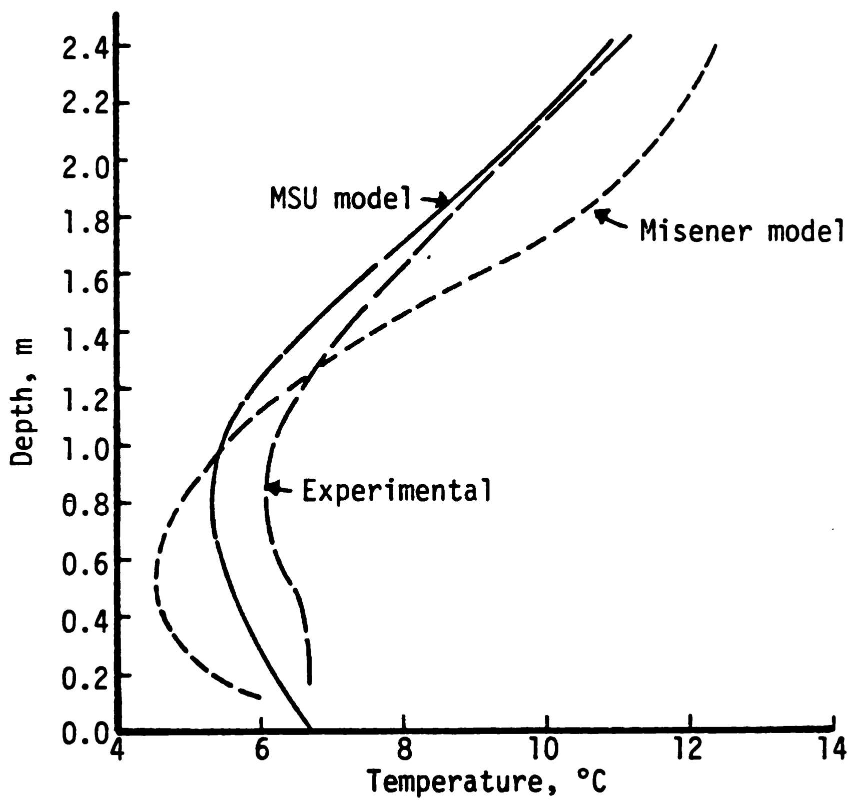


Figure 5.17. Comparison of Misener's experimental and predicted temperature profiles at 72 hours and profile predicted by the MSU model using revised equation (5.30) for heat generation rate.

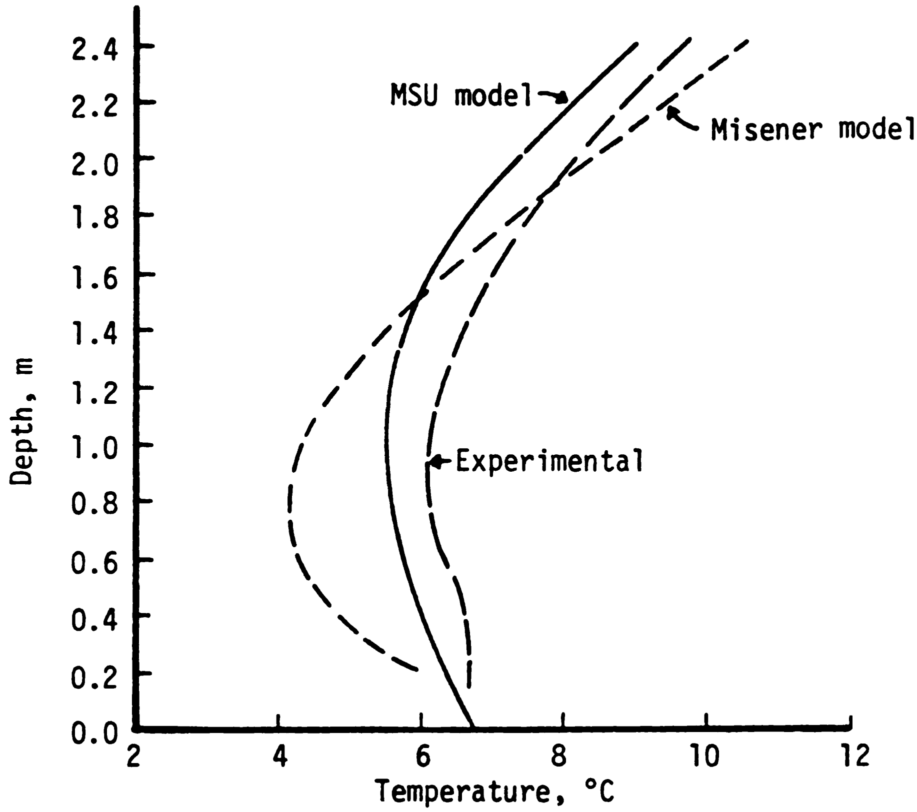


Figure 5.18. Comparison of Misener's experimental and predicted temperature profiles at 92 hours and profile predicted by the MSU model using revised equation (5.30) for heat generation rate.

equation. This substitution greatly improves the agreement between the experimental and MSU model temperatures.

The experimental temperatures show no evaporative cooling in the bottom 0.4 m of the bed at 72 and 92 hours. Misener makes no mention of this fact. It is likely that this results from fluctuations in the inlet conditions or experimental measurement error rather than representing a physiological response of the tubers.

5.5.2 Comparison With Nordreco Data

Precision matched thermocouples were installed at various locations in Nordreco commercial storages in Sweden and temperatures monitored during cooling of a pile. Details were published by Grähs et al. (1978). In a 1975 test, a storage containing approximately 600 tons of potatoes of the variety Bintje were cooled from an initial temperature of 9.9°C to a final average temperature of 7.4°C using continuous humidified ventilation at a rate of 72 m^3h/m^2 of floor area. Sprout inhibitors were applied prior to the test and ventilation was interrupted resulting in uniform initial temperatures from the bottom to the top of the pile. Inlet air temperatures were supplied at three-hour intervals showing nearly sinusoidal cycles with a minimum of 6.1°C and a maximum of 7.9°C with a 24-hour period over the 102 h duration of the test. The pile depth was 3.35 m. Average potato weight was determined to be 120 g with a specific gravity of 1.082. A void fraction of 0.40 was assumed in the simulation.

Accurate inlet air humidities were not determined. However, a humidifier was used and a relative humidity ranging from 85% to 100% was reported. From this it was reasoned that during those portions of the 24 h cycle when air temperature decreases, the duct work must first be cooled. Hence the air temperature will rise slightly before reaching the pile (temperature measurement point) and the relative humidity will fall during these periods. On the other hand, during periods when the air temperature is increasing, it must first heat the duct work. Thus, the air temperature will fall as it passes through the duct and the relative humidity will increase. Saturation and condensation on the ducts may occur. For purposes of comparing the model to the experimental data, a relative humidity of 85% or 100% is assumed depending upon whether the air temperature is decreasing or increasing.

The respiration rate of the pile was determined from the steady state at the end of cooling (Hylmö et al., 1975a,b) assuming saturated inlet conditions. From this and other values for the variety Bintje (Grähs et al., 1978) the following expression was developed (see Figure 5.6):

$$Q = \begin{cases} 4.375\,\Theta + 22.98 & \Theta \geq 7.0 \\ 53.61 & \Theta < 7.0 \end{cases} \qquad (5.38)$$

This rate is higher than that achieved when the potatoes have reached dormancy.

From equation (5.38) and the steady state temperature profile, a ratio of $\gamma/r\delta$ of 4.61 (γ = 0.065, $r\delta$ = 0.0141) was determined as the appropriate evaporation rate [when h and h_D are given by equations (5.10) and (5.20), respectively]. In other words, this rate of moisture loss, coupled with equation (5.38) for heat generation and the specified air flow rate, results in the measured steady state profile.

Figure 5.19 is a reproduction of the header page generated by the MSU model showing input values and parameters calculated in preparation for the simulation.

Figure 5.20 shows the predicted and measured air temperature profiles after 12 and 72 h and Figure 5.21 shows the profiles at 36 h and at the end of the test (102 h). Reasonable agreement exists between the model and experimental values.

Figures 5.22 and 5.23 show the experimental and predicted air temperature versus time at the 0.2 m and 0.4 m levels within the bed, respectively. Figure 5.24 shows the inlet air temperature as well as experimental and predicted temperatures at 1.4 m and 2.8 m. The model uses linear interpolation between data points for the inlet air temperature. At the 0.2 and 0.4 m levels the temperature fluctuations are dampened from the 1.8°C maximum difference at the inlet to 1.5° and 1.1°C, respectively. At the 1.4 and 2.8 m level, very little influence due to varying inlets is seen.

The model follows the fluctuations at 0.2 and 0.4 m quite well although a slight lag in response is evident. The model shows

P O T A T O   S T O R A G E   M O D E L   03/04/78

WITH UNIFORM POTATO TEMPERATURE

INLET AIR TEMP, C	9.9	INLET ABS HUM, KG/KG	.0064
INITIAL POTATO TEMP, C	9.9	INLET REL HUM, DECIMAL	.8500
AIRFLOW M**3/HR/M**3	21.79	AV POTATO WEIGHT, G	120.00
KG DRY AIR/HR/M**2	90.7	SURFACE AREA, M**2	.0109
M/HR IN BED	182.	VOLUME, M**3	.0001
BED DEPTH, M	3.4	TOTAL TIME, HR	102.
DELTA X, M	.0167	DELTA T, HR	.3750
SPECIFIC HEATS, J/KG/C		DENSITIES, KG/M**3	
DRY AIR	1005.	DRY AIR	1.243
POTATO	3510.	POTATO	1081.
LIQUID WATER	4187.	LIQUID WATER	999.2
WATER VAPOR	1884.	BULK POTATOES	648.7
LATENT HEAT, J/KG	2478600.	SP SUR AREA, M**2/M**3	59.1
AIR COND, J/HR/M/C	89.100	POTATO COND, J/HR/M/C	2000.
HT COEF, J/HR/M**2/C	20417.	INIT WEIGHT, TON/M**2	2.173
MASS TRANS COEF, M/HR	18.3	POROSITY, VOID/VOLUME	.40

Figure 5.19. MSU potato storage model header page for simulation of 1975 Nordreco data.

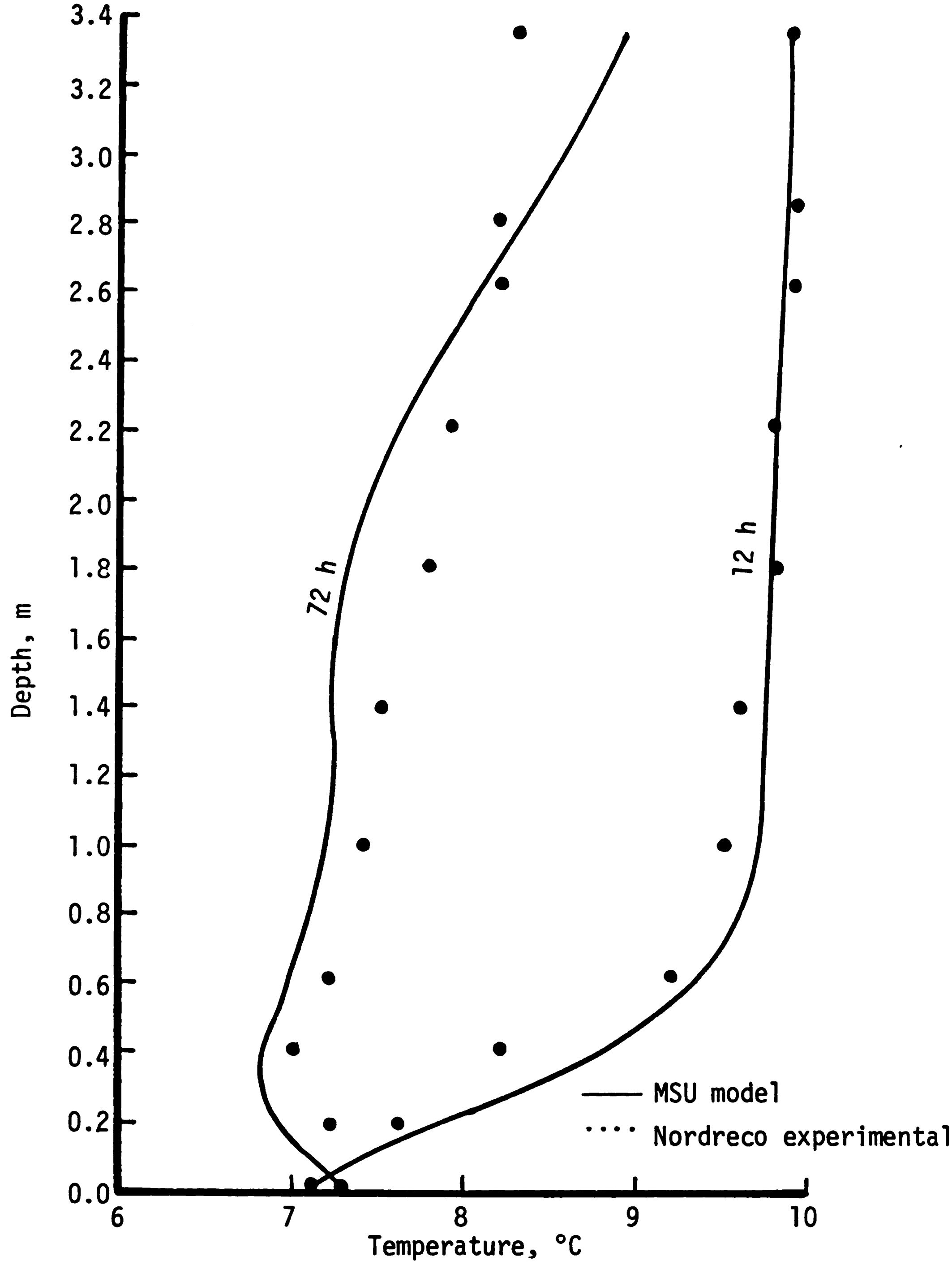


Figure 5.20. Comparison of measured and predicted air temperature profiles after 12 and 72 h of cooling (Experimental data from Nordreco, Bjuv, Sweden).

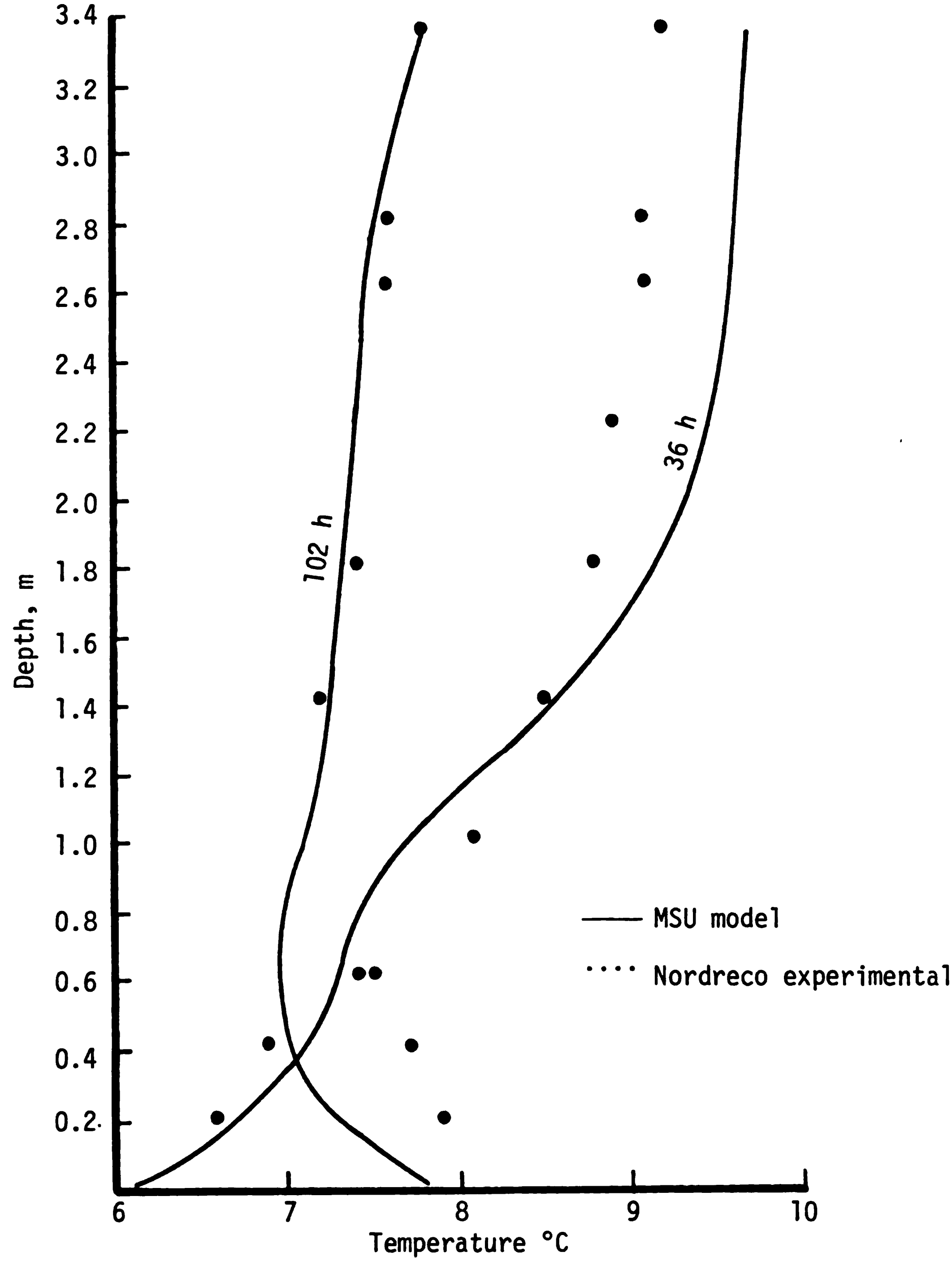


Figure 5.21. Comparison of measured and predicted air temperature profiles after 36 and 102 h of cooling (Experimental data from Nordreco, Bjuv, Sweden).

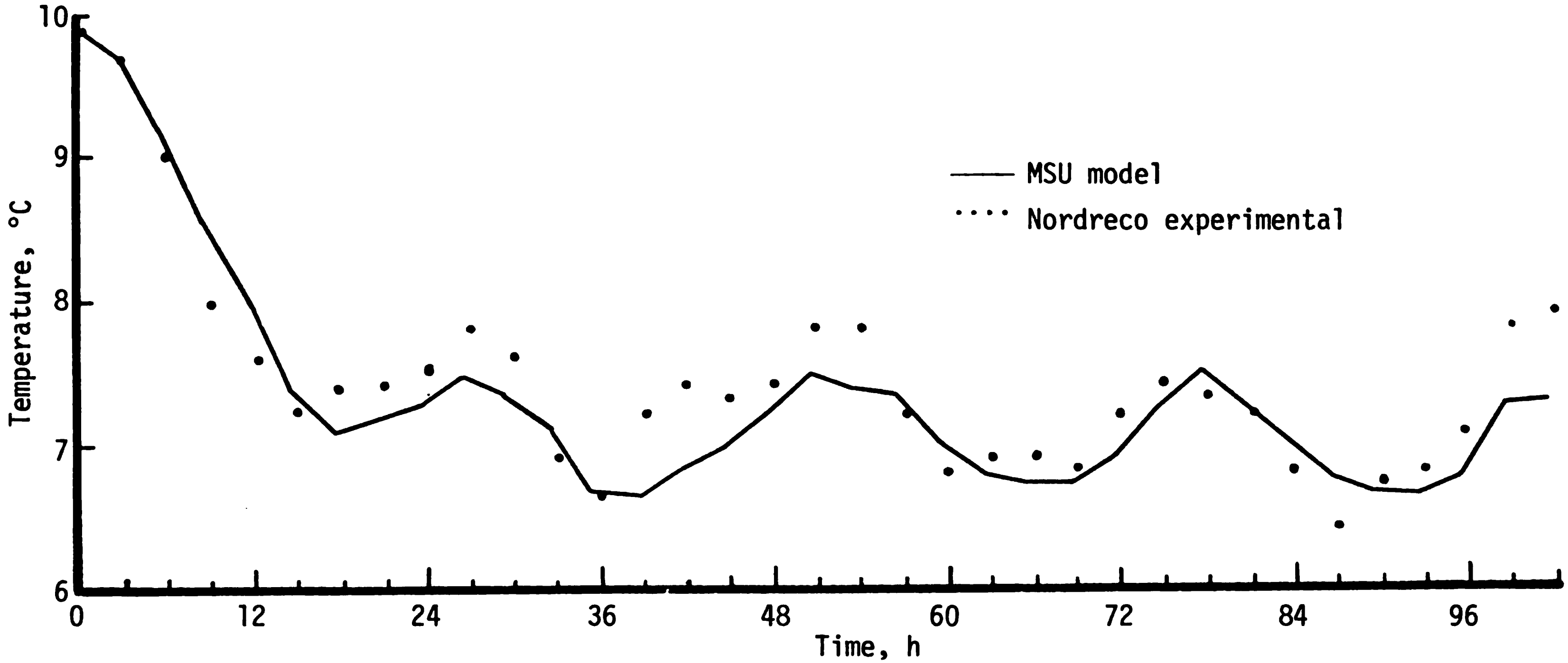


Figure 5.22. Air temperature history at 0.2 m level.

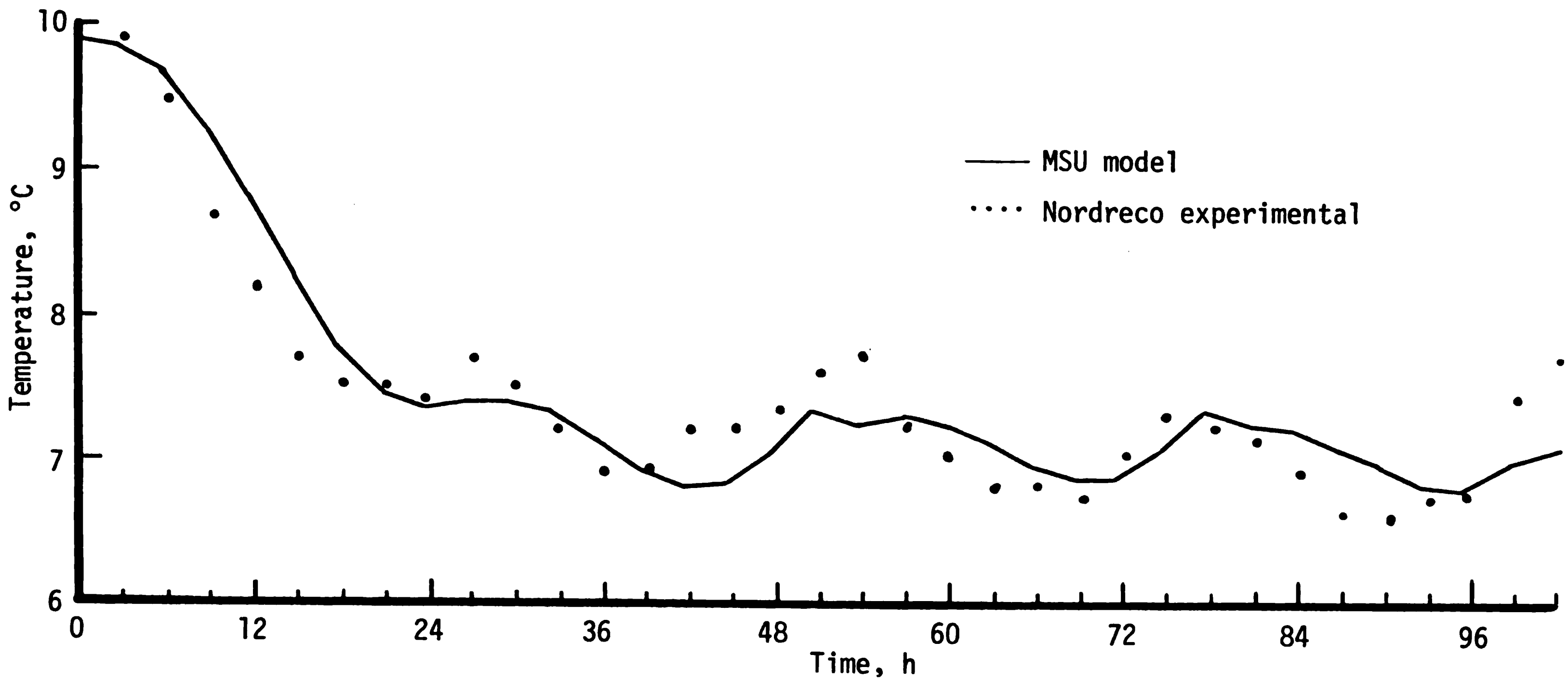


Figure 5.23. Air temperature history at 0.4 m level.

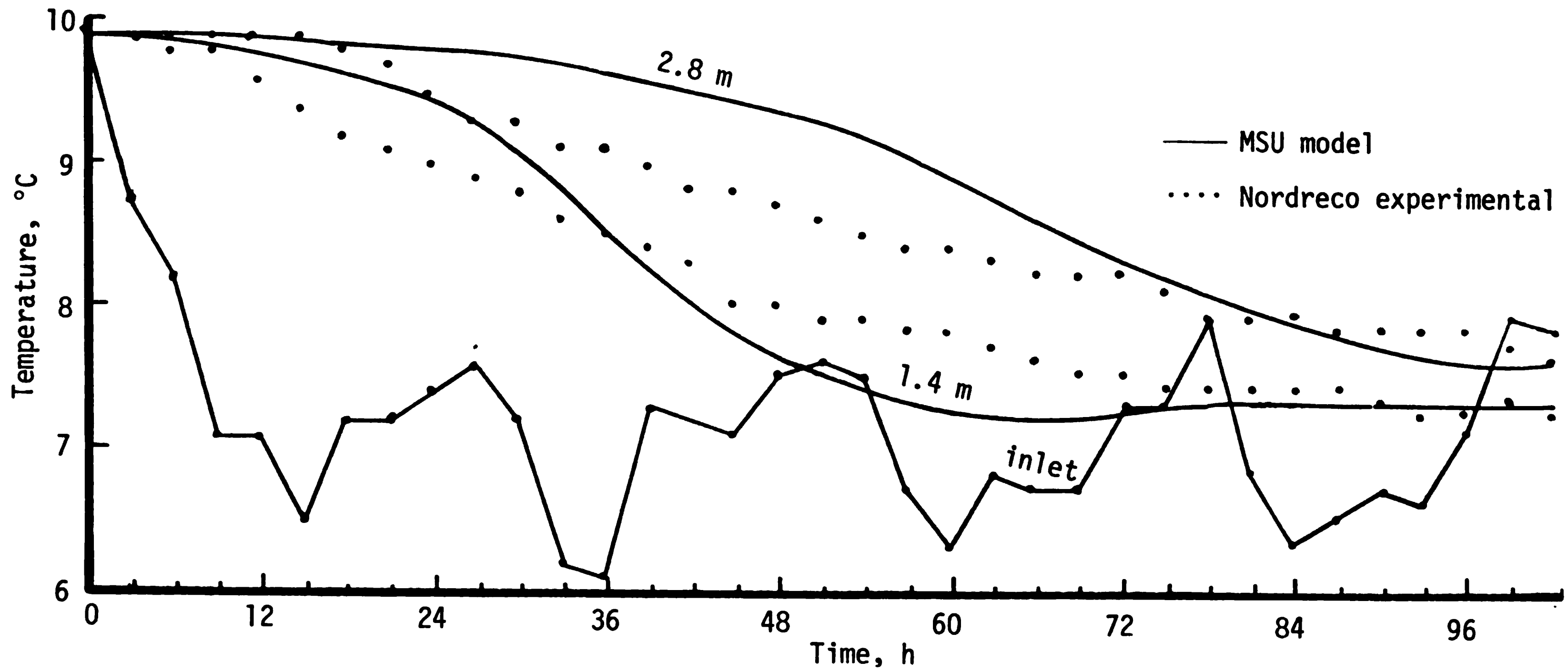


Figure 5.24. Air temperature history at 0, 1.4, and 2.8 m levels.

a generally slower rate of temperature change than the experimental data. At the 1.4 and 2.8 m levels, the overall influence of the lag is more pronounced. Here, the model does not follow the measured points as closely. However, the maximum difference between the experimental and predicted temperatures is on the order of 0.5°C.

A simulation was made using average inputs of 7.04°C and 95% relative humidity. The resulting temperatures at 1.4 and 2.8 m were graphically identical to those shown in Figure 5.24. This result demonstrates that the difference is not related to errors in the inlet conditions. It also was determined that no reasonable variation in average weight, specific gravity, void fraction, or convective heat transfer coefficient, individually or in combination, results in any substantial improvement. Hence, the difference must result from nonuniformities within the bed or physical factors and environmental influences not included in the model.

It should be noted that the MSU model does accurately predict both the time of and temperature profile at steady state. Hence the above differences are not critical. The maximum temperature difference between the predicted and measured values is on the order of 1°C. If the predicted temperatures are to be used for predicting rates of metabolic activity (respiration, sugar accumulation, etc.) a 1°C difference during the cooling period will result in little error.

Unfortunately, weight loss data were not available for the Nordreco tests. Any difference in the rate of evaporation at steady state would need to be compensated for by changes in the heat generation rate or flow of sensible heat in the air stream.

On the basis of the Misener and Nordreco test results, the MSU potato storage model is considered to adequately predict the temperature-humidity relationships and time course of change during forced ventilation periods in beds of potatoes.

6. APPLICATIONS OF THE POTATO STORAGE MODEL

A large number of applications of the potato storage model are possible. For example, if accurate rate expressions are available, the model can be used to predict the temperatures, weight loss, rot potential and so forth of a particular lot of potatoes in a particular storage. The model might also be used to study the influence of alternative management strategies or control systems for the same lot of potatoes. When used in conjunction with optimization techniques, the least cost or maximum return on investment design for a storage and its control system can be determined. The likelihood of successful storage relying on ambient air for ventilation can be studied using real or simulated weather data.

This section will apply the model to various combinations of continuous ventilation, time clock control and thermostatic control which might be used during the first month of storage, i.e., during suberization and cool-down. No attempt is made to determine the optimum control sequence, rather simulated results from a number of related but distinctly different systems are compared.

The initial storage period is characterized by high rates of metabolic activity and heat generation induced by harvest injury and the tubers' adjustment to the storage environment.

High rates of weight loss are also typical during the first month of storage. Diffusion of water vapor through wounded areas or unsuberized skin accounts for most of the weight loss.

6.1 Input Conditions

Unfortunately, neither the mechanisms nor kinetics of the increasing resistance to diffusion of water vapor and changing rate of heat generation are understood. Only empirical formulas are available for prediction of heat generation and evaporation rates. None of the empirical formulas previously reviewed are generally applicable. They apply only to the specific situation for which the constants were evaluated. It is therefore necessary to apply the model to hypothetical potatoes.

The evaporation rate equation developed by Villa (1973) for suberized potatoes is the most theoretical yet proposed. Time-temperature dependence can be imposed upon the permeable membrane fraction, γ, and thickness-resistivity, $r\delta$, to produce the expected evaporation rate response during suberization (section 5.3.1). To this end, γ takes the form:

$$\gamma = b_1 + b_2 e^{-K_1 t} \qquad (6.1)$$

where b_1 is the value at infinite time, the sum of b_1 and b_2 is the initial value of γ, and K_1 is the temperature dependent rate constant. The Arrhenius equation is assumed to express the temperature dependence of K_1:

$$\ln K_1 = -\frac{E_1}{R_o T_A} + \ln B_1 \qquad (6.2)$$

where E_1 is the activation energy and B_1 the Arrhenius frequency factor. The rate constant must be known at two specified temperatures in order to evaluate E_1 and B_1.

Villa (1973) found $r\delta$ to be a linear function of VPD, thus $r\delta$ is of the form:

$$r\delta = b_3 + b_4\,\text{VPD} + b_5 e^{-K_2 t} \qquad (6.3)$$

The value at infinite time is given by the first two terms on the right of equation (6.3) while the initial value is the final value plus b_5. The rate constant is assumed to result from the Arrhenius equation:

$$\ln K_2 = -\frac{E_2}{R_o T_A} + \ln B_2 \qquad (6.4)$$

Equations (6.1) through (6.4) predict an exponentially increasing diffusional resistance or decreasing rate of evaporation, the rate of change with time being greater at higher temperatures. The initial lag evident in Figure 5.5 is not predicted by the above equations. A similar cumulative weight loss may be obtained by specifying an initial value of γ which is larger than that actually expected.

Table 6.1 shows the initial and final values of γ and $r\delta$ and values of $\frac{E}{R_o}$ and B used here. The activation energy and Arrhenius frequency factors were evaluated by arbitrarily assuming that the values of γ and $r\delta$ would be 10% different from their final values after 200 and 300 hours at 20° and 15°C, respectively.

Section 5.3.1 implies that b_5 should be less than zero. The response desired here, using educated estimates, requires a positive b_5 and hence decreasing $r\delta$ with increasing time. No physical significance should be attached to this empirical expression.

Figures 6.1 and 6.2 show the influence of velocity on the weight loss rate per unit VPD at various times for constant temperatures of 20° and 10°C, respectively. Figure 5.3 shows similar data from Burton (1966). Burton reported rates of 0.7% and 0.2%/week/mm Hg VPD for freshly harvested (t = 0) and stored (t = 500) potatoes, respectively. As discussed previously, the initial value here is elevated to compensate for the initial lag in suberin synthesis

Table 6.1. Values used to determine the constants in equations (6.1) through (6.4).

	γ	$r\delta$
At t = 0	0.3333	0.02222 m[1]
At t = ∞	0.009	5.64×10^{-3} m[1]
E/R_o, °K	6848.7	4821.9
B, h^{-1}	4.172×10^{8}	2.372×10^{5}

[1]With VPD = 133.33 N/m^2.

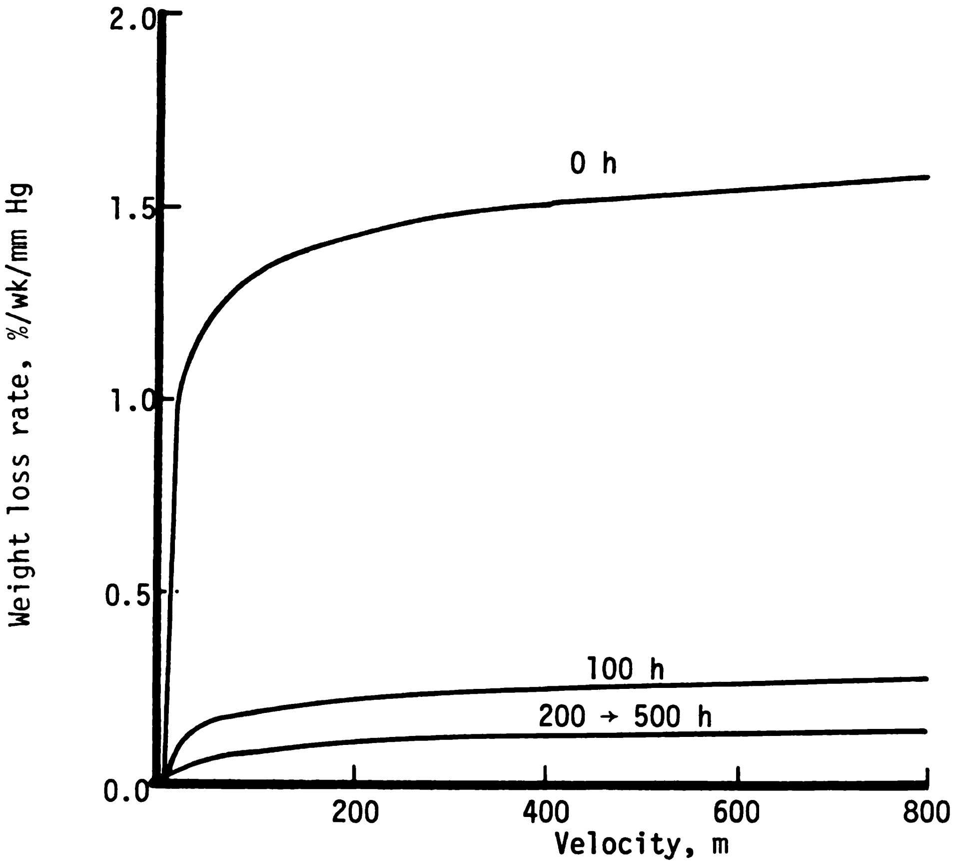


Figure 6.1. Weight loss rate per mm Hg VPD (133.33 N/m^2) versus velocity at 20°C after 0, 100, 200, and 500 hours of suberization.

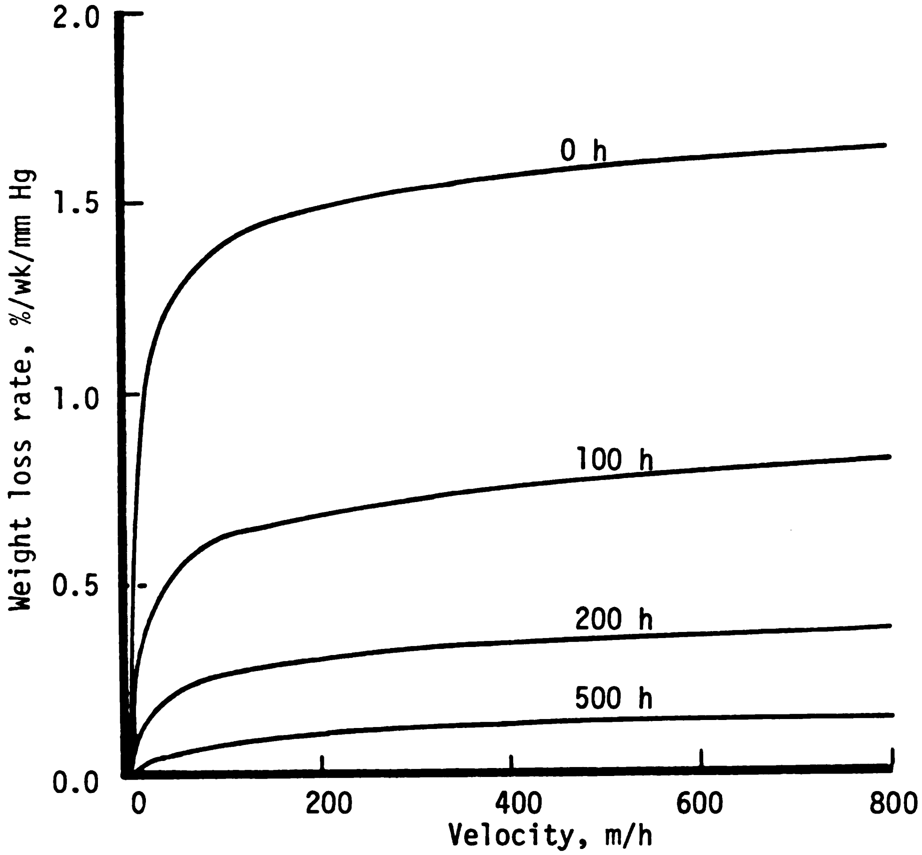


Figure 6.2. Weight loss rate per mm Hg VPD (133.33 N/m^2) versus velocity at 10°C after 0, 100, 200, and 500 hours of suberization.

and periderm formation. The final value of 0.12%/week/mm Hg VPD at 400 m/h approximates that reported by Schippers (1971d).

Figures 6.1 and 6.2 also indicate that temperature has little influence on the initial and final weight loss rates. However, at intermediate times of 100 and 200 hours, the higher temperature shows much lower rates of evaporation. In other words, suberization occurs more rapidly at 20°C and the weight loss rate drops to the final value sooner. Figure 6.3 shows the same effect at temperatures of 10°, 15°, and 20°C.

Figure 6.4 illustrates the influence of VPD or relative humidity on weight loss rate at 15°C with v_a = 150 m/h. For practical purposes, the final weight loss rate is reached at approximately 250 hours regardless of the VPD. Figure 6.5 shows the cumulative weight loss resulting from the rates shown in Figure 6.4.

Figure 6.6 depicts the cumulative weight loss at constant temperatures of 10°, 15°, and 20°C with a velocity of 425 m/h and 133.33 N/m^2 VPD (1 mm Hg). The dashed line segments indicate the final steady rate of loss when suberization is complete. The point of intersection approximates the time when suberization is complete. Figure 6.6 indicates much less cumulative weight loss at 20°C than at 10°C due to the faster rate of healing.

Equations (6.1) and (6.3) are for constant temperatures and cannot be applied directly to the model. If the rate constants are found for a specific temperature, the resulting values of γ and $r\delta$ from equations (6.1) and (6.3), respectively, for any value of

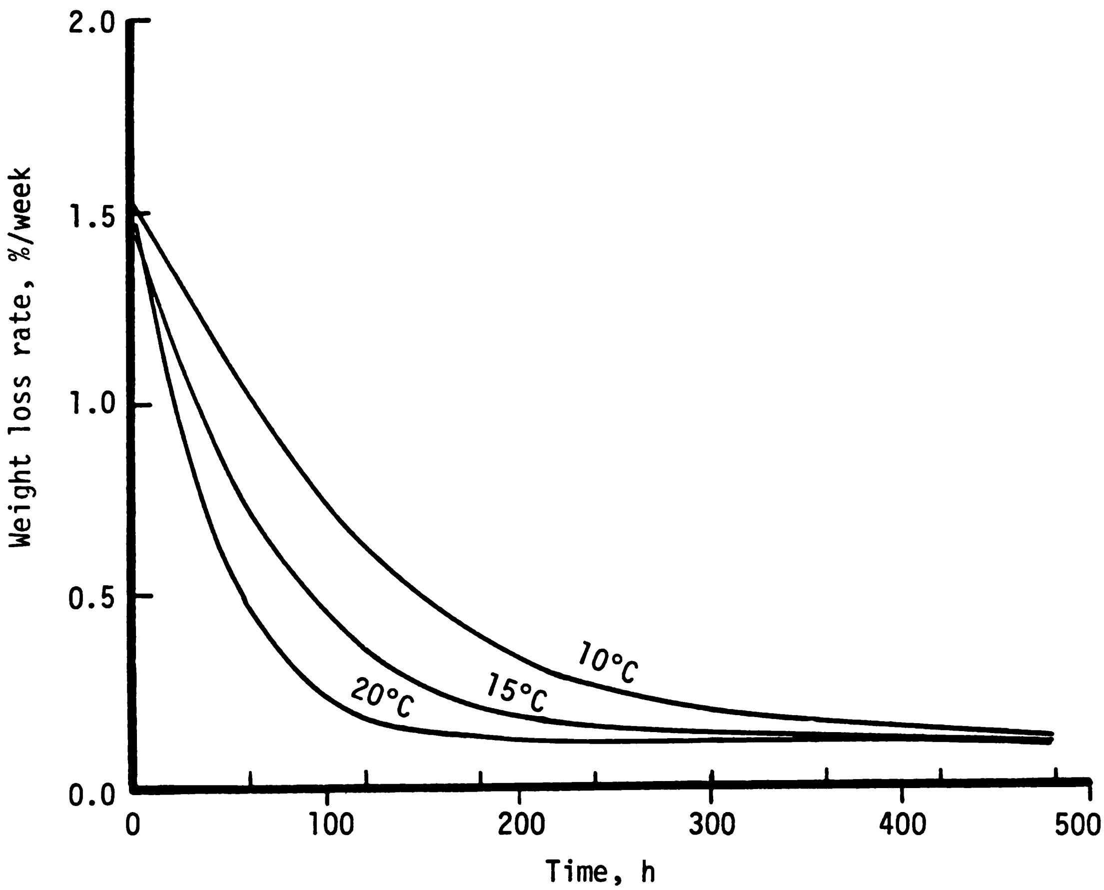


Figure 6.3. Rate of evaporative weight loss at three temperatures, 133.33 N/m^2 VPD, and v_a = 425 m/h.

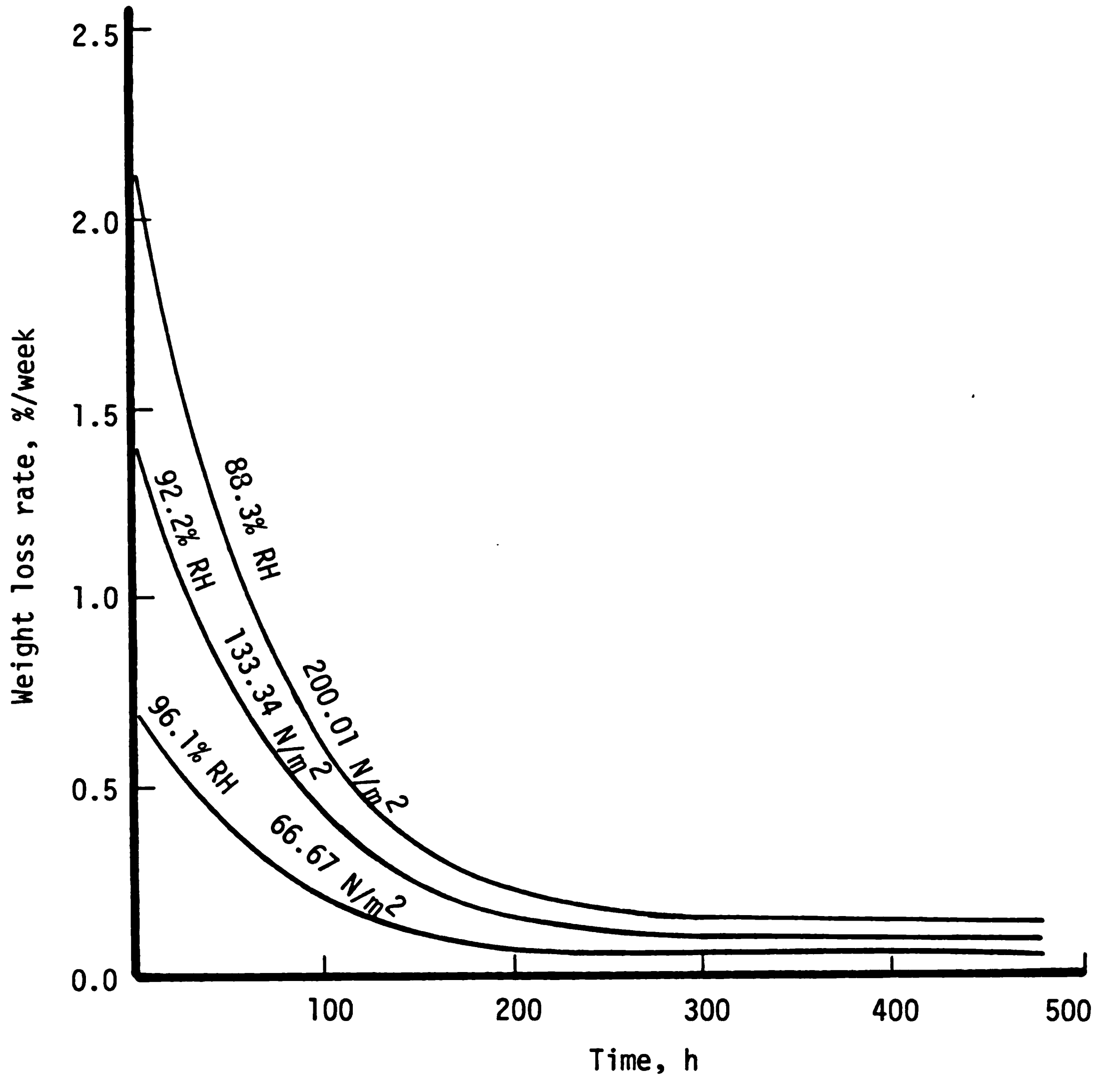


Figure 6.4. Rate of evaporative weight loss at three VPD (relative humidities), 15°C and v_a = 150 m/h.

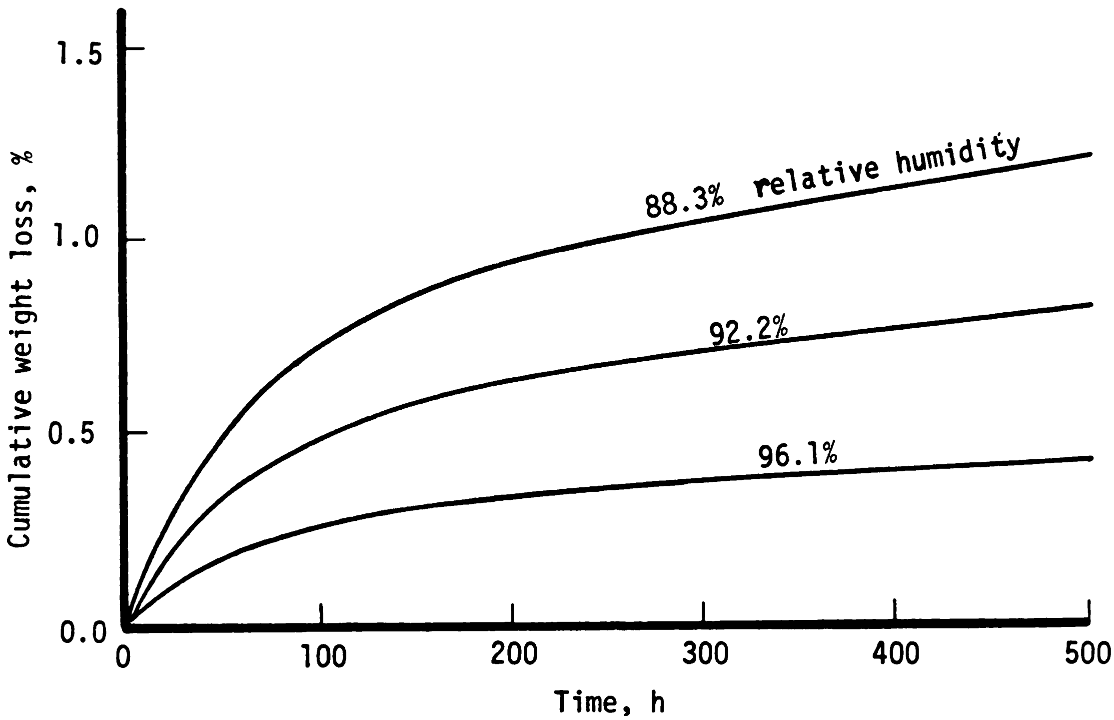


Figure 6.5. Cumulative weight loss at 88.3%, 92.2%, and 96.1% relative humidity at 15°C with v_a = 150 m/h.

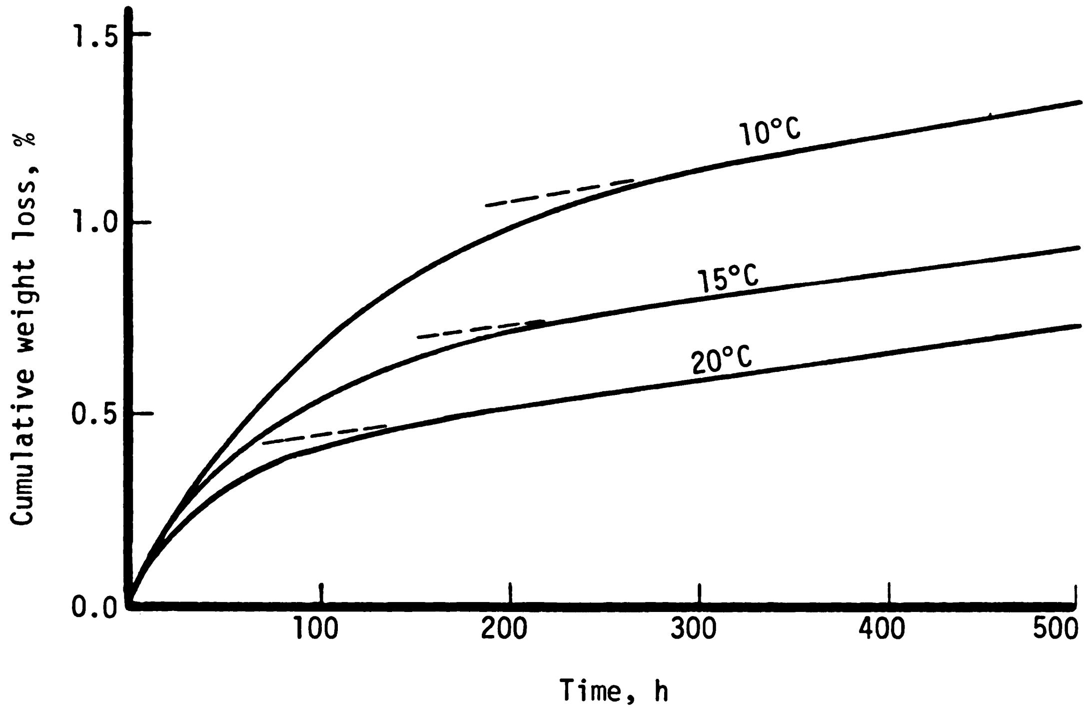


Figure 6.6. Cumulative weight loss at 10°, 15°, and 20°C, 133.33 N/m^2 VPD, and v_a = 425 m/h.

time, t, are valid only if the potatoes are maintained at the specified temperature for the entire time. During the initial storage periods, the temperature at any location within the storage is constantly changing. If the fans are off, the temperature increases due to heat generation. If the fans are on, the net result of variation in evaporation rate and heat generation rate with time is either heating or cooling. A steady state is not possible.

If the current values of γ, $r\delta$, and temperature are known at some point within the storage, equations (6.1) and (6.3) can be solved for the equivalent time, i.e., that time which would result in the same skin parameter values if the temperature had been constant. The time interval of the numerical integration, Δt, is added to the equivalent time and new values of γ and $r\delta$ are determined using equations (6.1) and (6.3). This process is repeated at each level in the bed for each time during the solution. The values of γ and $r\delta$ at each depth node must be maintained in arrays.

The change in heat generation rate with time and temperature is handled in a similar manner. Earlier, heat generation rate was approximated by a linear function of temperature [equation (5.30)]. During the early period of storage, heat generation rate is assumed to follow the form:

$$Q = b_6 T + b_7 + b_8 e^{-K_3 t} \qquad (6.5)$$

For large times, equation (6.5) reduces to the same linear form with the intercept given by the sum of b_7 and b_8. For short times the last term on the right of equation (6.5) increases the rate as a function of both time and temperature (K_3). An Arrhenius relationship identical to equations (6.2) and (6.4) is assumed for K_3; E_3/R_0 was taken as 6852 °K with $B_3 = 3.049 \times 10^8$ h^{-1}. These values result in a rate of change for respiration similar to that specified for weight loss rate. Both b_6 and b_7 were set equal to 4.0 with b_8 equal to 30.0 for the following simulations.

Figure 6.7 shows the variation of heat generation rate with time at constant temperatures of 10°, 15° and 20°C. At short times, a change of temperature results in a smaller change in Q than the same temperature change at longer times. The range of values predicted by equation (6.5) with the above constants is well within the range reported in the literature (Figure 5.6). The rate of change with respect to time or, specifically, the Arrhenius equation and value of E_3, was arbitrarily chosen.

Equation (6.5) must also use an equivalent time solution when applied to the model.

With the exception of γ and $r\delta$, properties listed in Table 5.5 are applied to describe the potatoes in the simulations. In addition, a pile height of 4 m, uniform initial tuber temperature of 17°C, and airflow of either 20 $m^3/h/m^3$ (188 m/h), 45 $m^3/h/m^3$ (423 m/h), or 70 $m^3/h/m^3$ (657 m/h) are chosen. In all cases the target temperature for storage is 7°C. During cooling, a constant 2°C differential is maintained between the temperature of the inlet air and the temperature of the top layer of tubers. The inlet air

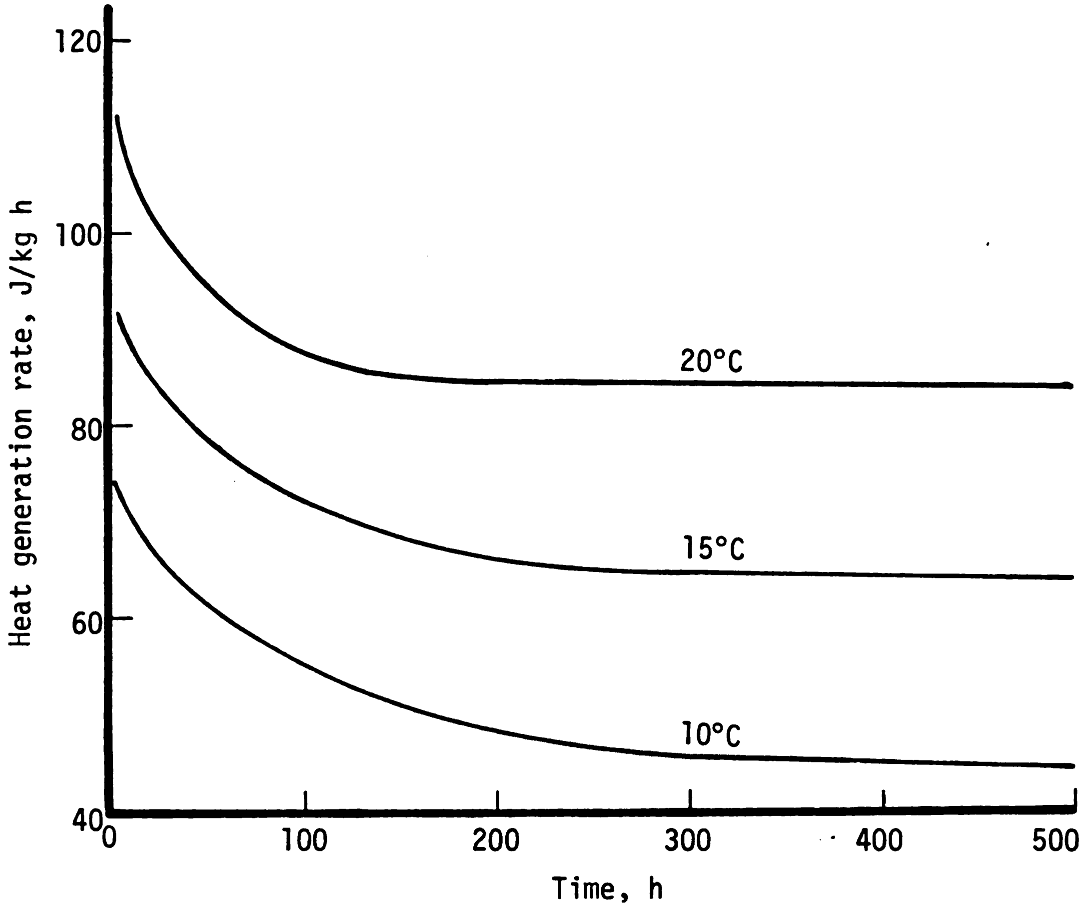


Figure 6.7. Variation of heat generation rate with time at temperatures of 10°, 15°, and 20°C.

temperature never goes below 7°C. Inlet relative humidity is constant at 96%. It is assumed that the ventilation system is capable of providing air at such conditions on demand.

6.2 Continuous Ventilation

Figures 6.8, 6.9, and 6.10 show the potato temperature at the top and bottom of the 4 m bed during the first 500 h (20.83 days) of storage under conditions of immediate cooling with ventilation rates of 20, 45, and 70 $m^3/h/m^3$, respectively. Only the low airflow, Figure 6.8, shows an initial temperature increase at the top due to respiration. Cooling is arbitrarily assumed to be complete when the temperature gradient across the pile is 0.5°C or less. Thus, cooling takes approximately 320, 110, and 60 hours for the low, medium, and high ventilation rates, respectively.

Figure 6.11 shows the cumulative weight loss for the entire bed which results from immediate cooling and continued ventilation at the three ventilation rates. The higher the rate of ventilation, the greater the weight loss at any particular time. However, Figure 6.11 indicates that less weight is lost during the cooling operation with higher airflow. Even though the rate of loss is higher, the rate of cooling is also faster resulting in less loss during the cooling operation. Continued ventilation after cooling results in continued high loss rates as shown by the slope of the curves on the right side of Figure 6.11.

The shape of the curves in Figure 6.11 is similar for the higher ventilation rates of 45 and 70 $m^3/h/m^3$. The difference

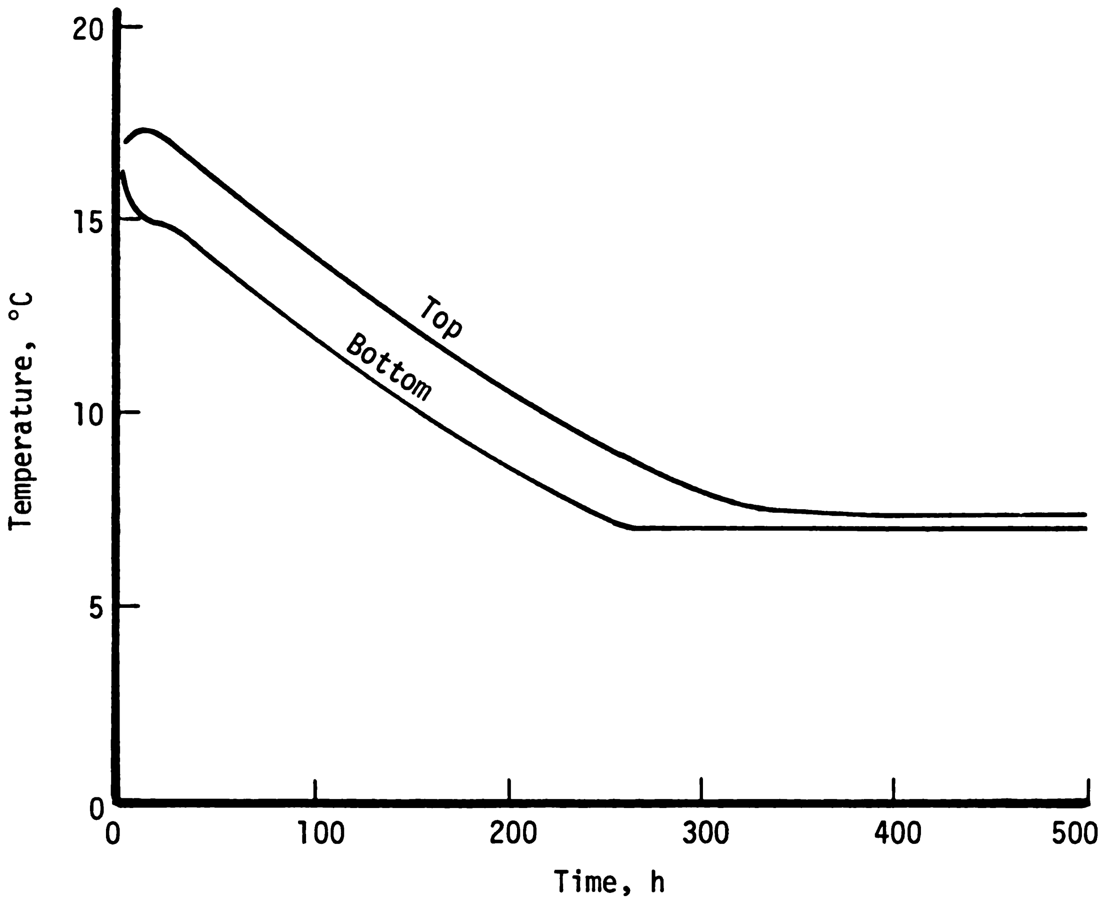
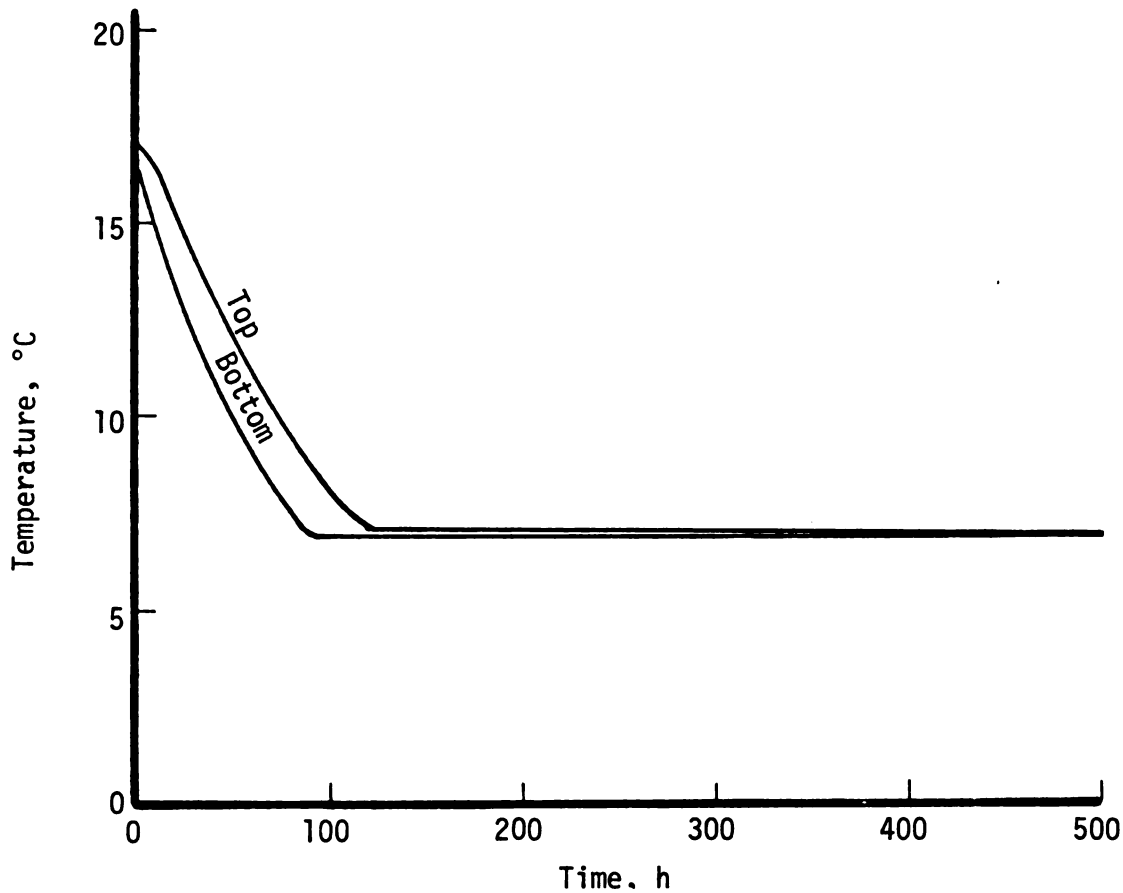


Figure 6.8. Top and bottom potato temperatures in a 4m bed ventilated continuously during suberization with 20 m^3 of air/h/m^3 of potatoes.



Fiqure 6.9. Top and bottom potato temperatures in a 4 m bed ventilated continuously during suberization with 45 m^3 of air/h/m^3 of potatoes.

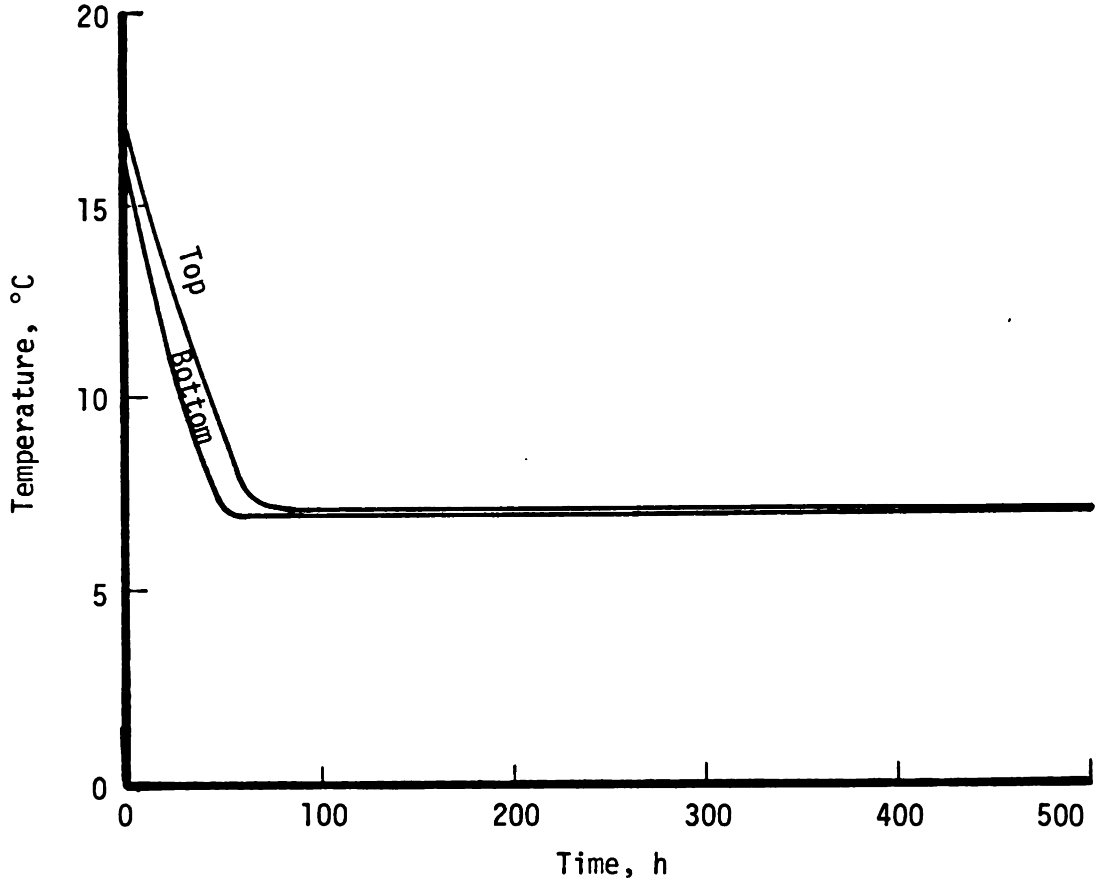


Figure 6.10. Top and bottom potato temperatures in a 4 m bed ventilated continuously during suberization with 70 m^3 of air/h/m^3 of potatoes.

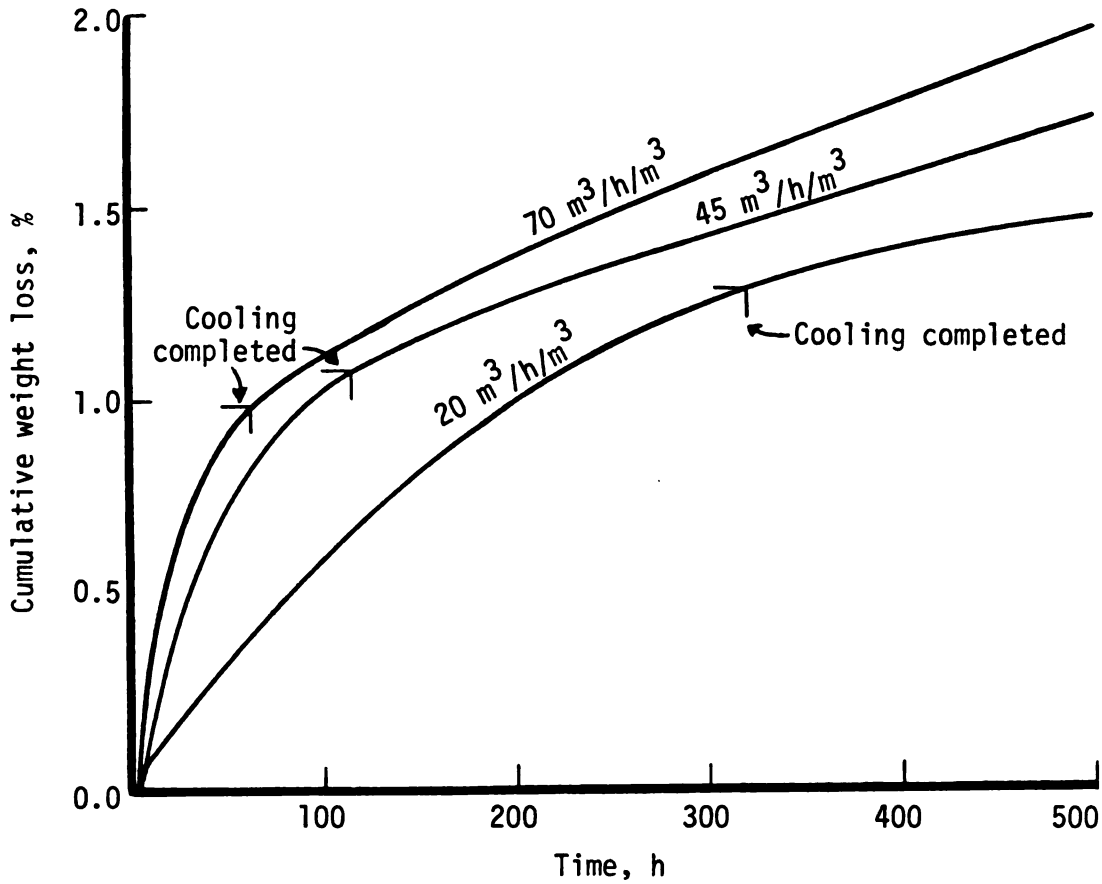


Figure 6.11. Cumulative weight loss during the initial 500 h of storage of a 4 m bed with immediate cooling and continuous ventilation at three rates.

results from the fact that the low rate results in an interstitial velocity of 188 m/h which is initially near the "critical" velocity (Figures 6.1 and 6.2). In other words, during the first few hours, weight loss is controlled by the quantity of air and convective resistance rather than by the skin parameters. The longer time at higher temperatures and hence higher heat generation also contribute to the difference in shape.

For all ventilation rates with immediate cooling, weight loss is more severe at the bottom of the pile than at the top. Table 6.2 lists the weight loss at the top and bottom of the bed for the three ventilation rates at various times. For all practical purposes, the weight loss at the top is identical regardless of airflow at any time after cooling has been completed. The weight loss at the bottom is on the order of 1.8% at the end of cooling irrespective of the time at which it occurs. Hence, the higher the airflow, the greater the weight loss gradient through the bed.

Table 6.2. Percent weight loss at the bottom and top of a 4 m bed which is cooled immediately at three ventilation rates. The arrows indicate when cooling was completed.

Time, h	$20\ m^3/h/m^3$		$45\ m^3/h/m^3$		$70\ m^3/h/m^3$	
	Bottom	Top	Bottom	Top	Bottom	Top
50	0.86	0.24	1.2	0.54	1.5	0.78 ←
100	1.2	0.50	1.7	0.94 ←	2.1	0.98
200	1.6	0.91	2.2	1.1	2.8	1.1
300	1.8	1.2 ←	2.6	1.2	3.3	1.2
400	2.0	1.3	2.8	1.3	3.6	1.3

Temperatures at the top and bottom of the 4 m pile with delayed cooling but with continuous ventilation of 20 $m^3/h/m^3$ are shown in Figure 6.12. The inlet air temperature is held at 17°C for the first 120 h after which time cooling begins. Figures 6.3 and 6.7 indicate that the time dependency of weight loss and heat generation rate is well advanced after 120 h at 17°C. Figures 6.13 and 6.14 show the temperature response when ventilation is delayed for 48 and 96 h, respectively, followed by cooling with 20 $m^3/h/m^3$. The increase in temperature which results from the high initial heat generation rate requires a longer cooling time. Whereas immediate cooling required 230 h, delaying cooling for 120 h with continuous ventilation required over 340 additional hours to complete cooling. Delaying ventilation for 48 and 96 h required 370 and 415 hours of cooling, respectively.

Cumulative weight loss resulting from immediate cooling, delayed cooling with continuous ventilation and delayed ventilation and cooling are shown in Figure 6.15. The times at which cooling was completed are also indicated. Ventilation without cooling produces less weight loss during the first 120 h than does immediate cooling. However, the final loss at the end of cooling is higher when cooling is delayed. The loss during actual cooling (from 120 h to 460 h) is less than that which occurred with immediate cooling (320 h) even though over 20 more hours were required. Delaying ventilation for 48 or 96 h yielded greater weight loss than immediate cooling due to the longer cooling time involved.

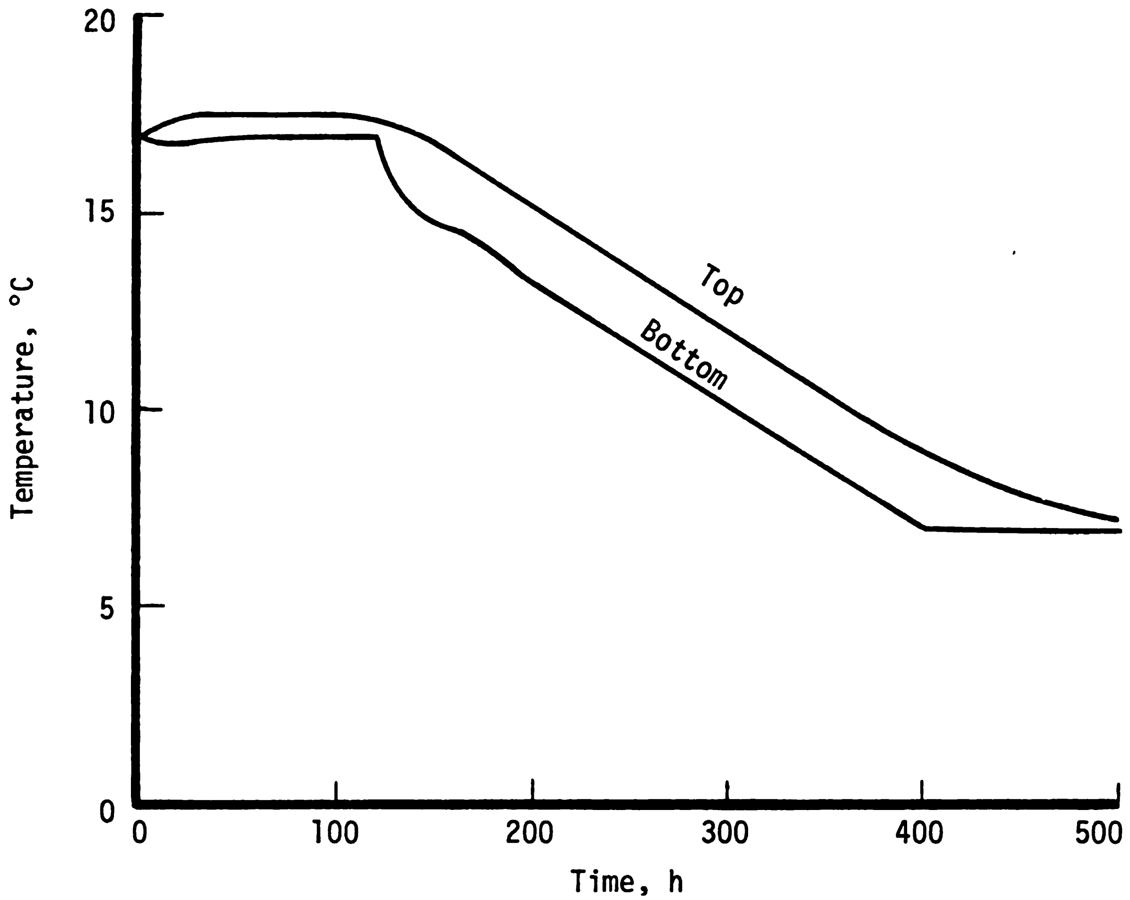


Figure 6.12. Top and bottom potato temperatures during suberization of a 4 m bed with continuous ventilation at 20 m^3 of air/h/m^3 of potatoes. Cooling begins at 120 h.

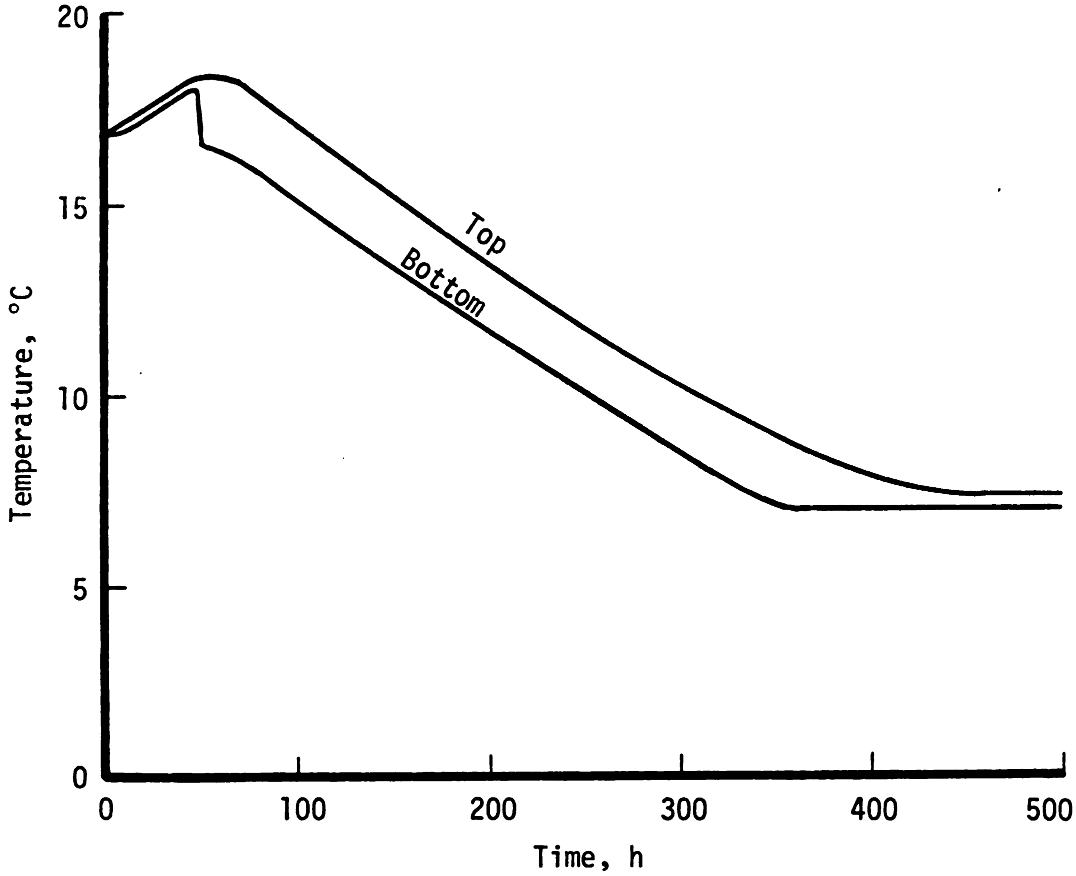


Figure 6.13. Top and bottom potato temperatures during suberization of a 4 m bed with no ventilation for 48 h followed by cooling with continuous ventilation at 20 m^3 of air/h/m^3 of potatoes.

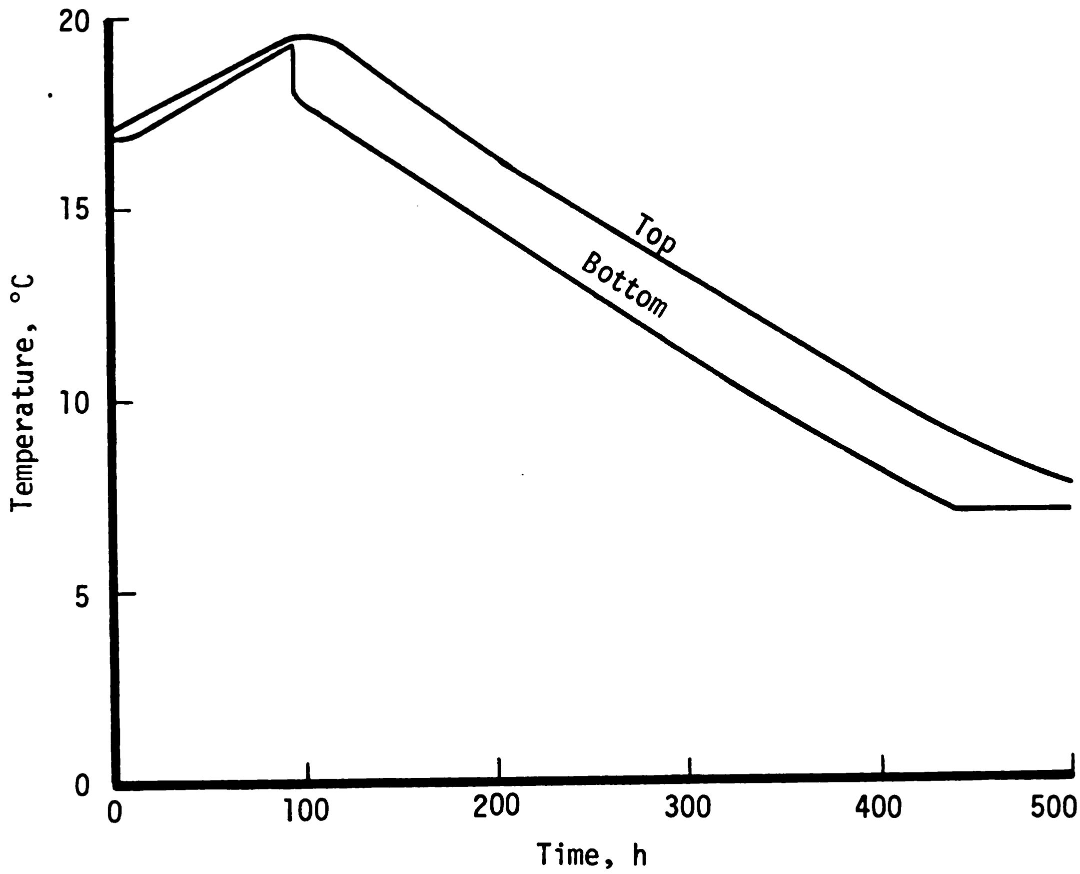


Figure 6.14. Top and bottom potato temperatures during suberization of a 4 m bed with no ventilation for 96 h followed by cooling with continuous ventilation at 20 m^3 of air/h/m^3 of potatoes.

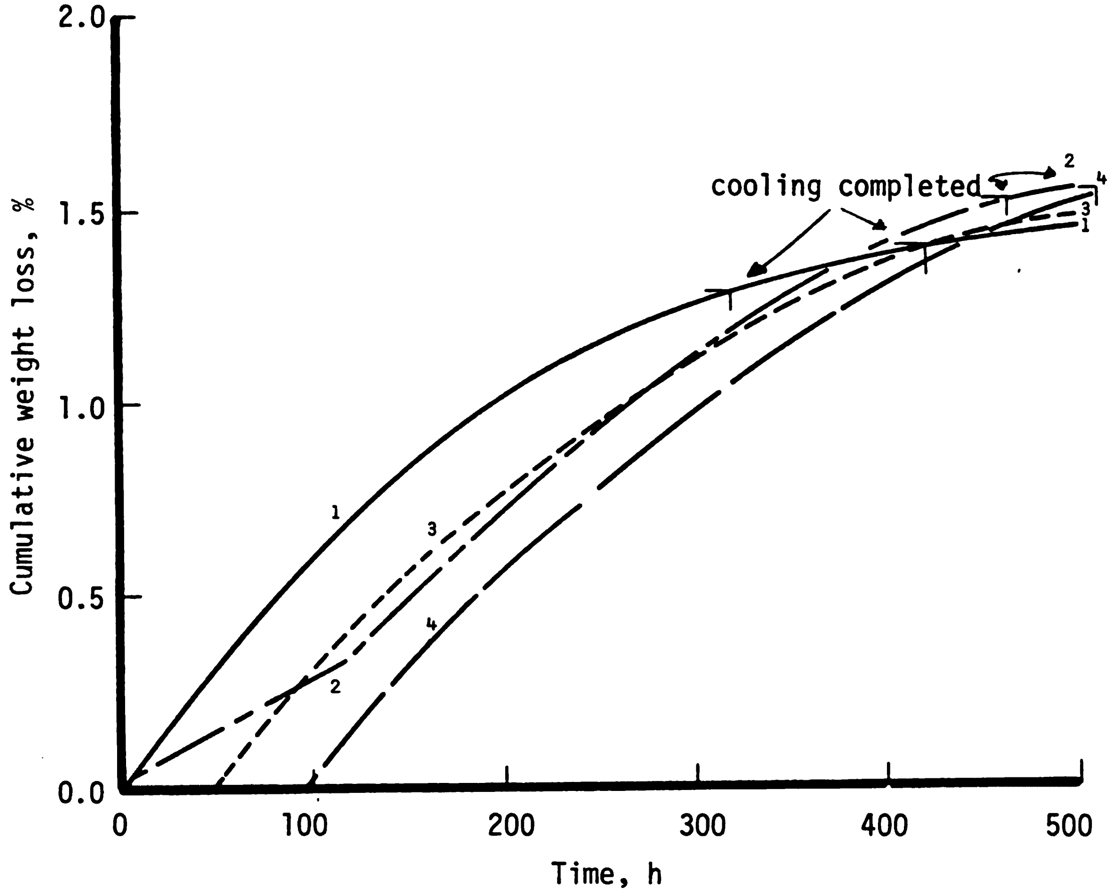


Figure 6.15. Cumulative weight loss during the initial 500 h of storage of a 4 m bed with 20 m^3 of air/h/m^3 of potatoes with (1) continuous ventilation, (2) continuous ventilation with cooling beginning at 120 h, (3) ventilation delayed for 48 h, and (4) ventilation delayed for 96 h.

Table 6.3 indicates that delayed cooling with continuous ventilation caused weight loss gradients across the bed similar to gradients from immediate cooling. The weight loss at the bottom when cooling is completed and at the top after cooling are both higher than the values found in Table 6.2.

When ventilation is delayed, a reversal of the weight loss gradient occurred during subsequent cooling (Table 6.3). If cooling or ventilation starts immediately and a 2°C temperature gradient is maintained, the rapid rate of evaporation resulted in a lower VPD at the top of the bed than at the bottom. Hence, less weight is lost from the top of the bed than from the bottom. If ventilation is delayed, the rate of evaporation is smaller giving rise to larger VPD at the top thus reversing the gradient so that more weight is lost from the top. The maximum weight loss may actually occur in

Table 6.3. Percent weight loss at the bottom and top of a 4 m bed in which cooling and/or ventilation is delayed.

Time, h	Cooling Delayed 120 h		Ventilation Delayed 48 h		Ventilation Delayed 96 h	
	Bottom	Top	Bottom	Top	Bottom	Top
48	0.93	0.086	0.014	0.0002	0.014	0.0002
96	1.3	0.20	0.36	0.23	0.014	0.0003
192	1.7	0.61	0.70	0.70	0.38	0.49
336	2.0	1.1	1.0	1.2	0.77	1.1
480	2.3	1.5	1.3	1.5	1.1	1.6

the middle of the pile, being related to the active heat transfer zone for step changes in temperature.

Figure 6.16 illustrates the cumulative weight loss associated with immediate cooling and delayed ventilation for the high flow rate of 70 $m^3/h/m^3$. The times at which cooling was completed are also indicated. Immediate cooling required just over 60 hours while 80 and 110 hours were required to complete cooling after delays of 48 and 96 hours, respectively. This is consistent with the findings using 20 m^3 of air/h/m^3 of potatoes. However, the cumulative weight loss at the high ventilation rate is less at the end of cooling when ventilation has been delayed than it is for immediate cooling, as indicated by Figure 6.16. This is opposed to the results shown in Figure 6.15 for the low ventilation rate. In spite of the heat generated during the delay and increased cooling time, weight loss decreases due to the increase in diffusional resistance which occurs during the delay.

With ventilation at 70 $m^3/h/m^3$ the weight loss continues to be greater for immediate cooling than for delayed cooling, i.e., the curves in Figure 6.16 do not intersect as those in Figure 6.15 for low ventilation do.

Table 6.4 lists the weight loss at the bottom and top for delayed cooling with 70 $m^3/h/m^3$ at various times. The 48 h delay yields a gradient similar to immediate cooling with much more weight lost at the bottom than the top. The 96 h delay shows more uniform losses throughout the bed at 480 h. However, if ventilation

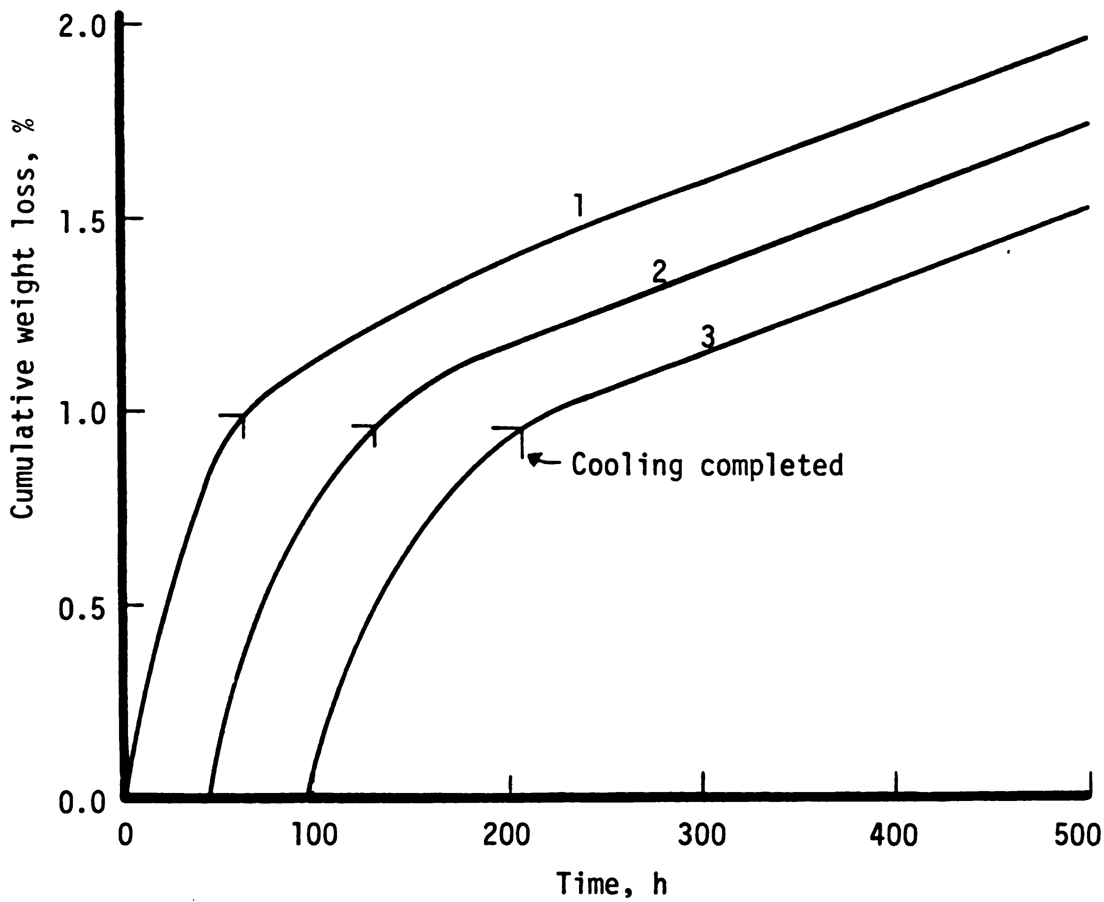


Figure 6.16. Cumulative weight loss during the initial 500 h of storage of a 4 m bed with 70 m^3 of air/h/m^3 of potatoes with (1) continuous ventilation, (2) ventilation delayed for 48 h, and (3) ventilation delayed for 96 h.

Table 6.4. Percent weight loss at the bottom and top of a 4 m bed in which ventilation is delayed.

Time, h	Ventilation Delayed 48 h		Ventilation Delayed 96 h	
	Bottom	Top	Bottom	Top
48	0.014	0.0002	0.014	0.0002
96	0.59	0.72	0.014	0.0003
192	1.1	1.1	0.49	1.1
336	1.5	1.3	0.91	1.3
480	1.9	1.5	1.3	1.5

were continued it appears as if the gradient would reverse giving greater loss at the air inlet.

Table 6.5 summarizes the results of cooling time and weight loss at the end of cooling and at 500 hours for the treatments considered.

The minimum weight loss at the completion of cooling occurred at the high ventilation rate when ventilation was delayed. The minimum weight loss at 500 hours occurred with continuous ventilation at the low rate with immediate cooling.

6.3 Time Clock Control

Potato storage ventilation is frequently controlled by time clocks. Two such control systems are considered here for control during the first 720 h (30 days) of storage. First, a 16 h off-8 h on schedule is applied at ventilation rates of 20 and 70

Table 6.5. Summary of results using immediate and delayed continuous ventilation.

Treatment	Ventilation Rate $m^3/h/m^3$	Cooling Time, h	Weight Lost, % During Cooling	Weight Loss, % at 500 h
Immediate cooling	20	320	1.28	1.47
Delayed cooling (120 h)/ continuous ventilation	20	340	1.52	1.56
Ventilation delayed 48 h	20	370	1.40	1.48
Ventilation delayed 96 h	20	415	1.55	1.53
Immediate cooling	45	110	1.08	1.58
Immediate cooling	70	60	0.99	1.95
Ventilation delayed 48 h	70	80	0.96	1.73
Ventilation delayed 96 h	70	110	0.96	1.52

$m^3/h/m^3$ with inlet air temperature 2°C less than the top potato layer temperature. After 336 h (14 days) the fan is run continuously until the bed is cooled. The 16 h off-8 h on schedule is then resumed. Second, the inlet air temperature is maintained at 17°C during the initial 336 h period under time clock control, followed by continuous cooling and then time clock holding at 7°C (16 h off-8 h on).

Table 6.6 lists the top and bottom temperatures at 48 h intervals (every second time that the fan is turned off) for the two treatments. At 20 $m^3/h/m^3$ the pile temperature is barely maintained during the first 336 h of storage. The heat (sensible and latent) removed during the 8 h fan on periods is nearly equal to the heat generated during a 24 h period. At 70 $m^3/h/m^3$, additional heat is removed by the higher volume of air during the forced ventilation period and the bed begins to cool. In fact, cooling was completed before 336 h elapsed so that the ventilation continues to cycle on the 16 h off-8 h on program. The second treatment with inlet air temperature held at 17°C and 70 $m^3/h/m^3$ is comparable to the first treatment with 20 $m^3/h/m^3$ in that the bed temperature is maintained near the initial value until 336 h, at which time continuous fan operation is initiated until cooling is complete.

Figure 6.17 shows the cumulative weight loss which results from the time clock controls. Delayed cooling using the low ventilation rate results in low weight loss during the first 336 h but a long cooling time and high weight loss later. At the high rate

Table 6.6. Bottom and top potato temperatures every second time that the fan is turned off during time clock controlled storage.

Time, h	20 $m^3/h/m^3$, $T_i = \Theta_n - 2°C$		70 $m^3/h/m^3$, $T_i = \Theta_n - 2°C$		70 $m^3/h/m^3$, $T_i = 17\ °C$	
	Bottom	Top	Bottom	Top	Bottom	Top
0	17.0	17.0	17.0	17.0	17.0	17.0
48	16.0	18.1	13.6	15.5	16.9	17.2
96	16.2	18.2	11.7	13.6	17.0	17.2
144	16.3	18.2	10.1	12.0	17.0	17.3
192	16.3	18.3	8.7	10.6	17.0	17.4
240	16.4	18.4	7.4	9.3	17.0	17.4
288	16.5	18.5	7.0	8.1	17.0	17.4
336	16.6	18.5	7.0	7.4	17.0	17.4
Continuous ventilation until cooling is completed						
384	15.8	17.7	7.0	7.3	10.4	12.3
432	14.1	16.0	7.0	7.3	7.0	8.0
480	12.5	14.4	7.0	7.3	7.0	7.5
528	11.0	12.9	7.0	7.2	7.0	7.4
576	9.5	11.4	7.0	7.2	7.0	7.4
624	8.0	9.9	7.0	7.2	7.0	7.3
672	7.0	8.5	7.0	7.2	7.0	7.3
720	7.0	8.0	7.0	7.2	7.0	7.2

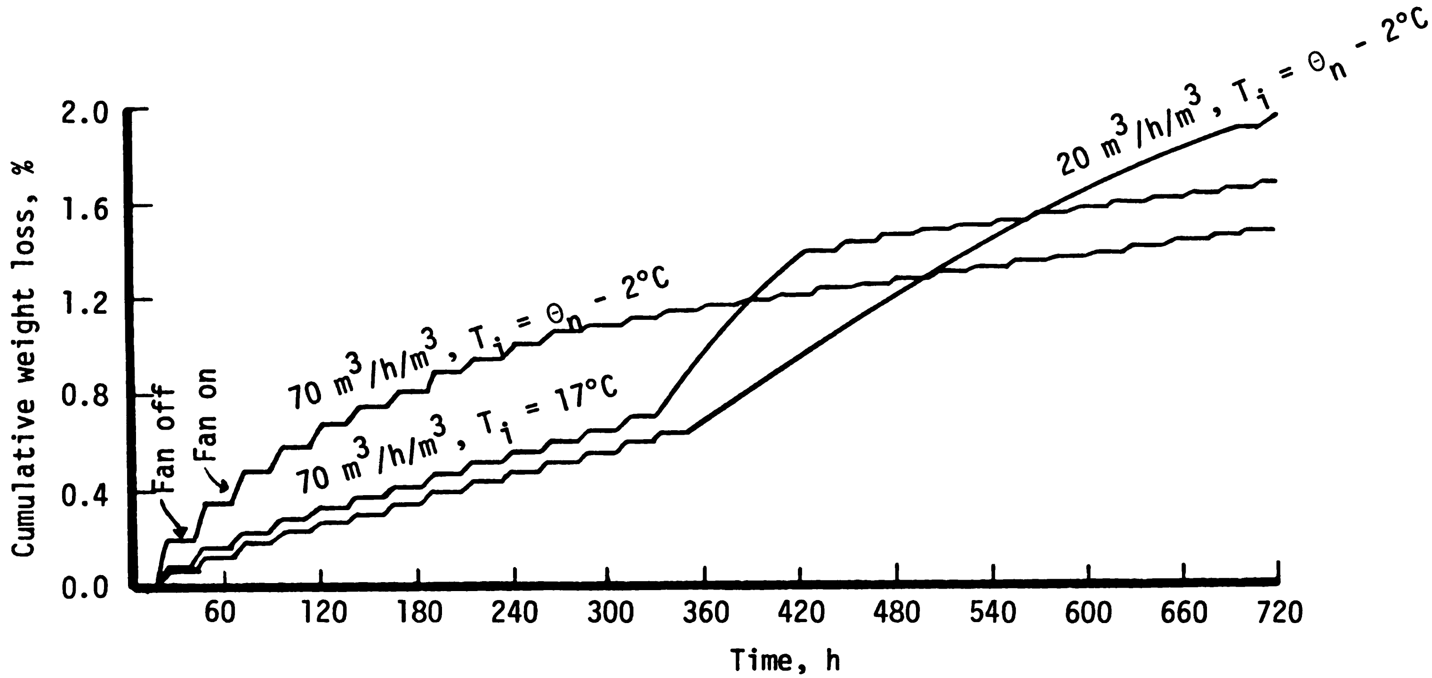


Figure 6.17. Weight loss using time clock controls (see text for details).

of ventilation, maintaining the tuber temperature near the initial value results in less weight loss than the treatment which cools the bed during the first 336 h. However, subsequent cooling causes sufficient weight loss to make faster cooling look favorable. If the 336 h period were shorter, maintaining the temperature at 17°C might prove more favorable.

The rate of weight loss at the low ventilation rate will be smaller than that of the high ventilation rates after cooling is complete; i.e., after 720 h. This will result in an intersection of the 20 $m^3/h/m^3$ curve with each of the 70 $m^3/h/m^3$ curves. Thus, at very long times the low ventilation rate will result in less weight loss.

The three time clock controls considered all result in more weight loss from the top of the pile than from the bottom.

The change in the slope of the weight loss curves in Figure 6.17 during the fan-on periods from left to right shows the progress of suberization and wound periderm formation. Each fan-on interval is 8 h long except during cooling after 336 h.

6.4 Thermostatic Control

One way to avoid too much ventilation is to use a thermostat at the top layer of potatoes (or warmest spot) to control the fan. For example, using a thermostat with a 1°C differential between cut-in and cut-out, the thermostat could be set to start the fan whenever the temperature rises to 18.5°C and stop the fan when the temperature is lowered to 17.5°C. As before, the inlet air temperature would be adjusted to 2°C below the temperature at the warmest spot. The pile could thus be maintained at a temperature which encourages rapid suberization and wound periderm formation without over ventilation resulting in unnecessary weight loss. To initiate cooling, the fan thermostat could be reset to cycle between 8° and 9°C.

Figure 6.18 shows the weight loss resulting from three variations on the above control system for a ventilation rate of 20 $m^3/h/m^3$. First, cooling was begun immediately and the fan thermostat does not begin cycling until the top of the bed reaches 8°C. Second, all ventilation was delayed for 84 h (3.5 days) at which time cooling was begun as above. Third, the fan thermostat was set at 18.5° to 17.5°C for 336 h (14 days) and then reset for 9° to 8°C.

Relatively large differences in weight loss are shown in Figure 6.18, particularly toward the left side or early times. As each control system completes cooling, the curves tend to converge. Since identical controls are applied after cooling, the curves will diverge at greater times only if (1) different steady state values of the skin parameters and heat generation rate exist, or (2) large differences in physical or thermal properties have resulted from the various controls. The first of these is a mathematical impossibility assuming correct computer programming. For immediate cooling, weight loss is 2.0% at the bottom and uniform at 1.5% from

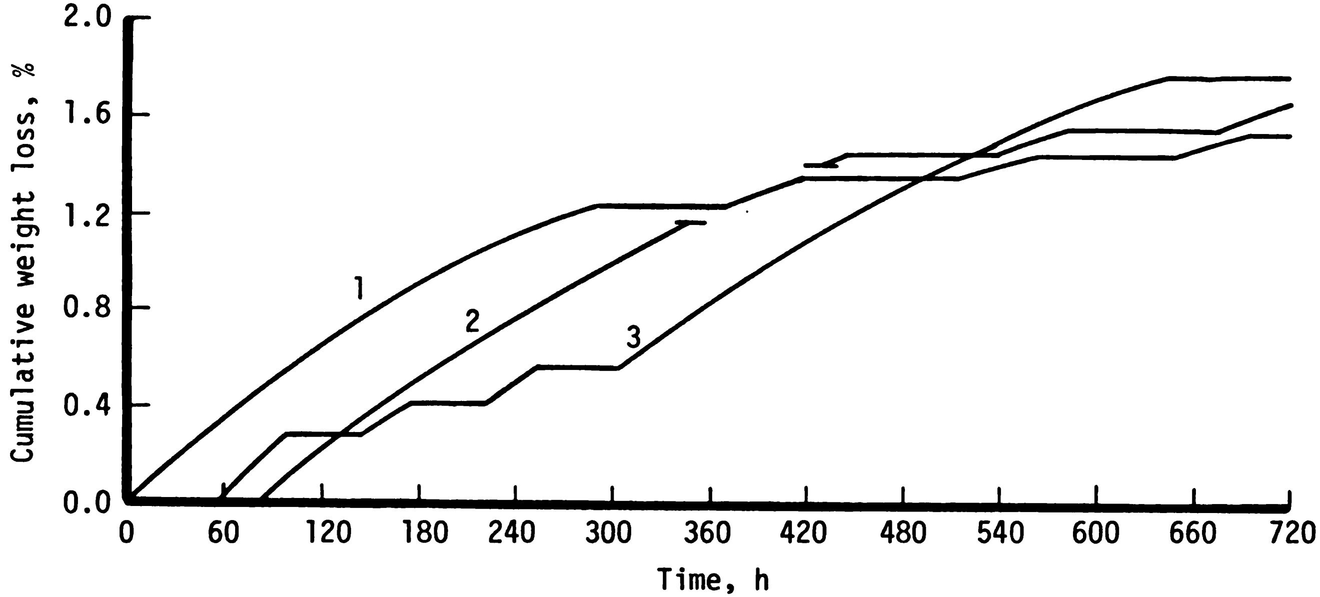


Figure 6.18. Cumulative weight loss of a 4 m bed ventilated with 20 m^3 of air/h/m^3 of potatoes thermostatically controlled to (1) cool immediately, (2) delay ventilation for 84 h, and (3) maintain at 17°C for 336 h before cooling.

0.4 m to the top after 720 h. Delaying ventilation for 84 h results in a distribution from 1.2% weight loss at the bottom to 1.8% at the top with an average of 1.66% at 720 h. Maintaining the temperature at 17°C for 336 h yields a similar distribution from 1.3% weight loss at the bottom to 1.9% at the top with an average of 1.79% at 720 h. Thus, it seems likely that at least the latter two control systems will result in approximately equal weight loss at times greater and 720 h.

Figure 6.19 shows the cumulative weight loss for the bed ventilated at 70 $m^3/h/m^3$ for immediate cooling and delayed cooling using the same thermostatic controls as above. In this case, convergence is more evident than for the previous figure. Weight loss ranged from 1.9% at the bottom to 1.4% from 0.4 m to the top for immediate cooling and from 0.77% at the bottom to 1.7% at the top with an average of 1.4% for delayed cooling.

6.5 Comparison of Control Systems

The control systems considered here are by no means comprehensive. Many additional variations or combinations of continuous, time clock, or thermostatic control are possible along with systems using more than one ventilation rate. No attempt has been made to determine the optimum control system for the potatoes described by equations (6.1) through (6.5). However, the systems simulated do span the range from continuous ventilation at three airflow rates to precise thermostatic control of the bulk temperature using minimum ventilation at two airflow rates.

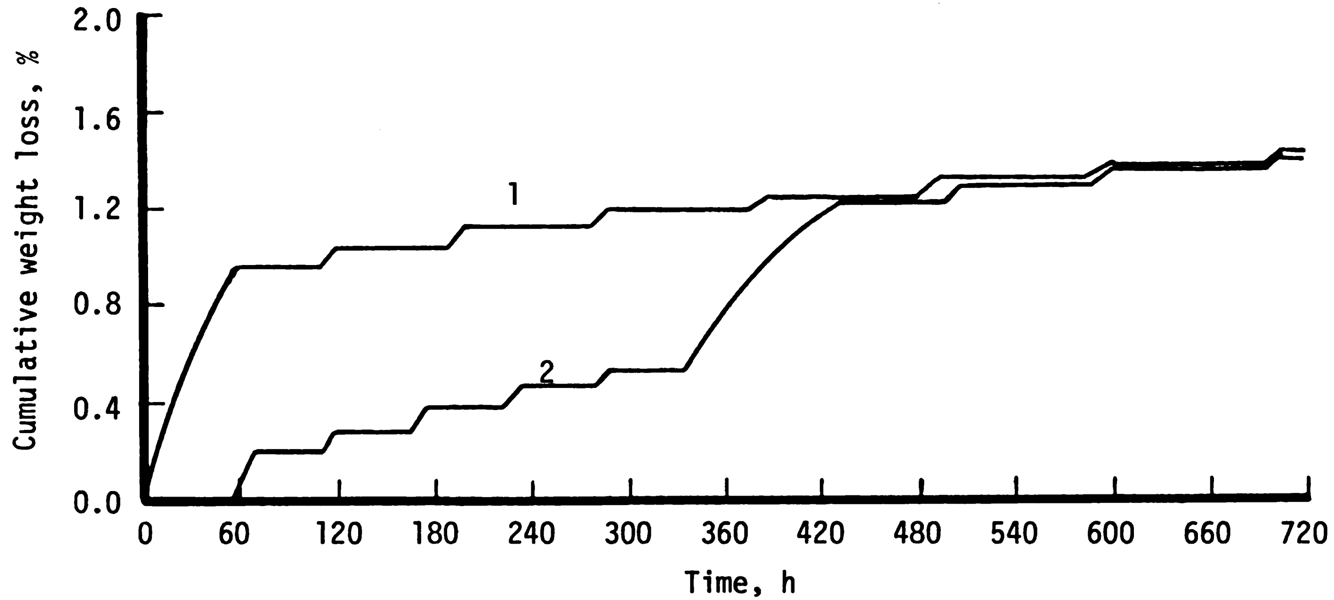


Figure 6.19. Cumulative weight loss of a 4 m bed ventilated with 70 m^3 of air/h/m^3 of potatoes thermostatically controlled to (1) cool immediately and (2) maintain at 17°C for 336 h before cooling.

It is apparent that continuous ventilation should be avoided. This result is expected since periods of no ventilation result in very little weight loss. Hence, ventilation which is not required for temperature control results in unnecessary weight losses.

Continuous ventilation at rates below the "critical" velocity do not result in as much excessive weight loss at higher air velocities but these low airflow rates are not adequate to maintain the required bed temperature. This is due to the fact that the amount of heat generated is greater than the heat removed, resulting in a continued temperature rise. Immature or severely injured tubers lose water readily and generate correspondingly greater amounts of heat. Even though the critical ventilation rate decreases with time in storage (Figures 5.3, 6.1, and 6.2), ventilation rates below the critical level are likely to permit a net temperature rise regardless of the degree of maturity or suberization.

It is evident that immediate cooling should be avoided. All treatments involving immediate cooling with constant ventilation show large weight losses at the bottom of the pile. Severe dehydration of the bottom layers may result in serious losses due to pressure bruising.

Time clock control has the possibility of providing either insufficient or excessive ventilation depending upon the ventilation rate and degree of suberization. Ventilation at 20 $m^3/h/m^3$

with a 16 h off-8 h on schedule and inlet temperature 2°C below the top tuber temperature, resulted in a slight temperature increase during the initial 336 h of storage. In other words, ventilation was insufficient. When the same controls were applied at 70 $m^3/h/m^3$, the pile cooled to 7°C during approximately the same time period.

When cooling was permitted to begin immediately using 70 $m^3/h/m^3$ on time clock control, 1.14% of the initial weight was lost before cooling was completed and 1.27% was lost during the first 500 h. Comparing these losses with those predicted for continuous ventilation at the same rate with immediate cooling (Table 6.5) revealed greater weight loss (1.14% versus 0.99%) before cooling was completed using time clock control but smaller losses (1.27% versus 1.95%) after 500 h. The loss was less after cooling because of fewer total hours of fan operation.

Thermostatic control restricts the total airflow over any time period to precisely that amount required to maintain the desired temperature gradient. When time clock control was used to maintain the pile at 17°C with 70 $m^3/h/m^3$ during the first 336 h, 0.71% weight loss occurred. Similar treatment using thermostatic control resulted in only 0.53% loss. Cooling requires approximately 90 h for either case and results in an additional loss of 0.70%. After cooling, when time clock or thermostatic control is resumed, the time clock control results in more total hours of fan operation and more weight loss as indicated by the slopes of the appropriate curves in Figures 6.17 and 6.19. Hence, the time clock control results in over ventilation at high rates.

A similar comparison can be made for the time clock control at 20 $m^3/h/m^3$ (which permitted slight net heating during the first 336 h) and thermostatic control (which maintained 17°C for 336 h) (see Figures 6.17 and 6.18). The time clock control produced less weight loss during this initial period. However, the additional heat which accumulated during this period required a longer cooling period and hence greater weight loss at the end of cooling and at 720 h (1.92% versus 1.80%). Thus, under ventilation during the initial 336 h resulted in greater final weight loss.

The results presented here favor high ventilation rates during cooling. Lower rates allow the average temperature of the pile to remain high enough so that additional heat is generated which requires longer cooling times and more weight loss. Even with immediate cooling the accelerated rate of suberization and resulting decrease in heat generation and evaporation rates which occurs at higher temperatures is not sufficient to overcome the tendency toward additional heat and longer cooling times when low ventilation rates are used. Drastic changes in the temperature-time relationships given by equations (6.1) through (6.5) would be necessary to change this relationship.

During temperature maintenance periods the choice of airflow rate is not as obvious. If time clock control is used, the ventilation rate must be high enough to remove the heat generated during the total cycle time but should be no higher than necessary. Higher rates of ventilation will result in unnecessary weight loss. Hence for any particular time clock control and heat generation rate, a corresponding ventilation rate exists which will remove the proper amount of heat without over-ventilating.

During suberization, when heat generation and evaporation rates vary with time, the best ventilation rate for a particular time clock setting will also vary. The magnitude and direction of variations in the ventilation rate depend upon the relative rates of change of the heat generation and weight loss rates. The latter controls the amount of latent heat available to aid the cooling process.

During later storage periods when heat generation and weight loss rates are essentially constant with time, high ventilation rates will remove more water than low ventilation rates due to the slight dependence of weight loss on velocity (Figures 6.1 and 6.2). However, the possibility again arises that the additional heat generated during the longer time period required to return the temperature to the desired level, using lower ventilation rates, will result in greater weight loss. The temperature of the storage and permissible temperature variation both influence the magnitude of this effect. Whereas heat generation rate is strongly dependent upon temperature, weight loss rate after suberization is influenced indirectly through the temperature influence on VPD throughout the pile. Short cycle times leading to small temperature variations minimize this influence.

With thermostatic controls, high ventilation rates are again favored due to the shorter time required to remove the heat generated. The storage temperature and temperature gradient within the pile have the same influence as discussed above. Smaller gradients can be maintained using high ventilation rates than low ventilation rates.

Thermostatic control must be used with caution since development of free convection currents and condensation may be possible during prolonged unventilated periods. The model does not include these phenomena.

The temperatures and weight losses shown in this section result from potatoes which respond according to equations (6.1) through (6.5). The magnitudes of these results are not applicable to potatoes in general. Potato variety and maturity are two factors affecting such responses. However, equations (6.1) through (6.5) are believed to be representative of the time-temperature influence on heat generation and evaporation rates exhibited by all bulk stored potatoes. Thus, the trends shown here in the temperature patterns and weight losses at the various control methods and ventilation rates are also believed to be representative for all potato storages.

Section 1.2 reviewed the recommended storage controls and showed a number of disagreements among researchers. In view of the results presented here, it is perhaps understandable that such disagreements have arisen and continue to exist. If recommendations are based on extensions of experimental results with small lots of tubers, the influence of temperature and weight loss gradients, which occur in commercial-sized beds, will not be discerned. If recommendations are based on larger scale experiments, it is imperative that statistically identical tubers are used and that full details of temperature, humidity, and ventilation rates as well as control method are taken into account.

Only the first month of storage was simulated. However, extrapolation of results to longer times is possible. At the end of the first month, both heat generation and weight loss rates have attained steady values. Although product density and heat capacity continue to change as additional weight is lost, the model is not sensitive to these as long as the weight loss remains within commercially acceptable limits. Therefore, linear extrapolation of the weight loss from 720 h to six or even eight months yields accurate results providing the control system and inlet conditions remain constant and sprouting or breakdown does not occur.

7. SUMMARY AND CONCLUSIONS

A mathematical model predicting the air temperature and humidity, and temperature and weight loss of bulk stored potatoes was developed. The model consists of a system of partial differential equations to describe forced convection which are solved numerically using finite difference techniques. Testing of the model showed the solution to be consistent, convergent, and stable at the step sizes used. Unventilated periods treated the bed as a solid with the air and tubers as parallel paths for heat conduction. Moisture and thermal equilibrium were assumed to exist at each level within the bed. Free convection currents were not modeled.

Two additional forced convection models were developed but not specifically applied to potatoes. One of these models assumed continuous thermal equilibrium between the air and product while the other modeled temperature gradients within spherical products.

The thermal equilibrium model predicts a different shaped temperature profile across the bed than either of the other models. The difference in shape occurs at the cooling or heating zone and is related to the temperature difference between the inlet air and potatoes.

The uniform product (potato) model and temperature gradient model predict similar results for air velocities within the range used in commercial storages. The Biot number for bulk stored potatoes is normally less than 1.0. Therefore, modeling internal temperature gradients was considered an unwarranted complication.

Heat conduction through the bed in the direction of airflow was also found to be an unnecessary complication. Results show that conduction is unlikely to be significant in ventilated beds of biological products.

Rate equations for heat generation and weight loss for well-suberized potatoes were taken from the literature. The heat generation rate was expressed as a linear function of temperature. The weight loss equation was based on a vapor pressure deficit driving force across a fraction of the surface area which behaved as a permeable membrane. The resistance of the membrane was expressed as a linear function of VPD.

The resulting model was named the MSU potato storage model.

Temperatures predicted by the MSU potato storage model were compared with experimental data for forced convection cooling of a laboratory scale bin and of a commercial storage. The agreement between the simulated and experimental data is not perfect, but the predicted profiles cannot be discredited any more than the experimental profiles.

The heat generation rate and weight loss rate equations were modified to predict values which exponentially decrease with time. The rate of decrease was assumed to vary with temperature according to the Arrhenius equation. This is the response generally reported in the literature for freshly harvested potatoes during the suberization period.

The heat generation and weight loss rate equations were added to the MSU potato storage model to simulate the first three to four weeks of storage for the hypothetical potatoes thus described. Continuous ventilation and fans controlled by time clock or thermostat were applied to a 4 m bed. The initial temperature was taken as 17°C and the target temperature after cooling was 7°C. The inlet air temperature was either constant or 2°C less than the potato temperature at the top of the bed. An inlet relative humidity of 96% was maintained at all times.

Continuous ventilation always resulted in excessive amounts of weight loss and should be avoided.

The optimum delay for suberization was not determined. However, allowing the temperature to rise unchecked resulted in large weight losses during cooling particularly when a low ventilation rate was used. Immediate cooling with no delay for suberization resulted in severe dehydration of the lower layers of potatoes. This trend was less severe when time clock controls (16 h off-8 h on) with ventilation rates large enough to promote immediate cooling (after the initial 16 h off period) were used. Nevertheless, dehydration of the bottom layers may lead to pressure bruising and hence limit the allowable pile depth.

A drying period was not simulated. However, it is expected that the free water on the surface of the bottom layers evaporates quickly and these layers dehydrate until the free water is removed from the top layers and ventilation discontinued. Thus, the same situation results as if immediate cooling were applied to dry potatoes. Potatoes harvested wet should be stored separately (so that dry potatoes are not dehydrated) and in a more shallow bed or for a shorter period of time to avoid pressure bruising.

For any given combination of heat generation rate, weight loss rate, and time clock setting an optimum ventilation rate exists which will maintain the bed temperature within prescribed limits without over ventilation and unnecessary weight loss. Lower rates of ventilation will permit a net heating of the pile. Later periods of longer ventilation to restore the temperature will result in greater cumulative weight loss than time clock ventilation with the optimum rate.

Thermostatic control which started ventilation when the top of the pile (warm spot) reached 9°C and terminated fan operation when the same location reached 8°C resulted in the smallest weight loss at the end of the first month for the potatoes simulated. Extrapolation of the results to longer times shows the same result. At any fixed ventilation rate, this thermostatic control can be viewed as a means of continually varying the settings of a time clock to meet the cooling requirement of the bed. In other words, the length of the fan-on and fan-off time periods is adjusted so that the prevailing ventilation rate maintains the desired temperature without over ventilating. High ventilation rates resulted in smaller weight losses for thermostatic control.

Unventilated periods lasting for several days were predicted using thermostatic controls. Free convection currents, not simulated by the model, develop in commercial storages with long periods of no ventilation.

The above results are based on hypothetical potatoes which behave in a manner generally consistent with trends reported in the literature. However, only one time clock setting, final temperature range, and inlet humidity were used. Different cumulative weight loss would be predicted if these were altered. Hence, the optimum controls and conditions for these potatoes have not been determined.

In conclusion, a very powerful tool for the design and management of bulk stored potatoes has been developed. Further work is required, however, if the model is to be applied to any particular lot of potatoes in a particular storage structure. Development of the model points directly to areas where additional research is most beneficial.

8. SUGGESTIONS FOR FUTURE RESEARCH

Knowledge of the complex biochemical interactions which occur within potatoes and similar biological systems is rudimentary at best. As new information becomes available, improvements to the potato storage model will become possible. The model predicts the potato temperatures as they change with time; these temperatures are essential to prediction of the rates of the biochemical reactions. Thus, additional variables related to the quality state of the tubers can be added to the basic model as knowledge relative to the rates of the reactions becomes available. Assumptions made in development of the model place restrictions on its range of applicability. New information may result in a relaxation or more accurate definition of these limits.

Knowledge of the physical processes of heat and mass transfer is incomplete. However, development of the system of partial differential equations which forms the basic model is based on accepted engineering principles. Significant advances which will result in improvements to the model are not likely.

Solution techniques for systems of partial differential equations are still a viable research topic in applied mathematics. Hence, faster and more accurate solution of the equations may become possible. Any decrease in solution time which does not sacrifice validity constitutes an improvement to the model. Some decrease in solution time is no doubt possible through more efficient coding of the FORTRAN program listed in Appendix B; the program requires less than 500 seconds on a typical CDC 6500 installation to simulate one month of storage for a 4 m bed (simulation time to time simulated ratio of 1.93×10^{-4}).

Research needs of the MSU potato storage model outside the areas of mathematical or computer programming techniques fall into four categories:

1. improvements to the auxiliary relationships,
2. additions to the model,
3. relaxation of restrictions on the model, and
4. applications of the model.

Table 8.1 lists the ten research areas in decreasing order of importance and shows the categories into which each area falls.

First, and of greatest importance, is research leading to better prediction of weight loss rates. This is especially critical for simulation of the suberization period. Research efforts have failed to produce a generally applicable equation, i.e., the rate-limiting parameters have not been well defined.

It is suggested that lenticels play an important role in determining the rate of weight loss after suberization, the skin being essentially impermeable. No attempt at such a correlation was found in the literature. Differences in lenticel physiology and number might explain variations currently attributed to variety, climate, cultural conditions and practices, and so forth.

Table 8.1. Recommended research areas in bulk potato storage.

Topic	Priority	Category
Weight loss rate kinetics	1	Improvement
Heat generation rate kinetics	2	Improvement
Dry matter loss prediction	3	Addition
Parameter studies	4	Application
Rot index	5	Restriction
Carbohydrate rate kinetics	6	Addition/ improvement
Occurrence/simulation of free convection	7	Restriction/ addition/ improvement
Optimization of storage control and management	8	Application
Sprouting/senescence	9	Restriction
Parameter measurement	10	Improvement

The amount and severity of harvest and handling injuries are important during the initial storage period. Knowledge of the time-temperature rates of suberin synthesis and periderm formation or healing of these wounds is essential. Empirical relationships may be required if the complicated biochemical mechanisms preclude a strict theoretical approach.

Regardless of the form of the resulting weight loss rate equation, any parameters which it contains should be quickly and easily determined (directly or indirectly) at the potato storage by the storage operator for the particular tubers being stored.

Further development of the heat generation rate equation is listed second in Table 8.1 because more data are already available for respiration or heat generation than for weight loss. Ideally, parameters developed to express the influence of injuries on weight loss rate could also be used to predict the "stimulated basal" or "developed" respiration intimately related to wound healing. All future research in the area of heat generation or respiration should attempt to differentiate between these types and pathways of respiration.

Basic biochemical research may lead to determination of the rate-limiting step (or steps) in the respiratory pathways. Such knowledge would be invaluable in the development of accurate prediction equations based on reaction kinetics theory or transport across membranes.

The third item in Table 8.1, dry matter loss prediction, rates a high research priority because of the relative ease with which it may be implemented. Theoretically, to add prediction of dry matter loss to the model, the derivation of the basic equations must be reworked. However, the rate of loss is small enough to have negligible influence on the mass transfer and tuber density. Hence, an estimate of dry matter disappearance based on heat generation rate can be readily incorporated into the present model.

Several types of parameter studies could be conducted on the potato storage model. Such studies could reveal important information on the character of the model and the significance of errors in the input data and potato properties. A large number of parameters are involved. Careful planning and sound experimental design should be exercised to minimze the expense. The relative importance of several parameters was shown earlier, additional information would result from more formal parameter studies. In some cases it is possible to derive mathematical expressions for the significance of individual parameters or terms. Dimensional analysis could be applied to show the relative influence of various combinations of the independent variables. Statistical methods could be included to study the influence of biological variations on the predicted results. This approach could lead to the determination of confidence intervals for the predictions. The knowledge gained from each parameter study should justify the costs incurred.

Arguments for a priority higher than fifth are easily made for development of a rot index. Nevertheless, the result of such research is merely a more precise definition of one of the limits of the model. Simulation of the progress of rotting as a salvage operation is less important than simulation of storage management which prevents rotting.

Carbohydrate reaction kinetics (reducing sugars in particular) is a very important research area. Many investigations have already been conducted on this topic. However, most of the effort has been directed toward macroscopic experiments with several varieties at several temperatures for several harvest dates and so forth. A few general response patterns have emerged. However, the bulk of this research has not yet benefited the industry. A more basic approach dealing with the enzyme systems involved in the carbohydrate balance looks more promising. Here the rate-limiting steps as well as equilibrium states are sought. Direct relationships between heat generation rate and carbohydrate metabolism are expected.

Seventh in priority in Table 8.1 is the simulation of free convection. Occurrence of free convection serves as a restriction on the present model. Accurate estimations of the time required for such currents to develop under specific situations would more clearly define the limit of applicability of the model. Unfortunately, occurrence of free convection currents is dependent upon factors unique to each storage bin (overall dimensions, wall and ceiling temperatures). Simulation of storages during periods of free convection would greatly extend the range of applications of the model. Unfortunately, free convection occurs in three dimensions and requires a more sophisticated and costly model.

Optimization is assigned a relatively low priority. Although an optimization study could proceed immediately with the model in its present state, better results would be obtained if the above projects were completed first. In the model's present form, unconstrained optimization for minimum weight loss would result in permitting the potatoes to generate heat and increase in temperature with <u>no</u> ventilation. Penalties associated with quality factors other than weight loss such as reducing sugar content, dry matter loss, or progression toward senescence need to be added before an optimum control system or management strategy is sought. If the optimization tends toward long unventilated periods, simulation of free convection and condensation on walls and ceilings becomes imperative.

Sprouting, senescence and other degradative physiological phenomena are grouped together with a priority of nine for several reasons. First, chemical treatment and good storage practices have greatly reduced the occurrence and severity of sprouting. Second, other degradative processes are closely associated with the carbohydrate balance. At most, this project appears to be an extension of priorities 1, 2 and 6 (weight loss, heat generation, and carbohydrate rate kinetics, respectively).

Finally, additional work may be useful in developing measurement methods for determining the input parameters for the model. These include the physical and thermal properties currently required plus any additional parameters or properties required by the previously outlined projects.

In its current state, the MSU potato storage model requires measurement of average tuber weight and specific gravity. These parameters are related to surface area, volume, initial moisture, initial density and initial heat capacity while "average" values are used for less easily determined parameters. Research leading to more accurate determination of values by storage operators or to better correlations would improve the model. For some parameters, accurate determination is not warranted by their influence on predicted results.

If the model is to be applied to the study of alternative controls which can be applied to a particular storage after some elapsed time, knowledge of gradients which exist in the bed at that time is desirable. In the case of temperature, this is easily measured. However, weight loss gradients and associated property gradients (ρ_p, c_p) are not easily determined. If the initial and boundary conditions which resulted in the bed's current state are known, a simulation of the elapsed time should give the resulting gradients. Measurement systems which record these required data may be of value.

The ten research areas listed in Table 8.1 represent the "ten most wanted" results for future development and application of the MSU potato storage model. Several of these research areas will require considerable time and research effort. Fortunately, the knowledge gained from these projects will have applications far beyond improvement of the MSU potato storage model.

APPENDICES

APPENDIX A

UNIT CONVERSIONS

APPENDIX A

UNIT CONVERSIONS

	Unit	Equivalent
Airflow	m^3 air/h/m^3 potatoes	4.600×10^{-2} cfm/cwt*
	m^3/h/ton (metric)	5.339×10^{-1} cfm/ton (2000 lb_m)
	$m^3/h/m^2$	5.468×10^{-2} cfm/ft^2
Apparent convective mass transfer coefficient (pressure driving force)	kg/N h	9.807 lb_m/lb_f h
Area	m^2	1.076×10^{1} ft^2
Convective heat transfer coefficient	J/h m^2 °C	2.778×10^{-4} W/m^2 °C 4.894×10^{-5} Btu/h ft °C
Convective mass transfer coefficient	m/h	3.281 ft/h
Density	Kg/m^3	6.243×10^{-2} lb_m/ft^3
Diffusivity	m^2/h	1.076×10^{1} ft^2/h
Energy	J	9.478×10^{-4} Btu 2.388×10^{-4} kcal
Force	N	2.248×10^{-1} lb_f
Heat generation rate	J/h kg	4.299×10^{-4} Btu/h lb_m
Heat transfer rate	J/h m^3	2.684×10^{-5} Btu/h ft^3
Latent heat	J/kg	4.299×10^{-4} Btu/lb
Length	m	3.281 ft

*Bulk density of 650 kg/m^3 assumed.

	Unit	Equivalent
Mass	kg	2.205 lb_m
Pressure	N/m^2	1.450×10^{-4} psi 7.500×10^{-3} mm Hg
Resistance to flow of vapor	N m h/kg	3.346×10^{-1} lb_f ft h/lb_m
Specific heat	J/kg °C	2.388×10^{-4} Btu/lb_m °F
Specific surface area	m^2/m^3	3.048×10^{-1} ft^2/ft^3
Temperature difference	°C (°K)	1.800 °F (°R)
Thermal conductivity	J/h m °C	2.778×10^{-4} W/m °C 1.605×10^{-4} Btu/h ft °F
Velocity	m/h	3.281 ft/h
Viscosity	kg/m h	6.719×10^{-1} lb_m/ft h
Volume	m^3	3.531×10^{1} ft^3
Weight loss rate	kg/h m^3	6.244×10^{-2} lb_m/h ft^3

APPENDIX B

FORTRAN LISTING OF MSU POTATO STORAGE MODEL

```
      PROGRAM POTATO(INPUT,OUTPUT,TAPE8)
C-----
C-----    MAIN PROGRAM FOR THE POTATO STORAGE MODEL.  CONTAINS
C-----     CONTROLS FOR SIMULATION INCLUDING ALL INPUT AND OUTPUT.
C-----
      COMMON/AIR/CA,GA,RA,TAIR,HAIR,XKA
      COMMON/WATER/CV,CW,HFG,RW
      COMMON/SPUD/CP,GAM1,GAM2,RP,SPG,THIN,XK,CPD,RPD,XM,RDEL
      COMMON/BED/EP,SA,DT,DX,N,TIME,TT,HD
      COMMON/CON/CON1,CON2,CON3,CON4,CCN5,CON6
      COMMON/FOC/FOC1,FOC2,FOC3,FOC4
      COMMON/APR/T(400),H(400),HBK(400),TH(400),DELW(400),CPO(400),RPO(4
     +00)
      DIMENSION MESS(8)
C-----
C-----    STATEMENT FUNCTION FOR CONVERSION TO ABSOLUTE TEMP.
C-----
      F(T)=T+273.2
      PI=3.14159
C-----
C-----    CONNECT FILE FOR OUTPUT NOT PRINTED THROUGH BATCH
C-----
      CALL CONNEC(8,2LOM)
C-----
C-----    ASK FOR EACH INPUT AND READ RESPONSES.
C-----
      WRITE(8,601)
      READ 200,TAIR
      WRITE(8,602)
      READ 200,HAIR
C-----
C-----    HAIR LESS THAN 1.0 IMPLIES ABS HUM.  HAIR GREATER
C-----    THAN 1.0 IS RELATIVE HUMIDITY.
C-----
      IF(HAIR.GT.1.) HAIR=HADBRH(F(TAIR),HAIR*.01)
      WRITE(8,603)
      READ 200,AIRIN
      WRITE(8,604)
      READ 200,THIN
      WRITE(8,605)
      READ 200,WGT
      WRITE(8,616)
      READ 200,SPG
      WRITE(8,606)
      READ 200,DEPTH
      WRITE(8,607)
      READ 200,TT
      WRITE(8,608)
      READ 200,TBTPR
      WRITE(8,614)
      READ 200,FON
      WRITE(8,615)
      READ 200,FOFF
      WRITE(8,609)
      READ 201,(MESS(I),I=1,8)
C-----
C-----    INITIALIZE FAN OFF AND TIME.
C-----
      IFAN=-1
      CTIM=FOFF
```

```
      TIME=0.0
C-----
C-----     CONVERT INPUTS TO VALUES NEEDED BY MODEL EQUATIONS.
C-----
      XM=1.-.01*(24.182+211.04*(SPG-1.0988))
      RP=RW*SPG
      RPD=RP*(1.-XM)
      CP=XM*(CW-CPD)+CPD
      A=3.6E-4*WGT**.713
      V=WGT/(RP*1000.)
      EP1=1.-EP
      SA=A*EP1/V
      RPBULK=RP*EP1
      POTIN=RPBULK*DEPTH/1000.
C-----
C-----     COMPUTE REL HUM, AIRFLOW AND TRANSFER COEFFICIENTS.
C-----
      RH=RHDBHA(F(TAIR),HAIR)
      GA=AIRIN*RA*DEPTH
      VA=GA/(RA*EP)
      RE=GA/(SA*.06354)
      HC=280.*(GA**.49)*(SA**.51)
      IF(RE.GT.50.) HC=247.28*(GA**.59)*(SA**.41)
      HD=8.966E-4*HC
C-----
C-----     DETERMINE STEP SIZES AND PRINT INTERVALS.
C-----
      DX=GA*CA/(HC*SA)
      NPR=(.2/DX+.5)*2
      DX=.2/NPR
      N=(DEPTH/DX+1.5)
      DT=RPBULK*CP/(HC*SA)
      K1=(TBTPR/DT+.5)*4
      DT=TBTPR/K1
      TPR=TBTPR
C-----
C-----     ASK IF COMPLETE HEADER WITH LIST OF INPUT AND COMPUTED
C-----     VALUES IS DESIRED.  IF SO, PRINT IT.
C-----
      WRITE(3,610)
3     READ 300,IC
      IF(IC.NE.1HY) GO TO 5
4     CALL DATE(DD)
      PRINT 210,DD
      PRINT 211,TAIR,HAIR,THIN,RH
      PRINT 212,AIRIN,WGT,GA,A,VA,V
      PRINT 213,DEPTH,TT,DX,DT
      PRINT 214,CA,RA,CP,RP,CW,RW,CV,RPBULK
      PRINT 215,HFG,SA,XKA,XK
      PRINT 216,HC,POTIN,HD,EP
      PRINT 217,(MESS(I),I=1,8)
C-----
C-----     EVALUATE CONSTANTS USED IN MODEL EQUATIONS.
C-----
5     CON1=DX/(VA*DT)
      CON2=DX*SA*HC/GA
      CON3=DX/GA
      CON4=XK*EP1*DT/(DX*DX)
      CON5=HC*SA*DT
      CON6=RW*SA
```

```
      FOC1=RP*CP*EP1
      FOC2=RA*EP
      FOC3=RP*EP1*DT
      FOC4=(XKA*EP+XK*EP1)*DT/(DX*DX)
C-----
C-----    IF INLET AIR IS SUPER-SATURATED, ADJUST HAIR.  THEN
C-----    DETERMINE SUITABLE VALUE FOR INITIALIZATION OF H.
C-----
      IF(RH.LT.1.0)GO TO 17
      HAIR=HADBRH(F(TAIR),.99999)
      PRINT 206,HAIR
17    HA=HAIR
      HAMAX=HADBRH(F(THIN),.99999)
      IF(HAMAX.LT.HA)HA=HAMAX
      IF(TIME.GT.0.0) GO TO 6
C-----
C-----    INITIALIZE ARRAYS TO BOUNDARY OR INITIAL CONDITIONS.
C-----
      DO 10 I=1,N
      T(I)=THIN
      H(I)=HA
      HBK(I)=HA
      TH(I)=THIN
      DELW(I)=0.0
      RPO(I)=RP
      CPO(I)=CP
10    CONTINUE
19    T(1)=TAIR
      H(1)=HAIR
C-----
C-----    DETERMINE STARTING VALUE FOR TH AT AIR INLET.
C-----
      DMMN=-(HADBRH(F(TAIR),1.0)-HAIR)/CON3
      CALL DMRATE(1,DMMN,DM)
      TH(1)=THIN+(CON5*(TAIR-THIN)+DM*DT*(CV*TAIR-CW*THIN+HFG)+
     +DT*RESP(THIN)*EP1*RP)/(RP*CP*EP1+CON6*CW*DELW(1))
C-----
C-----    CALCULATION LOOP FOR TIME INCREMENT.
C-----    RETURN TO THIS STATEMENT FOR EACH TIME STEP.
C-----
6     CONTINUE
      IF(IFAN.GT.0) GO TO 21
C-----
C-----    FAN IS OFF
C-----
      CALL CALCOFF
      GO TO 22
C-----
C-----    FAN IS ON
C-----
21    CALL CALCON
22    TIME=TIME+DT
C-----
C-----    SET INLET CONDITIONS ACCORDING TO CONTROL SYSTEM
C-----
      TAIR=TH(N)-2.
      IF(TAIR.LT.7.0) TAIR=7.0
      HAIR=HADBRH(F(TAIR),.96)
C-----
C-----    CHECK TIME FOR CRITICAL VALUES SUCH AS PRINT TIME,
```

```
C-----     CHANGE OF FAN STATE TIME, ETC.  PROCEED ACCORDINGLY.
C-----
      IF((TIME+DT).GE.TPR) GO TO 11
31    IF(TIME.GT.CTIM) GO TO 32
9     IF(TIME.GE.TT) GO TO 11
      GO TO 6
C-----
C-----     OUTPUT SECTION.  COMPUTE VALUES OF INTEREST AND PRINT.
C-----
11    TPR=TPR+TBTPR
      PRINT 202,TIME
      PRINT 203
      DO 20 I=1,N,NPR
      X=(I-1)*DX
      RH=RHDBHA(F(T(I)),H(I))*100.
      WGTLOST=100.*(RP-RPO(I))/RP
      FTH=DELW(I)/1000.
      PRINT 204,X,T(I),TH(I),RH,WGTLOST,FTH
20    CONTINUE
      WGTLOST=0.0
      DO 23 I=1,N
      WGTLOST=WGTLOST+(RP-RPO(I))*EP1*DX
23    CONTINUE
      WGTLOST=.1*WGTLOST/POTIN
      PRINT 205,WGTLOST
      IF(TIME.GE.TT) GO TO 999
      GO TO 31
32    IF(IFAN.LT.0) GO TO 33
C-----
C-----     TURN FAN OFF.  SET AIT TEMPERATURE AND HUMIDITY TO
C-----     EQUILIBRIUM VALUES.
C-----
      CTIM=TIME+FOFF-DT
      IFAN=-1
      DO 110 I=1,N
      CAM=CA+CV*H(I)
      T(I)=(FOC2*CAM*T(I)+FOC1*TH(I))/(FOC2*CAM+FOC1)
      HBK(I)=H(I)
      H(I)=HWDBRH(F(T(I)),.99)
110   CONTINUE
      GO TO 9
33    CTIM=TIME+FON-DT
C-----
C-----     TURN FAN ON.
C-----
      IFAN=1
      T(1)=TAIR
      H(1)=HAIR
      GO TO 9
999   CONTINUE
C-----
C-----
C-----
C-----     FORMATS.
C-----
200   FORMAT(F10.0)
201   FORMAT(8A10)
202   FORMAT(1H1,6(/),37X8HTIME, HRF7.2)
203   FORMAT(///19X5HDEPTH7X3HAIR4X6HPOTATO7X3HREL4X6HWEIGHT6X4HFILM/30X
     +4HTEMP5X4HTEMP7X3HHUM6X4HLOSS5X5HTHICK/22X2H M9X1HC9X1HC7X3HPCT7X
```

```
     +3HPCT8X2HMM/)
204   FORMAT(14X3F10.2,F10.1,2G10.2)
205   FORMAT(//27X26HTOTAL WEIGHT LOST, PERCENTG11.4)
206   FORMAT(///14X30HINLET HUMIDITY .GT. SATURATION/
     +14X12HAIR SET TO F8.6)
210   FORMAT(1H1,14(/),18X44HP O T A T O    S T O R A G E    M O D E L
     + A10//25X31HWITH UNIFORM POTATO TEMPERATURE)
211   FORMAT(///14X16HINLET AIR TEMP,C7XF5.1,4X19HINLET ABS HUM,KG/KG3X
     +F6.4//14X21HINITIAL POTATO TEMP,C2XF5.1,4X21HINLET REL HUM,DECIMAL
     +F7.4)
212   FORMAT(/14X20HAIRFLOW M**3/HR/M**33XF5.2,4X19HAV POTATO WEIGHT, G
     +3XF6.2//17X19HKG DRY AIR/HR/M**2 F6.1,8X18HSURFACE AREA, M**2F6.4
     +//24X12H M/HR IN BEDF6.0,8X12HVOLUME, M**36XF6.4)
213   FORMAT(/14X12HBED DEPTH, M11XF5.1,4X13HTOTAL TIME,HR10XF5.0//
     +14X10HDELTA X, M12XF6.4,4X10HDELTA T,HR12XF6.4)
214   FORMAT(/14X23HSPECIFIC HEATS, J/KG/C 9X19HDENSITIES, KG/M**3/
     +19X7HDRY AIR11XF5.0,9X7HDRY AIR11XF6.3//19X6HPOTATO12XF5.0,8X6HPOT
     +ATO13XF5.0//19X12HLIQUID WATER6XF5.0,8X12HLIQUID WATER7XF5.1//
     +19X11HWATER VAPOR7XF5.0,9X13HBULK POTATOES6XF5.1)
215   FORMAT(/14X18HLATENT HEAT, J/KG 2XF8.0,4X23HSP SUR AREA, M**2/M**3
     + F5.1//14X20HAIR COND, J/HR/M/C  F8.3,4X23HPOTATO COND, J/HR/M/C
     +F5.3)
216   FORMAT(/14X22HHT COEF, J/HR/M**2/C  F6.0,4X21HINIT WEIGHT,TON/M**2
     + 2XF5.3//14X21HMASS TRANS COEF, M/HR2XF5.1,4X20HPOROSITY,VOID/VOLU
     +ME3XF5.2)
217   FORMAT(///14X8A10)
300   FORMAT(A1)
601   FORMAT(10X*INLET AIR TEMP =    *)
602   FORMAT(10X*INLET HUMIDITY =  *)
603   FORMAT(10X,26HM**3 AIR/HR/M**3 POTATO = )
604   FORMAT(10X*INITIAL POTATO TEMP =  *)
605   FORMAT(10X*AVERAGE POTATO WEIGHT =  *)
606   FORMAT(10X*BED DEPTH =  *)
607   FORMAT(10X*TOTAL TIME =  *)
608   FORMAT(10X*TIME BETWEEN PRINTS =  *)
609   FORMAT(10X*TYPE IN COMMENT*/)
610   FORMAT(10X*DO YOU WANT PRELIMINARY VALUES? (Y OR N)  *)
614   FORMAT(10X*LENGTH OF FAN ON CYCLE = *)
615   FORMAT(10X*LENGTH OF FAN OFF CYCLE = *)
616   FORMAT(10X*SPEC GRAV =  *)
      END
```

```
      SUBROUTINE CALCON
C-----
C-----     SUBROUTINE CONTAINING THE MODEL EQUATIONS (EXCEPT
C-----     MOISTURE LOSS RATE AND RESPIRATION RATE). ENTER
C-----     ONCE FOR EACH TIME STEP.
C-----
      COMMON/AIR/CA,GA,RA,TAIR,HAIR,XKA
      COMMON/WATER/CV,CW,HFG,RW
      COMMON/SPUD/CP,GAM1,GAM2,RF,SPG,THIN,XK,CPD,RPC,XM,RDEL
      COMMON/BED/EP,SA,DT,DX,N,TIME,TT,HD
      COMMON/CON/CON1,CON2,CON3,CON4,CON5,CON6
      COMMON/ARR/T(400),H(400),HBK(400),TH(400),DELW(400),CPO(400),RPO(4
     +00)
C-----
C-----     STATEMENT FUNCTIONS FOR EVALUATION OF ABSOLUTE TEMP
C-----
      F(T)=T+273.2
C-----
C-----     SET BOUNDARY CONDITIONS.
C-----
      TB=T(1) $ HB=H(1)
      T(1)=TAIR
      H(1)=HAIR
      THB=TH(1) $ TH(N+1)=TH(N)
C-----
C-----     CALULATION LOOP FOR DEPTH INCREMENT.
C-----
      DO 20 I=1,N
      J=I+1
      TS=T(J) $ HS=H(J)
      CAM=CA+CV*H(I)
C-----
C-----     AIR TEMP EQUATION FOR X+DX AT TIME T.
C-----
1     T(J)=T(I)-CON1*(T(I)-TB)-CON2*(T(I)-TH(I))/CAM
C-----
C-----     FIND MINIMUM ACCEPTABLE RATE OF MOISTURE LOSS TO
C-----     AVOID SUPER-SATURATION.  (+ IMPLIES CONDENSATION).
C-----
      DMMN=-(HADBRH(F(T(J)),1.0)-H(I)+CON1*(H(I)-HB))/CON3
C-----
C-----     DETERMINE ACTUAL MOISTURE LOSS RATE.
C-----
      DELWT=DELW(I)
      RPT=RPO(I)
      CALL DMRATE(I,DMMN,DM)
C-----
C-----     ABS HUM EQUATION FOR X+DX AT TIME T.
C-----
5     H(J)=H(I)-CON1*(H(I)-HB)-DM*CON3
      THT=TH(I)
C-----
C-----     POTATO TEMP EQUATION FOR X AT TIME T+DT.
C-----
      TH(I)=THT+(CON5*(T(I)-THT)
     ++DM*DT*(CV*T(I)-CW*THT+HFG)+DT*RESP(THT)*(1.-EP)*RPT)/
     +(RPT*CPO(I)*(1.-EP)+CON6*CW*DELWT)
      CPO(I)=RPD*(CPD-CW)/RPO(I)+CW
      THB=THT
      TB=TS $ HB=HS
20    CONTINUE
999   CONTINUE
      RETURN
      END
```

```
      SUBROUTINE DMRATE(I,DMMN,DM)
C-----
C-----     SUBROUTINE TO DETERMINE MOISTURE LOSS RATE AND
C-----     AMOUNT OF FREE WATER PRESENT.
C-----
      COMMON/BED/EP,SA,DT,DX,N,TIME,TT,HD
      COMMON/SPUD/CP,GAM1,GAM2,RP,SPG,THIN,XK,CPO,RPO,XM,RDEL
      COMMON/CON/CON1,CON2,CON3,CON4,CON5,CON6
      COMMON/ARR/T(400),H(400),HBK(400),TH(400),DELW(400),CPO(400),RPO(4
     +00)
C-----
C-----     STATEMENT FUNCTION TO CONVERT TO ABS TEMP
C-----
      F(T)=T+273.2
C-----
C-----     FIND VAPOR PRESSURE DEFICIT AND SKIN PARAMETER.
C-----     SET G1 AND G2 TO AREA FRACTION OF POTATO.
C-----
      VPD=(PSDB(F(T(I)))-PVHA(H(I)))
      IF(VPD.LT.0.0) VPD=0.0
      RDEL=4.94E-4+3.31E-6*VPD
      G1=GAM1
      G2=GAM2
C-----
C-----     IF FREE WATER IS ON SURFACE, RESET G1 AND G2.
C-----
      IF(DELW(I).LE.0.0) GO TO 1
      G1=1.0
      G2=0.0
C-----
C-----   COMPUTE MASS LOSS RATE.
C-----
1     DM=-(2.16642E-3*HD/F(T(I)))*(G1+(.08454*G2/(RDEL*HD+.08454)))*SA
     +*VPD
C-----
C-----     RESET DM TO MINIMUM ALLOWABLE VALUE IF IT IS TOO
C-----     SMALL (TOO LARGE AND NEGATIVE).
C-----
      IF(DM.LT.DMMN) DM=DMMN
C-----
C-----     IF DM IS POSITIVE CONDENSATION OCCURS.
C-----
3     IF(DM.GT.0.0) GO TO 4
C-----
C-----     IF FREE WATER IS PRESENT, DETERMINE HOW MUCH
C-----     AND THE MINIMUM RATE OF LOSS WHICH WILL
C-----     REMOVE IT ALL.
C-----
      IF(DELW(I).LE.0.0) GO TO 5
      DMMN=-DELW(I)*CON6/DT
      IF(DM.LT.DMMN) DM=DMMN
C-----
C-----     FOR CASES OF CONDENSATION OR EVAPORATION OF FREE
C-----     WATER, DETERMINE NEW AMOUNT OF FREE WATER.
C-----
4     DELW(I)=DELW(I)+DM*DT/CON6
      RETURN
5     RPO(I)=RPO(I)+DM*DT/(1.-EP)
      RETURN
      END
```

```
      SUBROUTINE CALCOFF
      COMMON/AIR/CA,GA,RA,TAIR,HAIR,XKA
      COMMON/WATER/CV,CW,HFG,RW
      COMMON/BED/EP,SA,DT,DX,N,TIME,TT,HD
      COMMON/FOC/FOC1,FOC2,FOC3,FOC4
      COMMON/ARP/T(400),H(400),HBK(400),TH(400),DELW(400),CPO(400),RPO(4
     +00)
C-----
C-----    STATEMENT FUNCTION FOR CONVERSION TO ABSOLUTE TEMP.
C-----
      F(T)=T+273.2
      TB=T(1)
      T(N+1)=T(N)
      DO 10 I=1,N
      J=I+1
      TS=T(I)
      T(I)=TS+(-FOC2*(CV*TS+HFG)*(H(I)-HBK(I))+RESP(TS)*FOC3+FOC4*(T(J
     +)
     +-2.*TS+TB))/(FOC2*(CA+CV*H(I))+FOC1)
      TH(I)=T(I)
      HBK(I)=H(I)
      H(I)=H_DBRH(F(T(I)),.99)
      RPO(I)=RPO(I)-(H(I)-HBK(I))*FOC2/(1.-EP)
      TB=TS
10    CONTINUE
      RETURN
      END



      FUNCTION RESP(T)
      COMMON/BED/EP,SA,DT,DX,N,TIME,TT,HD
C-----
C-----    SUBPROGRAM TO EVALUATE RESPIRATION RATE.
C-----
      RESP=6.99*T+17.7
      RETURN
      END



      BLOCK DATA
C-----
C-----    BLOCKDATA TO INITIALIZE CONSTANTS AND SELDOM
C-----    CHANGED INPUTS.
C-----
      COMMON/AIR/CA,GA,RA,TAIR,HAIR,XKA
      COMMON/WATER/CV,CW,HFG,RW
      COMMON/SPUD/CP,GAM1,GAM2,RP,SPG,THIN,XK,CPD,RPD,XM,RDEL
      COMMON/BED/EP,SA,DT,DX,N,TIME,TT,HD
      COMMON/PRESS/PATM
      DATA CA,RA,XKA/1005.,1.243,89.1/
      DATA CV,CW,HFG,RW/1834.,4187.,2478600.,999.25/
      DATA CPD,EP,XK,RDEL/904.3,.426,2000.,.035/
      DATA GAM1,GAM2/0.0,.07/
      DATA PATM/101325./
      END
```

APPENDIX C

POTATO STORAGE MODEL WITH UNIFORM POTATO TEMPERATURE

P O T A T O   S T O R A G E   M O D E L   05/12/78

WITH UNIFORM POTATO TEMPERATURE

INLET AIR TEMP,C	4.0	INLET ABS HUM,KG/KG	.0019
INITIAL POTATO TEMP,C	15.0	INLET REL HUM,DECIMAL	.3781
AIRFLOW M**3/HR/M**3	25.00	AV POTATO WEIGHT, G	170.00
KG DRY AIR/HR/M**2	124.3	SURFACE AREA, M**2	.0149
M/HR IN BED	235.	VOLUME, M**3	.0002
BED DEPTH, M	4.0	TOTAL TIME,HR	108.
DELTA X, M	.0500	DELTA T,HR	.4500
SPECIFIC HEATS, J/KG/C		DENSITIES, KG/M**3	
DRY AIR	1005.	DRY AIR	1.243
POTATO	3454.	POTATO	1089.
LIQUID WATER	4187.	LIQUID WATER	999.2
WATER VAPOR	1984.	BULK POTATOES	625.2
LATENT HEAT, J/KG	2478600.	SP SUR AREA, M**2/M**3	51.5
AIR COND, J/HR/M/C	89.100	POTATO COND, J/HR/M/C	2000.
HT COEF, J/HR/M**2/C	22216.	INIT WEIGHT,TON/M**2	2.501
MASS TRANS COEF, M/HR	19.9	POROSITY,VOID/VOLUME	.43

SAMPLE RUN WITH SIN WAVE T AND H INLET CONDITIONS.

TIME, HR 18.00

DEPTH M	AIR TEMP C	POTATO TEMP C	REL HUM PCT	WEIGHT LOSS PCT	FILM THICK MM
0.00	1.03	1.62	76.4	.565E-01	0.
.20	3.07	3.95	68.8	.22	0.
.40	5.13	5.78	62.9	.33	0.
.60	6.63	7.08	60.5	.40	0.
.80	7.90	8.19	59.6	.44	0.
1.00	8.91	9.28	59.1	.46	0.
1.20	9.95	10.27	58.9	.46	0.
1.40	10.83	11.05	59.2	.45	0.
1.60	11.48	11.60	60.4	.44	0.
1.80	11.92	11.99	62.1	.42	0.
2.00	12.24	12.27	64.2	.39	0.
2.20	12.48	12.49	66.5	.37	0.
2.40	12.68	12.68	68.7	.35	0.
2.60	12.85	12.86	70.8	.33	0.
2.80	13.02	13.02	72.7	.31	0.
3.00	13.18	13.18	74.6	.29	0.
3.20	13.33	13.33	76.3	.27	0.
3.40	13.47	13.48	77.8	.26	0.
3.60	13.61	13.61	79.3	.24	0.
3.80	13.74	13.74	80.7	.22	0.
4.00	13.86	13.87	82.0	.21	0.

TOTAL WEIGHT LOST, PERCENT .3401

TIME, HR 36.00

DEPTH M	AIR TEMP C	POTATO TEMP C	REL HUM PCT	WEIGHT LOSS PCT	FILM THICK MM
0.00	5.47	6.69	93.3	.12	.97-175
.20	6.82	7.06	94.9	.26	.37E-07
.40	7.66	7.78	97.4	.39	.40E-07
.60	8.01	8.00	99.0	.50	.38E-07
.80	7.86	7.71	100.0	.57	.32E-07
1.00	7.05	6.74	100.0	.63	.20E-07
1.20	5.93	5.66	100.0	.67	.69E-09
1.40	5.24	5.23	100.0	.70	.16E-09
1.60	5.47	5.72	98.3	.73	0.
1.80	6.13	6.44	94.3	.74	0.
2.00	6.88	7.18	90.4	.74	0.
2.20	7.60	7.87	87.3	.73	0.
2.40	8.26	8.48	85.0	.71	0.
2.60	8.82	9.01	83.6	.69	0.
2.80	9.31	9.45	82.7	.67	0.
3.00	9.72	9.84	82.4	.64	0.
3.20	10.07	10.17	82.4	.61	0.
3.40	10.38	10.47	82.6	.59	0.
3.60	10.67	10.74	82.9	.56	0.
3.80	10.93	11.00	83.3	.54	0.
4.00	11.18	11.25	83.7	.51	0.

TOTAL WEIGHT LOST, PERCENT .6021

TIME, HR 54.00

DEPTH M	AIR TEMP C	POTATO TEMP C	REL HUM PCT	WEIGHT LOSS PCT	FILM THICK MM
0.00	8.97	8.25	96.6	.20	.37E-08
.20	7.98	7.66	100.0	.26	.45E-07
.40	6.60	6.14	100.0	.39	.28E-07
.60	4.98	4.56	100.0	.50	.12E-07
.80	3.84	3.67	100.0	.57	.18E-08
1.00	3.64	3.76	99.7	.63	0.
1.20	4.04	4.25	97.1	.68	0.
1.40	4.57	4.79	94.1	.71	0.
1.60	5.10	5.30	91.5	.74	0.
1.80	5.56	5.71	89.7	.76	0.
2.00	5.94	6.05	88.7	.77	0.
2.20	6.10	6.05	89.1	.93	0.
2.40	5.98	5.91	91.1	.91	0.
2.60	5.88	5.87	92.7	.89	0.
2.80	5.94	6.00	93.2	.88	0.
3.00	6.17	6.29	92.6	.87	0.
3.20	6.52	6.67	91.3	.85	0.
3.40	6.93	7.09	89.9	.84	0.
3.60	7.34	7.50	88.6	.82	0.
3.80	7.74	7.88	87.6	.80	0.
4.00	8.12	8.25	86.8	.77	0.

TOTAL WEIGHT LOST, PERCENT .7184

TIME, HR 72.00

DEPTH M	AIR TEMP C	POTATO TEMP C	REL HUM PCT	WEIGHT LOSS PCT	FILM THICK MM
0.00	4.53	3.26	91.2	.28	0.
.20	2.53	2.33	100.0	.26	.17E-08
.40	2.44	2.69	99.0	.39	.91-271
.60	3.14	3.45	94.3	.50	.46-248
.80	3.81	4.07	89.9	.57	.56-216
1.00	4.35	4.56	86.5	.63	.16-201
1.20	4.80	4.98	83.8	.68	.97-175
1.40	5.18	5.32	81.7	.72	.55-160
1.60	5.46	5.56	80.1	.75	.38-146
1.80	5.65	5.72	79.0	.78	.70-135
2.00	5.75	5.77	78.5	.80	.95-119
2.20	5.75	5.74	78.5	.97	.50-121
2.40	5.69	5.66	78.8	.96	.12-119
2.60	5.61	5.42	79.3	.99	0.
2.80	5.38	5.33	82.8	.97	0.
3.00	5.39	5.39	84.7	.96	0.
3.20	5.47	5.49	85.9	.94	0.
3.40	5.56	5.58	87.0	.93	0.
3.60	5.67	5.70	87.9	.92	0.
3.80	5.80	5.85	88.5	.91	0.
4.00	5.97	6.04	88.8	.90	0.

TOTAL WEIGHT LOST, PERCENT .7648

TIME, HR 90.00

DEPTH M	AIR TEMP C	POTATO TEMP C	REL HUM PCT	WEIGHT LOSS PCT	FILM THICK MM
0.00	1.03	1.64	76.4	.30	0.
.20	2.91	3.51	67.4	.26	.48-119
.40	3.84	4.02	63.1	.39	.94E-91
.60	4.22	4.41	61.4	.50	.47E-63
.80	4.67	4.82	59.6	.58	.23E-35
1.00	5.38	5.25	70.7	.64	.22E-21
1.20	6.84	6.93	95.1	.69	.21E-07
1.40	7.24	7.22	98.9	.73	.23E-07
1.60	7.07	6.93	100.0	.77	.19E-07
1.80	6.41	6.19	100.0	.80	.12E-07
2.00	5.66	5.50	100.0	.83	.45E-08
2.20	5.20	5.15	100.0	1.0	.59E-09
2.40	5.15	5.21	98.9	1.0	0.
2.60	5.29	5.36	98.9	1.1	0.
2.80	5.44	5.49	98.1	1.1	0.
3.00	5.53	5.55	97.7	1.0	0.
3.20	5.55	5.54	97.9	1.0	0.
3.40	5.51	5.49	98.4	.98	0.
3.60	5.45	5.43	99.0	.97	0.
3.80	5.41	5.40	99.4	.96	0.
4.00	5.40	5.42	99.5	.95	0.

TOTAL WEIGHT LOST, PERCENT .7969

TIME, HR 108.00

DEPTH M	AIR TEMP C	POTATO TEMP C	REL HUM PCT	WEIGHT LOSS PCT	FILM THICK MM
0.00	5.47	6.69	93.3	.36	.32-178
.20	6.82	7.05	94.9	.26	.36E-07
.40	7.66	7.78	97.4	.39	.40E-07
.60	8.01	8.00	99.0	.50	.39E-07
.80	7.87	7.71	100.0	.59	.35E-07
1.00	7.05	6.74	100.0	.64	.24E-07
1.20	5.87	5.55	100.0	.70	.12E-07
1.40	4.89	4.71	100.0	.74	.31E-08
1.60	4.51	4.52	100.0	.79	0.
1.80	4.65	4.77	99.0	.82	0.
2.00	4.94	5.06	97.3	.85	0.
2.20	5.21	5.31	95.9	1.0	0.
2.40	5.42	5.48	95.0	1.0	0.
2.60	5.55	5.58	94.9	1.1	0.
2.80	5.59	5.58	95.2	1.2	0.
3.00	5.52	5.46	96.2	1.1	0.
3.20	5.38	5.32	97.6	1.1	0.
3.40	5.26	5.23	98.6	1.1	0.
3.60	5.20	5.20	99.2	1.0	0.
3.80	5.20	5.21	99.3	1.0	0.
4.00	5.22	5.24	99.2	1.0	0.

TOTAL WEIGHT LOST, PERCENT .9346

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