11-7-1995

Malt Drying Model Verification for Efficiency Improvement

John David Kribs
Portland State University

Recommended Citation
Kribs, John David, "Malt Drying Model Verification for Efficiency Improvement" (1995). *Dissertations and Theses.* Paper 5214.
https://doi.org/10.15760/etd.7090

THESIS APPROVAL

The abstract and thesis of John David Kribs for the Master of Science in Mechanical Engineering were presented November 7, 1995, and accepted by the thesis committee and the department.

COMMITTEE APPROVALS: [redacted]

Craig A. Spolek, Chair

[redacted]

Gerald W. Recktenwald

[redacted]

C. William Savery

[redacted]

Stanley S. Hillman
Representative of the Office of Graduate Studies

DEPARTMENT APPROVAL: [redacted]

Herman J. Migliore, Chair
Department of Mechanical Engineering

* *

ACCEPTED FOR PORTLAND STATE UNIVERSITY BY THE LIBRARY

by [redacted] on 19 December 1995

ABSTRACT

An abstract of the thesis of John David Kribs for the Master of Science in Mechanical Engineering presented November 7, 1995.

Title: Malt Drying Model Verification for Efficiency Improvement.

The aim of this work has been to minimize the thermal energy required to dry malt in deep beds while maintaining malt quality, and without increasing the drying time more than one hour. Malt drying usually takes place in deep bed (.7-1 m) driers by forcing hot air through the bed.

Measurements of inlet and outlet relative humidity, temperature, and airflow at a drier at Great Western Malting Company's Vancouver, Washington facility were made to find average moisture content versus time. The measurements were used to develop a wetted surface model of a malt bed. However, the model was not detailed enough to accurately fit the drying data taken from the kiln. Thus it was necessary to consider a more complex model.

A diffusion based mathematical model of malt drying was coded using malt properties and drying equations found in the research of Bala (Ph.D. thesis, 1983). This program calculates moisture content and malt temperature in horizontal layers of a malt bed. Energy saving drying tests by airflow reduction methods were simulated with the program. The methods were designed to take advantage of the malt's internal drying mechanism, and they were effective at reducing energy consumption. However, model verification was necessary, and maintaining malt quality was essential.

A deep bed experimental malt drier was built at Portland State University to allow malt temperature and average moisture content data collection. Drying experiments were performed at constant airflow, for several different drying temperature cases, and the highest experimental temperature with acceptable malt quality was found to be 75 C. Drying at 70 C (158 F) rather than at 63 C (145 F) was found to cause a 20% reduction in the thermal energy consumption, but higher temperatures did not significantly improve efficiency. The experimental moisture contents and grain temperatures generally compared well with diffusion model simulations of the experiments. Airflow reduction experiments decreased thermal consumption by 20% compared to typical drying schedules. These experiments were based on the airflow reduction methods learned from the diffusion model. However, diffusion model simulations using the experimental conditions showed thermal energy reductions of 11%.

MALT DRYING MODEL VERIFICATION FOR EFFICIENCY IMPROVEMENT

by

JOHN DAVID KRIBS

A thesis submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE
in
MECHANICAL ENGINEERING

Portland State University
1995

ACKNOWLEDGEMENTS

I would like to give my thanks and appreciation to Dr. Graig Spolek, who supervised my work and encouraged me at all times. I also thank the members of my thesis committee, Dr. Gerry Recktenwald, Dr. C. William Savery, and Dr. Stanley Hillman. Each has been very helpful to me. I appreciate the assistance and ideas, for building my research malt drier, given to me by Mr. John Griffin of Portland State University's Mechanical Engineering Department.

This research would not have been possible without the support of GWM (Great Western Malting Company, of Vancouver, Washington). My special thanks go to Mr. John Cuti, Process Research Manager at GWM, who helped me learn a great deal about the malting process. Finally, I thank my wife Lourdes for her unending interest in my research, and for her encouragement of my personal advancement.

TABLE OF CONTENTS

APPENDICES

LIST OF TABLES

LIST OF FIGURES

NOTATION

Operators

Δ	incremental
d	differential
δ	partial differential
ln	natural logarithm

Lower case

a	constant
c_{pa}	specific heat of air, kJ/kg/K
c_{pg}	specific heat of malt grain, kJ/kg/K
c_{pl}	specific heat of water liquid, kJ/kg/K
c_{pv}	specific heat of water vapor, kJ/kg/K
d. b.	dry basis, moisture per unit dry mass
$\dot{m}_{air}$	total mass flow rate of air, kg/s
f()	ratio of fan input power to max. fan input power
g()	search function for wetted-surface model
h	convective heat transfer coefficient, W/ m^2 /K
$h_{ambient\ air}$	specific enthalpy of ambient air, kJ/kg
h_a	specific enthalpy of air, kJ/kg
h_{cv}	volumetric heat transfer coefficient, kJ/ m^3 /min./K
h_g	specific enthalpy of grain, kJ/kg
h_m	convective mass transfer coefficient, m/s
$h_{moisture}$	specific enthalpy of moisture from grain, kJ/kg
k	drying constant, 1/time
$\dot{m}_{air}$	mass flow rate of air, kg/s
$\dot{m}_{water}$	evaporation rate of water, kg/s

m.c.	moisture content
$p_{w,ex}$	partial pressure of water vapor in exhaust air, atm
r	correlation coefficient
rh	relative humidity of drying air, % or decimal
t	time
w.b.	wet basis, moisture per unit wet mass
z	arbitrary height in bed, m

Upper case

A	total surface area of malt in malt bed
D_p	effective grain diameter, m,
G	mass flow rate of air per unit area, kg/ m^2 /min.
G_{max}	maximum G for given fan and system
H	absolute humidity, kg water vapor/kg dry air
L_a	latent heat of water vapor from free water, kJ/kg
L_g	latent heat of water vapor from malt grain, kJ/kg
M	moisture content, % or ratio, d.b.
Mcdb	moisture content, d.b., %
M_e	dynamic equilibrium moisture content, d.b., %
M_{ew}	dynamic equilibrium moisture content, w.b., %
M_w	moisture content, w.b., % or ratio
M_{wi}	initial moisture content, w.b., %
P_{max}	input power to fan at G_{max}
Q	total thermal energy, J
R_0	universal gas constant (8.315 J/kmole/K)
S	bed shrinkage, %
S.E.	standard error of estimate
T_a	temperature of air, C
T_g	temperature of grain, C
W	absolute humidity, kg water vapor/kg dry air
$W_{fan\ input}$	total fan input energy

Greek

ρ	density
$\theta, \phi, \gamma, \omega, \kappa$	constants
μ	viscosity of air, kg/h/m

CHAPTER I

INTRODUCTION

This study attempted to determine if simple changes in the operation of deep-bed malt driers can reduce thermal energy consumed to heat air for drying. In a local malting facility owned by GWM (Great Western Malting Company, Vancouver, Washington), which sponsored this research, drier airflow is typically reduced from its initial level for 33% or less of the total drying time. Drying temperatures are often kept low until the last four hours of drying time. However, airflow and temperature were considered changeable in the effort to reduce energy consumption. Drying physics appeared to indicate that airflow and drying temperature are strong factors in the efficient consumption of thermal energy in malt drying. Malt chemistry showed that the airflow changes could be made with no degradation of product quality. Experience suggested that small changes in drying temperature were possible without risk of unacceptable malt quality.

HYPOTHESES FOR THERMAL ENERGY SAVINGS

Drying Temperature Increases Raise Thermal Efficiency

It was hypothesized that higher malt drying temperature reduces thermal energy consumption in malt drying during the constant-rate period. The constant-rate drying period is characterized by drying surfaces being saturated with moisture. Internal moisture movement in the substance brings moisture to the surface rapidly enough that the surface remains saturated and the drying rate (evaporation rate) is controlled by varying drying temperature, air humidity, and airflow. The hypothesis was based on the fact that air drying efficiency increases at higher drying temperatures (Bruce 1983). The principle can be demonstrated by convective mass-transfer theory predictions for the effect of increasing drying temperature. The increase in saturated water vapor density at the drying surface with increasing temperature, and the change in drying air vapor density (which is inversely proportional to drying temperature) combine to make air drying more efficient at higher drying temperatures.

The controllable factors for the constant-rate drying period are formulated in convective mass-transfer theory. This theory states that the mass transfer rate from a body is proportional to the difference between the surface vapor density and the vapor density of the surrounding air. Mass transfer rate is also proportional to the surface area of the body and the mass transfer coefficient, which is experimentally or analytically determined. Since the body's (malt's) surface is saturated with moisture, increasing drying temperature causes the surface vapor density to increase and the drying air vapor density to decrease, inversely proportional to temperature. The effect is to increase the drying rate a larger percentage than the increase in the rate of thermal energy input for drying.

Timed Airflow Reductions Save Energy Without Impeding Drying

Employees at the local malting company typically feel airflow is crucial to dry malt within a specified time period. They have increased blower size and power to boost production. On one hand, convective mass transfer theory agrees with the belief in high airflow during constant-rate drying. Conversely, after constant-rate drying, high airflow not only does not boost production, it is hypothesized to waste energy. This view is supported by the following evidence:

1. Air drying includes a constant-rate period and one or more falling-rate periods.
2. Many authors accept that during falling-rate drying, grains typically dry by diffusion (Bruce 1985), or at least that the principal rate-determining step is internal mass transfer (Chirife 1983).
3. Since internal mechanisms control drying during the falling-rate period, the influence of external variables (temperature, humidity, airflow, state of subdivision, etc.) diminishes (Perry 1984).
4. The thermal energy consumed in drying is directly proportional to the level of airflow.

The falling-rate period begins with a transition from external to internal control of drying rate. This transition marks the point when not all the surface of the drying body is saturated. A hypothetical substance's drying curve illustrating the constant and falling-rate drying periods is shown in Figure 1. As the body becomes drier, the point when the entire surface is unsaturated marks when the internal drying mechanisms dominate the drying rate.

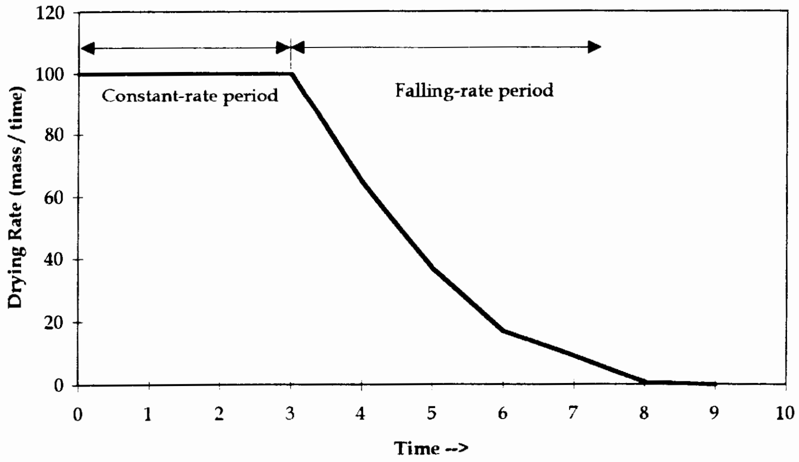


Figure 1. Drying Periods.

After the constant-rate drying period, the drying air typically no longer becomes saturated with moisture. Since the amount of drying air no longer dominates the drying rate, it is clearly wasting some thermal energy to use the same amount of airflow as in the constant-rate period. The thermal energy consumption of drying is proportional to the airflow rate. Thus, any reduction in airflow rate that does not affect drying rate is pure thermal energy savings.

Malt Quality Can Be Maintained in Spite of Temperature and Airflow Changes

It was hypothesized that airflow level has a weak bearing on finished malt quality, and that small temperature increases can be made without damaging malt quality. No malt quality parameters mentioned in Briggs (1981) are said to be dependent on airflow, although high airflow is said to increase the evaporative cooling effect, which indirectly connects airflow to quality, through malt temperature. Evaporative cooling occurs because the heat transferred from air to grain is used in changing water from liquid to vapor. Thus, the high temperature of the air is reduced as it becomes saturated with vapor near the grain and the grain is heated only to the wet-bulb air temperature. Since the hot air is typically very dry, the wet-bulb temperature is much lower than the hot air temperature. This temperature difference is what is known as evaporative cooling. Extremely high airflow may cause heat damage by rapid heat and moisture transfer, but sharp airflow reductions are likely to have a weak effect on quality, at least at lower malt moisture contents.

Increasing initial drying temperature and holding it constant until roasting appeared to be possible. (Roasting is the high temperature final drying stage that builds the color, flavor, and aroma of the malt). The following observations relate to this view:

1. Enzymatic inactivation increases with increasing temperature (Briggs 1981).
2. Industrial drying schedules include several stages of drying at successively higher temperatures before roasting.

Predictive malt quality models that consider industrial malt quality requirements do not exist, to the author's knowledge. Tradition guided nearly all malt drying schedules, but testing of temperature effects on quality has not been pursued in the effort to reduce thermal energy consumption. Even though Briggs (1981) recognized that enzymatic inactivation rises with increasing temperature, the rate or extent of the increase is unknown. Typical industrial use of several temperature increases during the constant-rate drying period suggest that the maximum of these temperatures could be used throughout drying, up to the roasting stage.

HISTORY OF THE PROBLEM

To the author's knowledge, no experiments or model-based tests have been published which show both airflow and temperature changes can reduce thermal energy consumption for deep-bed malt driers. Kuntze (1994) developed a deep-bed wetted-surface drying model. He used it with a drier model, which included heat exchangers and drying air recirculation, in order to save thermal energy. He also used his model to predict when the target moisture content (the amount of water per wet or dry material) would be reached to avoid thermal energy loss due to over drying. Bala (1983) developed an adsorbed-liquid diffusion model and applied it to thermal energy comparisons between driers using gas-fired heat, indirect steam heat, and gas-fired heat with drying air recirculation. Bruce (1983) developed a complex moisture-dependent diffusion model of barley drying in order to model driers that use high drying temperature to increase thermal efficiency. However, he emphasized using new driers (continuous counter-flow) rather than improving the process in existing ones.

THERMAL ENERGY-SAVING RESEARCH DIRECTION

To approximately determine the maximum possible constant drying temperature, drying tests were done with an experimental drier. Experiments were also done, after making simulations with a diffusion-based drying model, to find airflow schedules that would increase the thermal efficiency of drying. Although higher drying temperature raises thermal efficiency (Bruce 1983), malt enzyme levels decrease with increasing temperature (Briggs 1981). The enzyme levels are required if the malt is to produce useful wort and, finally, acceptable beer (pale ale, for the malt studied in this work). A balance between malt quality changes and thermal energy reduction had to be found.

Industrial malting processes start out by alternately immersing and draining barley in a tank for a total of 40 hours. The malt, at about 45% w.b. moisture content, has begun germinating at this point, and it is then put through a germination process lasting from 4-6 days. Since drying, or kilning, is the last phase in the malt production sequence, it must fit in the time schedule of the other operations. Changes in the airflow schedule for drying could not cause drying delays of more than an hour, perhaps. Thus the effect of schedule changes on the time required to dry from 45% w.b. to 4% w.b. had to be determined.

Since malt drying schedules depend on the malt bed thickness, drying airflow uniformity, and the ambient humidity, different industrial kilns and different ambient weather conditions may require that different lengths of time be used for drying. Rather than making in-process moisture content checks or kiln-specific schedules, using drier control strategies based on exhaust air conditions was considered.

QUALITY AND MOISTURE CONTENT DEFINITIONS AND DESCRIPTIONS

The quality parameters of interest in the finished malt are the moisture content, soluble protein, alpha amylase, diastatic power, extracts, malt color, clarity, viscosity, and beta glucan. Several of these parameters are described in the following list:

- *Alpha amylase,* an enzyme, degrades starch to a complex mixture of sugars. Alpha amylase is degraded during kilning (Briggs 1981).

- *Beta glucans,* made up of glucose, may contribute to beer foam and palate fullness. However, they are, and must be, degraded during kilning (Briggs 1981).

- *Clarity* denotes the transparency of the resulting wort in brewing. Clear wort is desirable. Values of clarity: 1 is clear,..., greater than 5 is unacceptable for pale ale malts (Cuti 1995).

- *Color* is created by Malliard reactions and Amadori rearrangements, and its formation rate is proportional to temperature and increases with increasing moisture content (Briggs 1981).

- *Diastatic power,* a mixture of barley enzymes (alpha-glucosidase and 'debranching enzyme(s)'), is degraded during kilning (Briggs 1981).

- *Dry basis, d.b.,* describes the water mass of a substance as a ratio or percentage of the total dry mass of the substance.

- *Enzymes* are degraded during kilning, at a rate which increases with increasing moisture content and increasing temperature (Briggs 1981).

- *Extracts* are given by the percentage of the water soluble portion of dry malt that goes into solution (Cuti 1995).

- *Moisture content, m.c.,* is the water content that can be removed without changing the chemical composition of the substance. It is given on a dry or wet basis.

- *Soluble protein* is given by the percentage of the total protein that is soluble in water (Cuti 1995).

- *Viscosity* refers to the viscosity of the wort. It is measured by the time required to pass 2 ml of wort through an orifice, and in units of centistokes (cs). Values less than 1.6 cs are acceptable for pale ale malts (Cuti 1995).

- *Wet basis, w.b.,* describes the water mass of a substance as a ratio or percentage of the total mass of the dry substance and water.

THESIS PREVIEW

This thesis reviews the solution process of decreasing the thermal energy consumption of malt drying. Its initial, unsuccessful efforts to it final achievements are described. The hypotheses that spawned the productive experimental work initially focused on temperature-based thermal energy savings. The realization that the falling-rate drying period offers its own unique mechanism, which can be exploited, came considerably later. In the spirit of illuminating what worked as well as what did not work, Chapters II and III consider the unfruitful attempts at energy saving. Chapter II summarizes an attempt to estimate average malt moisture contents in-process at a GWM kiln. The analysis is based on psychrometrics using temperature, and relative humidity where necessary, measurements at single points in each level of the kiln. Chapter III looks at the determination of parameters for a simple wetted-surface drying model. The model calculates average moisture content as well as temperature and humidity of the drying exhaust air. Chapter IV reviews the development of an adsorbed-liquid diffusion model that was made by Bala (1983). The model inspired the airflow schedules tested in malt drying experiments. Chapter V describes the research malt drier used for drying experiments. Drying temperature and airflow experiments are presented in Chapter VI. Chapter VII compares the moisture content and grain temperature results of diffusion model simulations with malt drying experiments. Finally, Chapter VIII summarizes the results and conclusions of the thesis.

CHAPTER II

IN-PROCESS MOISTURE CONTENT ANALYSIS

OVERVIEW OF COMPARTMENT HOUSE KILN OPERATION

In-process malt drying measurements were made at a kiln at GWM. The results were used to determine each bed's drying curve (a graph of a substance's moisture content versus time) and to analyze whether the method was reliable for in-process moisture content estimation. A two-deck kiln, called the Compartment House, was used for the measurements because these kilns produce the majority of the company's malt. Figure 2 shows the layout for a two-deck kiln, with numbered points for future reference.

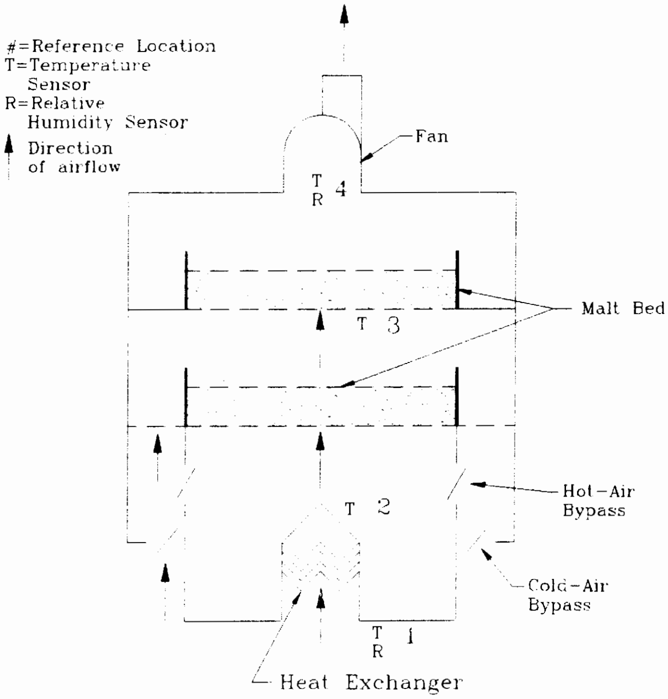


Figure 2. Compartment House Kiln Schematic.

The two-level kiln draws air from the outside, point 1, into the heat exchanger, and heated air at 2 is used to dry both beds, which are supported by perforated floors. Hot-air bypasses (HABs) are opened to let heated air at 2 bypass the lower deck to concentrate drying on the upper deck. HABs are usually open while cold-air bypasses (CABs) are shut, and vice versa. CABs are opened to allow outside air to enter the kiln at 3 to limit the drying temperature of the upper deck malt, so it, which is moister than the lower-deck malt, is not heat damaged.

METHOD OF MOISTURE CONTENT ESTIMATION

Moisture content estimates were made with the temperature data taken from single points at each level in the kiln and the relative humidity data taken at the inlet to the heat exchanger and at the inlet to the roof blower. (See Figure 2). The air absolute humidity was calculated using psychrometric relations, and the airflow was estimated through the lower and upper decks. These calculations required several assumptions, which are listed below, to completely determine all the necessary variables.

The assumptions used in the moisture content determination were as follows:

1. No heat is transferred between the drying air, the malt, and the kiln structure. Only moisture transfer is considered.
2. Each bed is at a uniform moisture content.
3. Air pressure changes between the numbered points in Figure 2 are negligible.

4. Outside air flowing through the CABs does not go through the hot-air bypasses to point 2.

Using the above assumptions, the drying rates for the lower and upper decks were estimated using the temperature and relative humidity sensors shown in Figure 2 and knowledge of the airflow through the heat exchanger. Then the malt drying rate was found by a simple mass balance on the airflow moisture. Analyzing the drying rates was complicated by the CABs. However, the assumptions allowed the conditions to be determined at all the numbered points. Temperature, relative humidity, and absolute pressure at any point determine the absolute humidity (referred to as 'humidity' in the rest of this work) and all other properties of the air.

At point 1, the temperature and relative humidity were known. The air humidity was constant from 1 to 2, thus allowing determination of the moisture content of the air entering the lower bed. Two different methods, which depend on the state of the HABs and CABs, were used to determine the humidity at 3. The four possible states for the HABs and CABs are listed below.

Case A: HABs and CABs both closed.

Case B: HABs open and CABs closed.

Case C: HABs closed and CABs open.

Case D: HABs open and CABs open.

For cases A and B, the drying air enthalpy was assumed constant from 2 to 3, allowing the air humidity at 3 to be calculated from the enthalpy and temperature of the air at 3.

For cases C and D, the drying air enthalpy is not constant from 1 to 2. It was necessary to resort to the assumption that the drying air enthalpy remains constant from 4 to 3. Then the air humidity at 3 was calculated from the enthalpy and temperature of the air. Although outside air from 1 adds to the airflow at 3, the only airflow that gains humidity is the airflow through the lower bed, allowing one to ignore the airflow through the CABs and to calculate the drying rate of the lower bed by a moisture mass balance on the airflow through the heat exchanger. The method for cases C and D may also be used for cases A and B to reduce the chance of using the wrong method.

Given the airflow through the heat exchanger, the airflow through the upper deck was estimated. When the CABs are open and outside air bypasses the lower deck, the amount of the bypass air can be calculated from an energy balance using the enthalpy of the outside air, the enthalpy of the air from the heat exchanger, and the enthalpy at 3 (which is equal to 4). When the CABs are closed the airflow through the heat exchanger is the same as the airflow through the upper deck. So, with the airflow through the upper deck known, the enthalpy at point 3 was set equal to the enthalpy at 4, the humidity at 3 was calculated, the humidity at 4 was calculated, and the upper-deck drying rate was found. Equations (in English units) to calculate air conditions required for each deck moisture content estimate are given in the Appendix.

The airflow through the heat exchanger was estimated by doing an energy balance on the hot water and the airflow through the heat exchanger. Since the energy input of water into the heat exchanger, and the temperature difference of air through the heat exchanger, is measured, the mass flow of air required to remove the energy from the water can be calculated. Airflow was checked using a vane-anemometer to measure at the air inlets under the heat exchanger, at the inlets to the roof fans, and at the leaky grain chutes in the roof. The measurements were converted into mass flow rates, and they agreed within

1.7%. They also typically agreed within 8.6% with the airflows calculated from the heat exchanger energy-balance method.

The lower and upper-deck moisture content estimates from the method described above did not turn out to be accurate, with the lower-deck estimates often going considerably into negative moisture contents. This may have been partly due to the fact that all moisture content estimates depended on the initial value of the bed moisture content, which was estimated by a one-point measurement for the upper and lower decks. Accuracy may also have been limited by using only one-point for each level of the kiln for the estimate of air enthalpy and humidity. Since this method did not provide any good information, it was not followed up with any large-scale energy tests.

TYPICAL PROCESS THERMAL ENERGY CONSUMPTION

The basis for comparison of drying thermal energy efficiency used in this work is energy per mass of finished malt. The energy considered was the thermal energy required to heat air from the ambient temperature to the drying temperature. The total thermal energy consumption, Q, to dry malt can be estimated by

$$Q = \int_0^{t_1} \dot{m}_{air} \cdot c_{pa} \cdot (T_a - T_{ambient}) \cdot dt. \qquad (1)$$

Where

t_1 = total drying time,

$\dot{m}_{air}$ = airflow (mass/time),

T_a = drying air temperature,

and

$T_{ambient}$ = ambient air temperature.

Estimates for energy consumption were made from two-deck kiln data that was available from June through September 1994, and which showed an average of 3.2 MJ/kg of malt. This value is lower than the average of 3.9 MJ/kg in the U.K., mentioned by Bala (1984). The difference in values may be attributed to the fact that two-deck kilns are typically more efficient than one-deck kilns, which were also included in the U.K. average. Also, the average for the GWM kiln was only for summer months, which means the average thermal energy input to the drying air was lower than that for the other seasons.

Calculations were made by the author that estimated the minimum thermal energy to dry malt from 46% to 4%, w.b. to be 2.1 MJ/kg. The minimum thermal energy can be considered to be the baseline case against which all other drying energy requirements may be measured. It was calculated assuming:

1. Water heat of vaporization from malt, L_{malt}, = 2370 $\frac{kJ}{kg}$,
2. An average malt temperature of 54.4 C during evaporation,
3. Malt is heated from 26.7 C to 82 C at an average moisture content of 31% w.b.,
4. An average specific heat of malt, c_{pg}, = 2.928 $\frac{kJ}{kg}$.

The minimum thermal energy per mass of malt includes the latent and sensible heat required to dry the malt and heat it from the initial to the final temperature.

CONCLUSIONS

Two-deck malt drying moisture content estimates made by measuring temperature at one point per drier section and relative humidity at the drier inlet and outlet are not accurate enough to use for drier control or drier efficiency studies. The minimum estimated thermal energy to dry malt from 46 to 4% w.b. moisture content is 2.1 MJ/kg. This estimate would never be achievable in practice, though it shows that current drying efficiencies can be improved.

The drying moisture content data from the upper deck was used to develop a wetted-surface drying model. It was hoped that the model would closely predict the overall drying response of the kiln since the high initial moisture content of the malt causes it to dry like pure water. The model development is described in Chapter III.

CHAPTER III

WETTED-SURFACE MODEL

The wetted-surface drying model's development was motivated by the desire to make a simple model of average malt moisture content as well as drier exhaust air temperature and humidity. Using data directly from industrial malt drying in the local kiln, it was hoped that the model would closely predict the average malt moisture content estimated as in Chapter II, at least for the upper deck. Its use in this work was motivated by the need to estimate efficiency improvement by changing drying temperature.

Only average properties of a malt bed were modeled. The malt bed was assumed to be a point of malt that had the average moisture content and temperature of the bed. Outside air temperature and humidity, drier airflow, initial malt moisture content, and target moisture content were the inputs to the model. The model was coded in Microsoft Excel 4.0 macro language and is listed in the Appendix. Average malt moisture content, malt temperature, drier exhaust air temperature and humidity, and cumulative thermal energy were calculated. Heat transfer between the drying air and the malt was assumed negligible, and only evaporation from the malt to the air was considered, although the malt surface temperature was increased as necessary to be in thermal equilibrium with the air at the malt surface.

A desorption isotherm for malt was the basis for determination of the drying rate. Desorption isotherms, which are for a substance undergoing dehydration, plot the equilibrium air relative humidity for the substance against the moisture content of the substance. The isotherm data is found by fixing the relative humidity and temperature of the air surrounding a sample of the substance, then waiting for the substance's moisture content to come to equilibrium with the surrounding air, and finally measuring the moisture content of the substance. A desorption isotherm is made at a constant temperature for a succession of decreasing air relative humidities. Several graphs are made for a substance at various air temperatures. Equilibrium relative humidity typically increases with increasing temperature. For the wetted-surface model, however, only one desorption isotherm from Briggs (1981), for malt at 36 C, was used.

DERIVATION OF MODEL PARAMETERS FROM COMPARTMENT HOUSE DATA

The model was developed using upper-deck drying-rate data from the local kiln during the constant-rate drying period. The drying rate for the upper-deck was found as in Chapter II. The drying air water vapor density was found using the air's water vapor pressure, temperature, and the ideal gas law. Malt surface water vapor density was found using the malt surface vapor pressure, temperature, and the ideal gas law. The convection mass-transfer equation was solved for the product of the mass-transfer coefficient and the total grain surface area ($h_m A$). The convection mass-transfer equation is given by

$$\dot{m}_{water} = h_m A(\rho_{surface} - \rho_{\infty}) \tag{2}$$

where,

$\dot{m}_{water}$ = rate of evaporation of water for the upper deck,

h_m = convection mass transfer coefficient,

A = total grain surface area of the upper deck,

$\rho_{surface}$ = malt surface vapor density at the upper deck's average moisture content,

ρ_{∞} = drying air vapor density.

The following assumptions were used in developing the model from kiln data:

1. The malt temperature is assumed equal to the temperature of the air at its surface, where the air has the malt equilibrium relative humidity and has the enthalpy of the drying air
2. The malt equilibrium relative humidity is given by the malt's desorption isotherm, for 36 C, as a function of the bed moisture content.
3. The drying air vapor density is taken as the log-mean value of the vapor density of the drying air into and out of the upper deck.
4. The entire upper deck of malt is assumed to be at the same moisture content and the same temperature.
5. There is no heat transfer between the drying air, the malt, and the kiln structure.

In assumption one, the thermal equilibrium statement is true to a close approximation (Bala 1983). The second assumption is used in the calculation of the malt surface vapor density. It states that the malt moisture content instantaneously comes to equilibrium with the drying air, which is not likely, though it is necessary for this crude model. The third assumption is reasonable, though not well tested. The log-mean drying air vapor density mentioned in the third assumption is given by

$$(\rho_{\text{surface}} - \rho_{\infty})_{LM} = \frac{\rho_{\infty 2} - \rho_{\infty 1}}{\ln\left(\dfrac{\rho_{\text{surface}} - \rho_{\infty 1}}{\rho_{\text{surface}} - \rho_{\infty 2}}\right)}, \tag{3}$$

where 1 refers to the drying air entering the bed and 2 refers to the air leaving the bed. Assumption four is very approximate, and assumption five is good to the extent that moisture transfer dominates the energy consumption in drying and that the heat loss from the kiln structure is small, which was true for measurements taken in summer months.

Once $h_m A$ was found for several sets of constant-rate drying data, the average value was used in a wetted-surface model that worked under the assumptions given above. The mass-transfer coefficient, and thus $h_m A$, was assumed to depend on the mass-flow rate of air per unit cross-sectional area of the bed, G, and the diameter of a sphere with the same surface area as a malt grain, D_p (Geankoplis 1983). The functional dependence used was developed for heat transfer, but it applies to malt drying in accord with the heat-mass transfer analogy. The heat transfer convection coefficient function is given by

$$\begin{aligned} h &= .151\frac{G^{.59}}{D_p^{.41}}, \quad \frac{D_p G}{\mu} > 350 \\ h &= .214\frac{G^{.49}}{D_p^{.51}}, \quad \frac{D_p G}{\mu} \le 350 \end{aligned} \tag{4}$$

where,

h = convective heat transfer coefficient, $\frac{W}{m^2 K}$,

D_p = effective grain diameter, m,

G = mass flow rate per unit area, $\frac{kg}{h \cdot m^2}$,

μ = viscosity of air, $\frac{kg}{h \cdot m}$.

WETTED-SURFACE MODEL SOLUTION SCHEME

The model determines the malt bed's average moisture content, the malt temperature, the drying air exhaust temperature, and the drying air humidity. The solution process starts by calculation of the following drying air properties: humidity, enthalpy, wet-bulb temperature, partial pressure of saturated water vapor at the drying air temperature, and actual partial pressure of drying air water vapor. Exhaust air temperature is initially assumed to be the wet-bulb temperature of the drying air. The malt equilibrium relative humidity, rh_{malt}, is found from a curve-fit equation of the desorption isotherm. The equation, a curve-fit with a third-order polynomial to a desorption isotherm (at 36 C) from Briggs (1981), is given by

$$rh_{malt} = \frac{-0.0272 \cdot M_w^3 + 0.7561 \cdot M_w^2 + 0.3735 \cdot M_w + 0.9431}{100}, \qquad (5)$$

where M_w is given as a percentage and rh_{malt} is given as a decimal. The malt equilibrium relative humidity actually is scaled such that it declines from 100% relative humidity when the moisture content falls below 30% w.b. Using the desorption isotherm, however, the equilibrium relative humidity remains at 100% until the moisture content falls below 19% w.b. The scaling is necessary to make the model agree with kiln data, at least down to the 30% w.b. moisture content range.

For the first time step, the partial pressure of the exhaust air water vapor is initially guessed equal to 98% of the drying air's saturated partial pressure of water vapor. For subsequent time steps, it is initially guessed equal its previously calculated value. For each time step, the new malt temperature is guessed, using assumption 1. The new partial vapor pressure at the surface of the malt, and the new partial saturated-vapor pressure (at the malt temperature) are calculated with the malt temperature guess. Then an iterative routine, which seeks the new value of the malt surface vapor pressure and the new exhaust air temperature, is performed.

The two primary unknowns in the iterative routine are the exhaust air humidity (given by the partial pressure of the exhaust air water vapor) and the drying rate of the malt bed. Each must be solved in order to find the other, since the partial pressure of water vapor in the exhaust air, $p_{w,ex}$, is required to solve eq. (3) and it is required to find the exhaust air humidity. A Newton-Raphson root-finding search is made for $p_{w,ex}$ such that the drying rate given by the convection mass transfer equation equals the drying rate given by a moisture mass balance on the airflow into and out of the malt. The function, g, for which the search seeks a zero, is expressed as

$$g(p_{w,ex}) = h_m A \cdot (\rho_{surface} - \rho_\infty)_{LM} - \dot{m}_{air} \cdot (H_2 - H_1), \tag{6}$$

After $p_{w,ex}$ is found, the exhaust temperature and humidity are calculated, and the malt moisture content is updated. The updated malt equilibrium relative humidity is found. Malt temperature is calculated, using assumption 1. The iterative routine is repeated until the iteration updates for malt surface vapor pressure and exhaust air temperature converge to a set criterion.

After the iterative routine succeeds, the exhaust air humidity is found, the new moisture content of the malt is calculated using the amount of moisture evaporated, the thermal energy consumption is solved, and the new equilibrium relative humidity of the malt is found using the malt moisture content and the desorption isotherm. The solution process is repeated until the target moisture content is reached.

MODEL SIMULATION RESULTS

The model indicated higher thermal efficiency for drying during the constant-rate period using increased temperatures. Thermal energy savings up to 50% were realized when drying at a constant 99 C as opposed to typical industrial drying schedules that only reach 83 C for several hours. The model did not fit the drying data taken from the local malting company well, and it tended to predict drying rates at low moisture contents that were much higher than found in typical kilns. Although efficiency improvements from higher drying temperatures were possible, the model did not reveal the maximum possible constant drying temperature that would produce malt of an acceptable quality. Since the model also did not include an internal malt drying mechanism, it was necessary to consider a more sophisticated model, which led to the use of the model described in Chapter IV.

CHAPTER IV

ADSORBED-LIQUID DIFFUSION MODEL

In order to develop potential energy saving methods in an efficient and direct fashion, a mathematical model of malt drying based on internal moisture diffusion was coded and developed for this study. The model was derived by Bala (1983), and reported in Bala (1984), from thin-layer drying experiments in which a layer of malt less than two kernels deep was dried on a scale. The drying air temperature was assumed equal to the malt temperature in the thin-layer experiments, and the drying model equations were fitted to the data. The program's algorithm is in the form of Bala's "model one," which uses a style of grain drying simulation developed at the University of Michigan. The properties of the malt varieties Triumph and Sonja were used to develop the model. These malts are classified as two-row, as opposed to six-row, in reference to the way they grow on the stalk of the barley plant.

MODEL OVERVIEW

Model one uses the solution sequence of Bala (1983). The Turbo C version 3.0 source code of model one is listed in the Appendix. A system of partial differential equations model changes in malt temperature, moisture content, and drying air temperature and humidity through the depth of a bed. A finite difference scheme using a number of horizontal layers is used for the solution of the system of partial differential equations because there is no known closed-form solution. Typically, one-hundred layers were used with model one for a typical deep bed thickness of malt.

Input to the model consists of a sequence of ambient air temperatures, relative humidities, drying airflows and temperatures versus time. The other input includes initial malt moisture content and temperature, and the depth and density of the bed. The model output includes the moisture content, air and grain temperature (and humidity) at each layer, the exhaust air temperature and humidity, the average bed moisture content, and the depth of the bed (taking into account shrinkage).

The solution of the layer variables begins at the bottom of the bed and propagates up through the layers. Heat transfer between the malt and the drying air is included. No heat transfer between the malt and the kiln, or the air and the kiln, is considered. An equation that models deep-bed shrinkage as a function of moisture content adjusts the layer thickness after each time step to improve the model's accuracy. The maximum relative humidity of drying air allowed is 98%, to avoid instability as well as impossible relative humidity conditions. When the drying air relative humidity for a layer goes above 98%, a condensation routine is performed which recalculates the amount of evaporation until the relative humidity drops to 98% or less.

Moisture is modeled as an adsorbed liquid, that is, as water chemically held to the malt. The drying rate is found using an equation typically used in grain drying models because it is easy to solve and gives reasonable results. This equation, the "single-exponential" drying rate equation, may be expressed as

$$M = ae^{-kt} + M_e \tag{7}$$

where,

M = moisture content, %,

a = constant,

k = drying constant,

M_e = dynamic equilibrium moisture content, %.

An equivalent expression is

$$\frac{dM}{dt} = -k(M - M_e). \tag{8}$$

Equations (7) and (8) implicitly assume that the moisture within each grain of malt is uniformly distributed. The dynamic equilibrium moisture content differs from the equilibrium moisture content described in Chapter II in connection with the malt desorption isotherm. Since there is not enough time for the malt to come to equilibrium with the drying air because the malt moisture content is changing relatively quickly, the dynamic equilibrium moisture content was hypothesized by McEwen (1954) to make the drying rate equation fit thin-layer drying experiments better.

PARTIAL DIFFERENTIAL EQUATIONS

The equations of this section are as derived by Bala (1983). Using the variables for updated values of drying air temperature, drying air humidity, malt temperature, and malt moisture content, the equations consider a thin horizontal layer in a malt bed. A schematic diagram of the malt layer is shown in Figure 3.

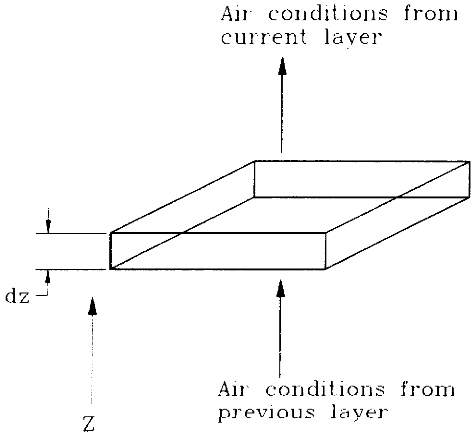


Figure 3. Control Volume of Malt and Air in Deep Bed Layer.

Mass Balance Equation for a Control Volume

The statement of conservation of moisture mass for the control volume with air flowing vertically through it is

moisture loss of malt = moisture gain of air.

This is given as an equation by

$$\rho_{db} \cdot dz \cdot \left(-\frac{\partial M}{\partial t} \right) \cdot dt = G \cdot dt \cdot \left(\frac{\partial H}{\partial z} \right) \cdot dz, \tag{9}$$

$$\frac{\partial H}{\partial z} = \frac{\rho_{db}}{G} \cdot \left(-\frac{\partial M}{\partial t} \right),$$

or in finite difference form,

$$\Delta H = -\rho_{db} \cdot \frac{\Delta z}{G} \cdot \frac{\Delta M}{\Delta t}. \tag{10}$$

Drying Rate Equation

The drying rate is given by eq. (8), and in finite difference form, by

$$\Delta M = -k \cdot (M_{t+\frac{\Delta t}{2}} - M_e) \cdot \Delta t$$

$$= \quad -k \cdot \left((M + \frac{\Delta M}{2}) - M_e \right) \cdot \Delta t$$

$$\Delta M \cdot (1 + \frac{k}{2} \cdot \Delta t) = -k \cdot (M - M_e) \cdot \Delta t$$

where the subscript $t + \frac{\Delta t}{2}$ indicates the average value of the variable over Δt.

The final form is

$$\Delta M = \frac{-k \cdot (M - M_e) \cdot \Delta t}{1 + \frac{k}{2} \cdot \Delta t} \quad . \tag{11}$$

Heat Balance Equation

The statement for energy conservation for a control volume with air flowing vertically through it is

change in enthalpy of air flowing through control volume = - change in grain enthalpy.

This analysis neglects the change in enthalpy of air stored in the control volume. The equation form of the heat balance equation is given by

$$G \cdot dt \cdot dh_a = -\rho_{db} \cdot dz \cdot dh_g , \tag{12}$$

or in finite difference form, by

$$G \cdot \Delta t \cdot \left[(h_a + \Delta h_a) - h_a \right] = -\left[\rho_{db} \cdot \Delta z \cdot \left((h_g + \Delta h_g) - h_g \right) \right] ;$$

$$\begin{aligned} G \cdot \Delta t \cdot [(c_{pa} \cdot (T_a + \Delta T_a) + c_{pv} \cdot (H + \Delta H) \cdot (T_a + \Delta T_a) + L_a \cdot (H + \Delta H)) - \\ (c_{pa} \cdot T_a + c_{pv} \cdot H \cdot T_a + L_a \cdot H] = \end{aligned}$$

$$-\rho_{db} \cdot \Delta z \cdot \left[(T_g + \Delta T_g) \cdot (c_{pg} + c_{pl} \cdot (M + \Delta M)) - T_g \cdot (c_{pg} + c_{pl} \cdot M) \right] . \tag{13}$$

Substituting for ΔH from eq. (10) into eq. (13), rearranging, and then solving for ΔT_a,

$$\Delta T_a = \frac{\frac{-\rho_{db}\cdot\Delta z}{G\cdot\Delta t}\cdot\left[\Delta T_g\cdot(c_{pg}+c_{pl}\cdot(M+\Delta M))-\Delta M\cdot(T_a\cdot c_{pv}+L_a-T_g\cdot c_{pl})\right]}{c_{pa}+c_{pv}\cdot(H-\rho_{db}\cdot\frac{\Delta z}{G}\cdot\frac{\Delta M}{\Delta t})}. \qquad (14)$$

Heat Transfer Rate Equation

The statement for the heat transfer rate to a control volume around a thin horizontal slab of air and grain is

heat loss from air to grain = gain in sensible heat of grain + gain in enthalpy of evaporated moisture.

This is given in equation form as

$$h_{cv}\cdot dz\cdot(T_a-T_g)\cdot dt=\rho_{db}\cdot dz\cdot dh_g+\rho_{db}\cdot dz\cdot(-dM)\cdot dh_{moisture}. \qquad (15)$$

In finite difference form, we have

$$\begin{aligned} h_{cv}\cdot\Delta z\cdot\left[\left(T_a+\frac{\Delta T_a}{2}\right)-\left(T_g+\frac{\Delta T_g}{2}\right)\right]\cdot\Delta t \ &= \ \rho_{db}\cdot\Delta z\cdot\Delta T_g\cdot(c_{pg}+c_{pl}\cdot M)+ \\ &\quad \rho_{db}\cdot\Delta z\cdot(-\Delta M)\cdot(L_g+c_{pv}\cdot T_a-c_{pl}\cdot T_g); \end{aligned} \qquad (16)$$

$$\begin{aligned} 2\cdot(T_a-T_g)+(\Delta T_a-\Delta T_g) \ &= \ \frac{2\cdot\rho_{db}}{h_{cv}\cdot\Delta t}\cdot[\Delta T_g\cdot(c_{pg}+c_{pl}\cdot M)- \\ &\quad \Delta M\cdot(L_g+c_{pv}\cdot T_a-c_{pl}\cdot T_g)]. \end{aligned}$$

Setting

$$\theta=2\cdot(T_a-T_g),$$
$$\phi=c_{pg}+c_{pl}\cdot M,$$
$$\gamma=L_g+c_{pv}\cdot T_a-c_{pl}\cdot T_g,$$

then

$$\Delta T_a \ = \ -\theta+\Delta T_g\cdot(1+\frac{2\cdot\rho_{db}}{h_{cv}\cdot\Delta t}\cdot\phi)-\frac{2\cdot\rho_{db}}{h_{cv}\cdot\Delta t}\cdot\Delta M\cdot\gamma. \qquad (17)$$

Setting

$$\omega = c_{pa} + c_{pv} \cdot (H - \frac{\rho_{db} \cdot \Delta z}{G} \cdot \frac{\Delta M}{\Delta t}),$$
$$\kappa = c_{pv} \cdot T_a + L_a - T_g \cdot c_{pl},$$

and substituting into eq. (14),

$$\Delta T_a = \frac{-\rho_{db} \cdot \Delta z}{G \cdot \omega \cdot \Delta t} \cdot \left[\Delta T_g \cdot (\phi + c_{pl} \cdot \Delta M) - \Delta M \cdot \kappa \right]. \tag{18}$$

Equating eqs. (17) and (18) and solving for ΔT_g,

$$\Delta T_g = \frac{\theta + \frac{\rho_{db} \cdot \Delta M}{\Delta t} \cdot \left(\frac{2 \cdot \gamma}{h_{cv}} + \frac{\Delta z \cdot \kappa}{G \cdot \omega} \right)}{1 + \frac{\rho_{db}}{\Delta t} \cdot \left[\frac{2 \cdot \phi}{h_{cv}} + \frac{\Delta z}{G \cdot \omega} \cdot (\phi + c_{pl} \cdot \Delta M) \right]}. \tag{19}$$

MALT PROPERTIES AND DRYING RATE EQUATION

Equations for malt properties and drying rate are based on Triumph and Sonja varieties, as determined by Bala (1983). The specific heat capacity of malt is given by

$$c_{pg} = 1.651 + 0.04116 \cdot M_w, \quad r^2 = 0.99, \tag{20}$$

where M_w is set as a percentage and r is the correlation coefficient for the equation.

The volumetric heat transfer coefficient equation is

$$h_{cv} = 4.932 \times 10^4 \cdot G^{.6906}, \quad r^2 = 0.9. \tag{21}$$

The deep bed malt depth percent shrinkage is

$$S = 15.91 \cdot \{1 - \exp[-0.0996 \cdot (M_{wi} - M_w)]\}, \quad S.E. = 0.6871, \tag{22}$$

where M_{wi} and M_w are set as percentages. S.E. is the standard error of estimate.

The heat of vaporization of water evaporating from the malt, L_{malt}, is given by

$$\frac{L_{malt}}{L_{water}} = 1 + 0.5904 \cdot \exp(-0.1367 \cdot M), \quad r^2 = 0.99, \tag{23}$$

where L_{water} is the heat of vaporization of water evaporating from pure water and M is set as a percentage.

The drying constant, used in the single exponential equation, is

$$k = 1.196 \times 10^7 \cdot \exp\left[\frac{-6820}{T_a + 273.15}\right], \quad r^2 = 0.96. \tag{24}$$

Dynamic equilibrium moisture content, M_e, is found from

$$\ln(rh) = \left[\frac{-37360}{R_0 \cdot (T_a + 273.15)} \cdot \exp(-0.2999 \cdot M_{ew})\right], \quad r^2 = 0.84,$$

or, equivalently,

$$M_{ew} = \frac{10.47 - \ln(-8.315 \cdot (T_a + 273.15) \cdot \ln(rh))}{0.2999}, \tag{25}$$

where M_{ew} is given as a percentage and rh is given as a decimal value.

MODEL ONE PROGRAM STRUCTURE

For each layer, the solution process starts by calculating k (drying constant) and M_e (dynamic equilibrium moisture content) for the given T_a (drying air temperature) and rh (drying air relative humidity). ΔM (moisture content change) of the malt is calculated using the old moisture content (M), M_e, and k. ΔT_g (grain temperature change) of a layer is calculated using the old moisture content (M), the old drying air temperature (T_a), the old grain temperature (T_g), and ΔM. ΔT_a (air temperature change) for the layer is calculated using the old grain temperature (T_g), ΔT_g, the old air temperature (T_a), the old moisture content (M), and ΔM. H (drying air humidity) is updated using ΔM. If rh (drying air relative humidity) is above 98%, the condensation procedure is performed. In the condensation procedure, ΔM is incrementally reduced until the updated rh is less than 98%.

When the calculations are complete, layer variables for H, rh, T_a, T_g, and M are saved. The solution process is repeated for the next layer up, and after the last layer is solved, the program calculates the average bed moisture content and the new bed depth after shrinkage. Time is incremented and the layer solution process continues until the program end criterion is met. The end criterion is always met when the simulated drying time exceeds the maximum set point time in the array of ambient air temperature and relative humidity. Also, the end criterion will either stop the program when a particular target moisture content is reached or when a minimum moisture content change limit is not achieved, depending on the user's preference.

Fan and Thermal Energy Calculations

Fan input energy is estimated for a kiln with a variable-speed fan drive. The estimate is made using data from the BPA (1992) for the ratio of fan power input to maximum fan power input, as a function of the ratio of airflow to the maximum airflow. The maximum fan power input was taken from in-process electrical measurements at GWM and checked against fan data tables. A fourth-order polynomial was fitted to the fan input power ratio (P/P_{max}) versus the airflow ratio (G/G_{max}). The total fan input energy, $W_{\text{fan input}}$ (kWh), is found from

$$W_{\text{fan input}} = \sum_{t=0}^{t_1} f\left(\frac{G}{G_{\max}}\right) \cdot P_{\max} \cdot \Delta t, \tag{26}$$

where

$f(\ )$ = fan input power ratio function $(P/P_{\max})$,

G = mass flow rate/unit area,

$G_{\max}$ = maximum G for given fan and system,

P = input power to fan at an airflow of G,

$P_{\max}$ = input power to fan at $G_{\max}$,

Δt = time increment,

t_1 = time at which $W_{\text{fan input}}$ is calculated.

The total thermal energy Q is calculated by an energy balance on the drying air. This is given by

$$Q = \sum_{t=0}^{t_1} \dot{m}_{\text{air}} \cdot (h_a - h_{\text{ambient air}}) \cdot \Delta t, \tag{27}$$

where

$\dot{m}_{\text{air}}$ =total mass flow rate of air through the drier,

h_a = enthalpy of drying air before entering the bed,

$h_{\text{ambient air}}$ = enthalpy of ambient air.

THERMAL ENERGY STUDY AND RESULTS

Different drying schedules that decreased airflow following the completion of the constant-rate drying period were tested and the energy consumption was evaluated. The airflow reduction strategy was chosen to take advantage of the malt's internal drying mechanism, which dominates the drying process during the falling-rate drying period. Several tests were made with model one to show the potential for thermal energy savings. Model batch A, shown in Figure 4, is the baseline case that simulates constant-temperature, constant-airflow drying. The airflow and the ambient conditions for Model batch A were taken from the experimental batch 3 (discussed in Chapter VI). 'Heat' refers to the cumulative thermal energy per kg (finished malt) to dry the malt. The simulated energy consumption per kg of finished malt was 3.4 MJ/kg.

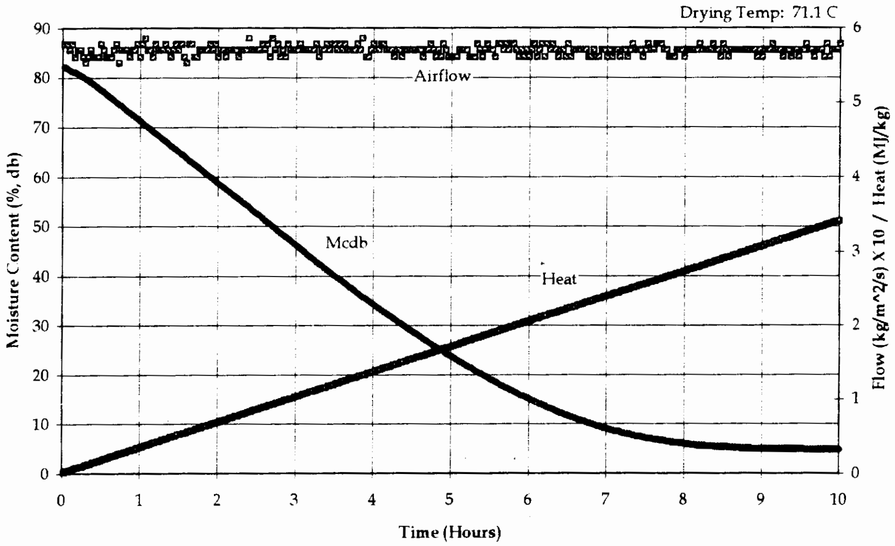


Figure 4. Model Batch A Thermal Energy to Dry.

The next tests used some form of airflow reduction after the constant-rate drying period. Model batch B, Figure 5, had a linear airflow reduction from 0.57 to 0.24 kg/ m^2 /s, starting at hour 3 and ending at hour 6, and its energy consumption was 2.78 MJ/kg. Model batch B took 13 hours to reach the minimum moisture content change limit, whereas A took 10 hours. The 'Heat' curve for B changed slope from hour 3 to hour 6 due to the linear airflow reduction.

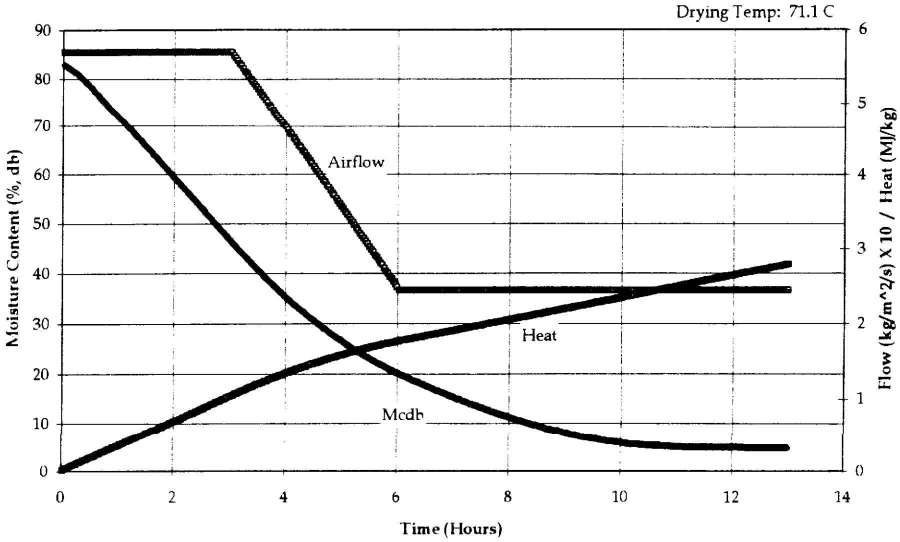


Figure 5. Model Batch B Thermal Energy to Dry.

Model batch C, seen in Figure 6, used a more aggressive airflow reduction, going from 0.57 to 0.2 kg/ m^2 /s between hours 3 and 6, and from 0.2 to 0.08 between hours 6 and 13. The energy consumption for model batch C was 2.37 MJ/kg. Batch C required 14 hours to reach the minimum moisture content change limit. Compared to A and B, C's 'Heat' curve ended up with a very shallow slope.

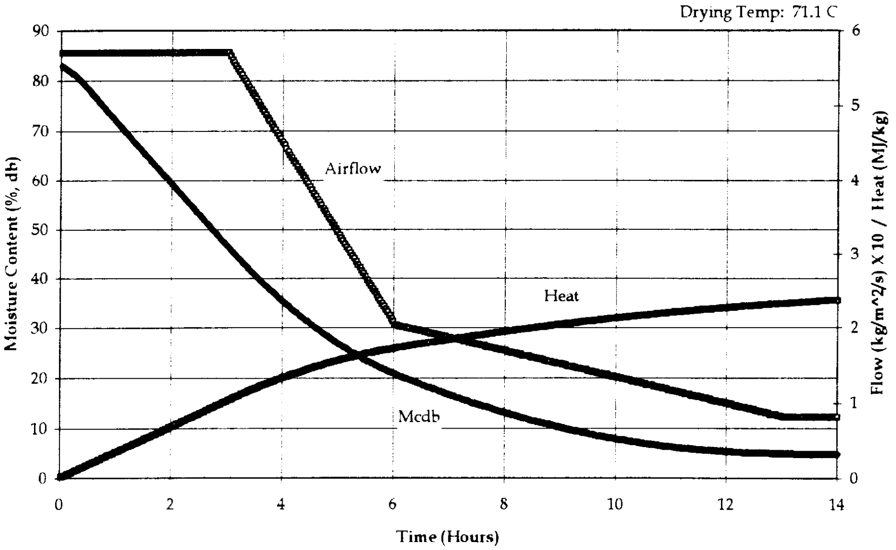


Figure 6. Model Batch C Thermal Energy to Dry.

The model-based tests show an energy savings trend with larger amounts of airflow reduction. They unfortunately also show a considerable increase in time required to reach the minimum moisture content change limit as the airflow reduction becomes more marked. Model verification required comparison with other malts and drying conditions than those used in the model's development. Bala's verification of his model was limited to constant airflow experimental tests. He compared data from experiments with model simulations, and the comparison was very good, probably within 2 to 3% for the average moisture content and the grain temperature.

Energy saving methods also required experimental tests to check the finished malt for quality before attempting any industrial-scale trials. Thus malt drying tests were performed to investigate the effects of temperature and airflow changes on the thermal energy consumption required to dry malt, as well as to determine if changes in the drying process would produce acceptable malt quality. Chapter V describes the research malt drier setup used in the next phase of this thermal energy investigation.

CHAPTER V

RESEARCH MALT DRIER

Quality concerns and verification of model one required the design and construction of a research malt drier. Its function is to perform energy savings tests on a small-scale that mimic the performance of a large-scale industrial drier.

DRIER DESCRIPTION

A layout of the whole drier system is shown in Figure 7. Not all sensors are shown.

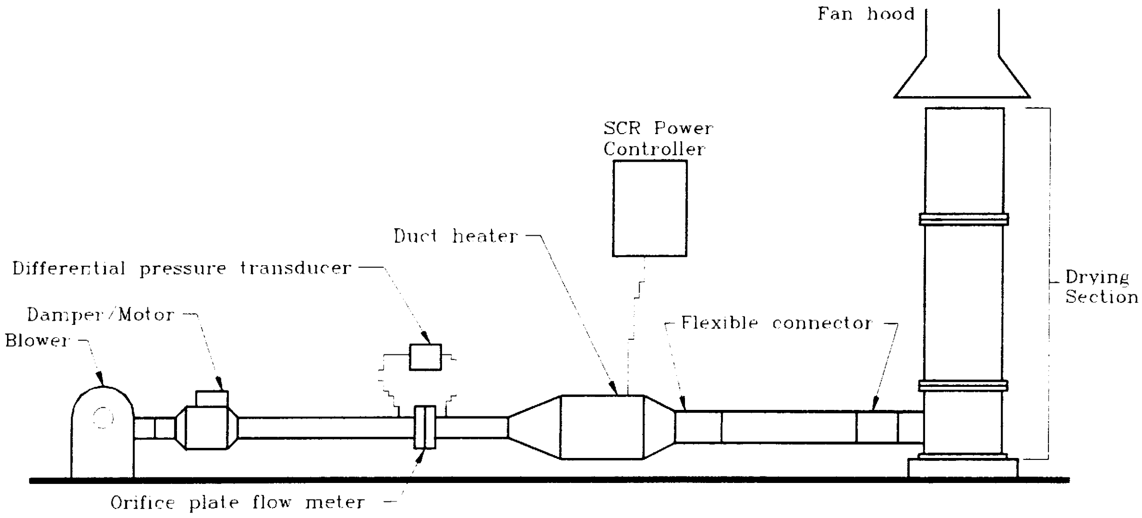


Figure 7. Drier System Layout.

Drying Section

The malt is supported in a 0.3 m diameter, 0.92 m long PVC pipe by a perforated aluminum plate. This section, the drier chamber, is shown in Figure 8. The drier section is insulated with 2.5 cm thick Armaflex AP insulation to minimize thermal loss. The drier chamber is attached by a flange at the bottom to the drier plenum, and at the top to the exhaust tube. The exhaust tube, 0.53 m long, forms a controlled space for measuring exhaust air temperature and relative humidity. Heat loss, however, causes air temperature measurements in the exhaust tube to be 5 C or more below the reading of the 0.7 m grain thermocouple (see Figure 9) when the malt bed temperature has approximately reached the drying air temperature. The source of the heat loss was not determined, so the drier exhaust temperature could not be used for drying schedule optimization with respect to thermal energy consumption. Thermocouple and relative humidity sensor positions are shown in Figure 9. The drying air temperature is measured just below the malt in the drier plenum. The drier plenum functions to mix the drying air and ensure that it is all close to the same temperature for accurate control of the drying temperature.

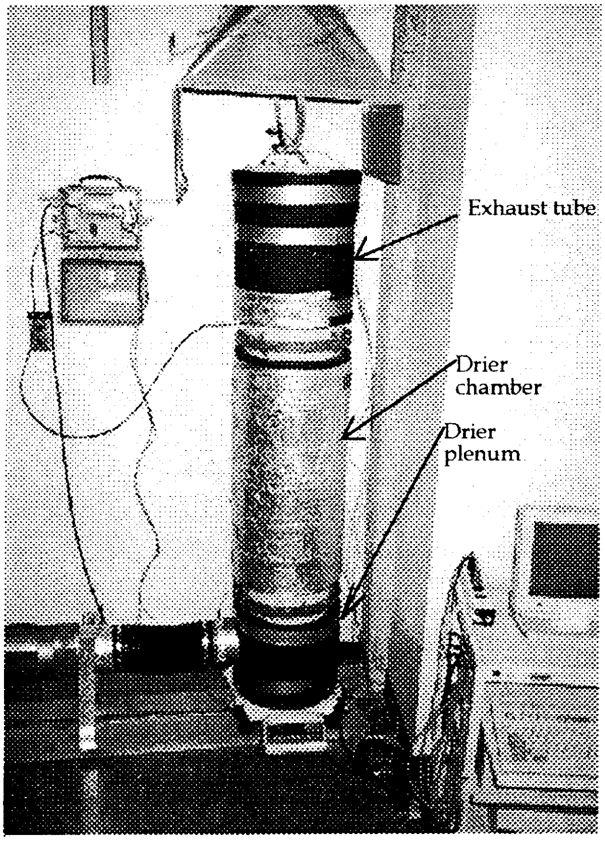


Figure 8. Photo of the Drying Section of Malt Drier.

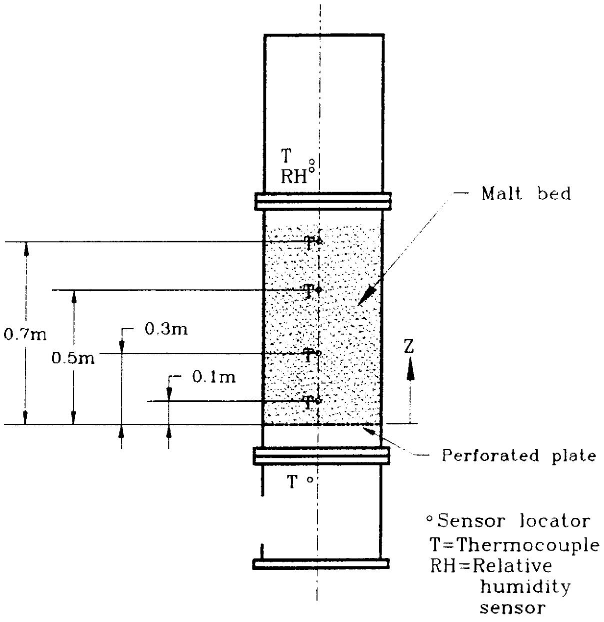


Figure 9. Drying Section Sensor Location Schematic.

The drier plenum is supported by an AND FG-150K digital scale, which is used to sample the weight change of the malt for moisture content estimates. Drier exhaust air is removed from the lab through a fan hood, which also supports wires for thermocouples. The thermocouples measure malt temperature and drier exhaust temperature.

Heating System

Air is heated through a bank of resistance heating elements in a removable 4100 W, 480 V, 3-phase duct heater. The heater is powered by an Athena SCR power controller, which varies power input to the duct heater by the zero-voltage switching method. Figure 10 shows the duct heater section.

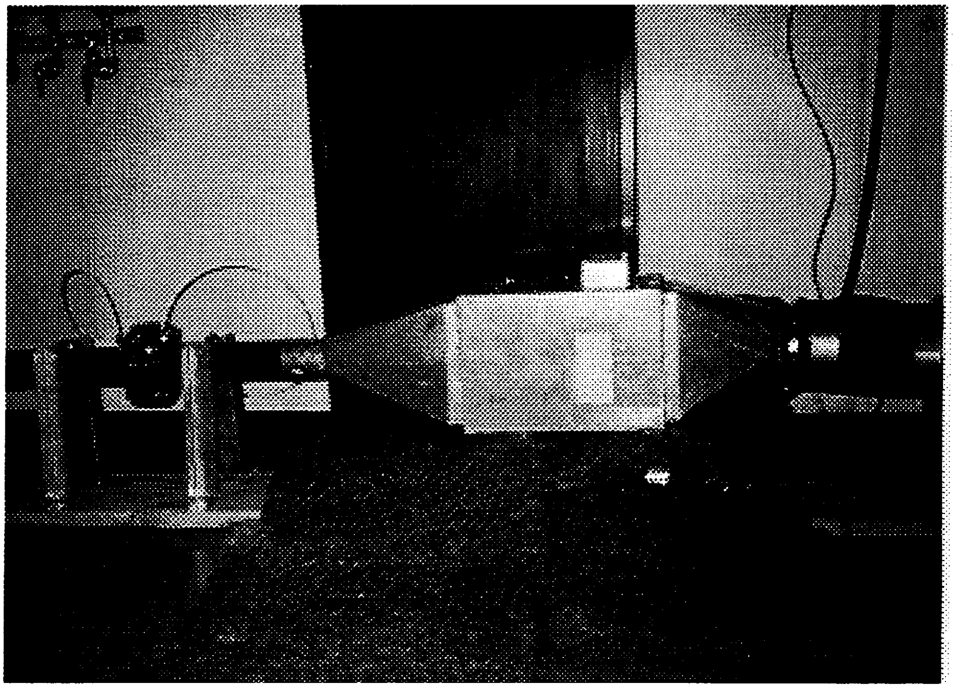


Figure 10. Duct Heater Photo.

Blower System

Air is taken from the room through a centrifugal blower, which produces a maximum pressure difference of 25 kPa. Refer to Figure 11 for a photo of the blower. A square damper and a damper motor regulate the airflow. A 7.62 cm (3 in.) schedule 80 pipe, which is 1.47 m long, with a 7.27 cm (2.864 in.) internal diameter follows the damper. The pipe connects to a sharp-edge orifice plate by means of a Van-Stone flange. In this discussion, 1-D refers to 7.27 cm (2.864 in.), which is the internal diameter of the 7.62 cm (3 in.) schedule 80 pipe. A flow straightener made of a bundle of 1.27 cm (0.5 in.) copper tubing that is 2-D long is positioned a minimum distance of 8-D from the upstream face of the orifice plate. This straightener installation is recommended by ASME (1971) for flowmeter installations downstream of a pump. The orifice plate flowmeter has pressure taps located 1-D upstream, and 0.5-D downstream, of the upstream face of the orifice plate. The taps are connected to a differential pressure transducer. The equation, used in the control system, to calculate the mass flow rate of air as a function of the differential pressure measured across the orifice plate is developed in the Appendix. A 5-D length of the 7.62 cm pipe is located downstream from the orifice plate, as suggested by ASME (1971). Following the pipe are a duct heater enclosure, a 15.2 cm (6 in.) diameter flexible connector, and a sheet metal duct. Another flexible connector is used to connect the sheet metal duct to the drier plenum inlet in order to isolate the duct from the drying section and minimize its effect on measurement of the malt weight.

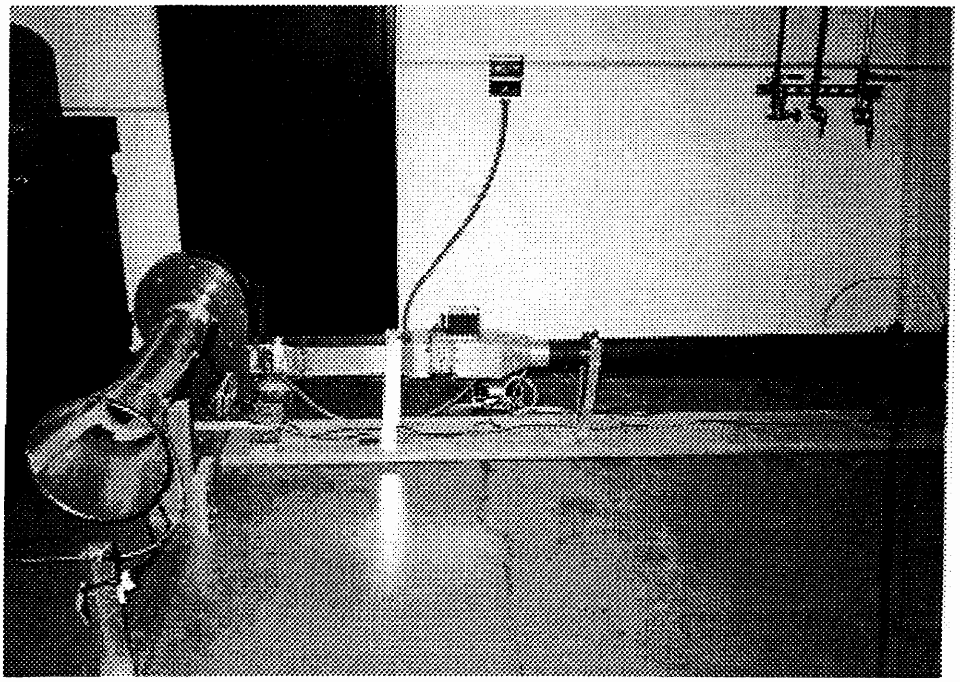


Figure 11. Blower and Damper Photo.

Data Acquisition

The data acquisition system consists of an 80286 PC-compatible computer and a Keithley Series 500 Data Acquisition System. The computer samples the malt weight from the AND scale, at a 0.05 kg resolution, using a serial communication code (Grofton 1986). Inter-grain air temperature is measured in the malt bed at the centerline of the drier chamber at 0.1 m, 0.3 m, 0.5 m, and 0.7 m above the perforated floor (refer to Figure 9). These measurements are made with J-type thermocouple wire that is welded to form a thermocouple. The thermocouple, seen in Figure 12, is covered with a perforated 2.5 cm length of 3.2 mm inner diameter PVC tubing, which was made to isolate the thermocouple from the grain surrounding it. Up to experimental batch 14, grain temperature was measured in the drier chamber with hypodermic needle thermocouples. Due to failure of those thermocouples, inter-grain air temperature was measured instead. Deep-bed experiments showed no temperature difference greater than 3.5 C between the internal grain temperature and the inter-grain air temperature measurements at the same heights in the drier. Some results showed the air temperature greater than the grain temperature, while other results showed the opposite. The PVC shielded thermocouples were used to measure inter-grain air temperature. The hypodermic needle thermocouples, with about six grains of malt laced on the tips, were used to measure grain temperature. Temperatures were sampled at two minute intervals. Positioning the two sensors at exactly the same bed height was difficult, and the sensors were not at exactly the same cross-sectional position, but the closeness of their measurements indicates that the positions were not significantly different. Bala (1983) noted that grain and air temperature are approximately equal after a warm-up period of three to four minutes, which agrees with the thermocouple comparison. Grain temperature and inter-grain air temperature will be considered synonymous for the remainder of this work. Finally, air temperature and relative humidity are measured at the inlet to the blower and in the exhaust tube just above the top of the malt column.

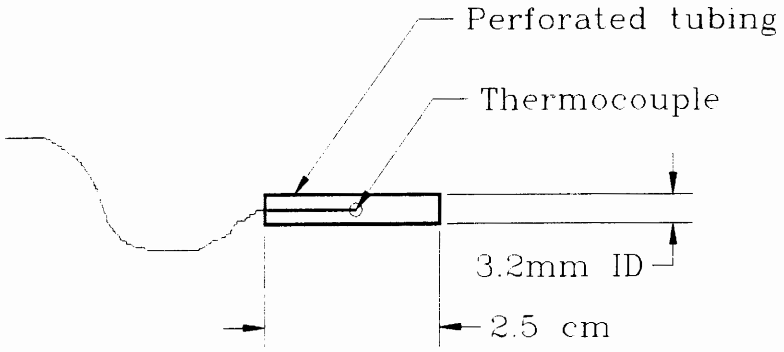


Figure 12. Inter-Grain Air Thermocouple.

The control system, using the same computer and Keithley hardware as the data acquisition system, controls the mass flow rate of air into the drier and the air-on temperature (drying-air temperature) under the malt. The control system software allows programmable drying schedules that can follow any path of drying conditions desired, within the drier's limits. Proportional-integral feedback control parameters for drying temperature and airflow were experimentally determined (Smith 1985), using the Chien-Hrones-Reswick tuning procedure (Stefani 1994), and then fine tuned by trial-and-error. Approximately a 4 C drying air temperature overshoot occurs at full airflow when the drier is cold-started with a 0.57 $kg/m^2/s$ air flow and a 70 C drying temperature set point. The airflow into the drier plenum is split with a wedge at the plenum inlet. Although the swirl induced by the wedge is meant to mix the air for a uniform temperature throughout the plenum, the grain temperature along the centerline of the drier chamber is typically 1-2 C above the set point. No attempt is made to control the inlet humidity of the drying air, which normally changes when the building ventilation system starts or stops in the morning and evening, respectively.

DRIER PERFORMANCE AND MEASUREMENT UNCERTAINTIES

The design goals of the drier were intended to make it perform as closely as possible to an industrial kiln. The airflow desired, with a 0.8 m deep bed of malt at 47% w.b. moisture content and at an initial density of 638 kg/m^3, was about 0.7 $kg/m^2/s$. The airflow achieved in the test drier under the design conditions was 0.57 $kg/m^2/s$. A maximum drying air temperature of 93 C at the maximum airflow was desired. The PVC pipe used for the drier plenum, chamber, and exhaust tube limited the maximum to 88 C. Moisture content sensitivity of the scale due to the malt weight change was designed for 0.2% d.b., and the actual value was 0.2% d.b.

The measurement uncertainties are estimated where bias and offset errors are known. Precision errors are not considered unless specifically noted. A total malt temperature variation of 2 C is estimated for the malt cross-section at the top of the bed when the drying temperature is 80 C. Malt temperature is measured within ± 0.5 C using either the T-type hypodermic probes or the J-type PVC covered probes. Thermocouple voltages were converted to temperatures using built-in functions of the data acquisition system's software.

The moisture content error estimate during drying was made by considering the weight offset added by the flexible connector to the drying section. The difference in weight offset between the beginning and end of an experimental batch was taken as the uncertainty in the weight measurement for the batch. This error was considered a precision error. Weight offset from the flexible connector was due to the position in which it connected to the drier plenum and to the force exerted upon its walls by the airflow. Moisture content estimates for batches 2-14 are estimated to be within ± 0.5% d.b., estimates for batches 20-22 are estimated to be within ± 1.0% d.b. (due to a longer flexible connector), and estimates for batches 24 and 25 are estimated to be within ± 0.15% d.b. (due to a shorter, straighter flexible connector).

Airflow readings were checked with a venturi flow meter, which was calibrated by a Roots Meter. The Roots Meter calibration is NIST traceable. The percentage differences between the airflows measured and the estimated values are given in Table I.

TABLE I

AIR FLOW UNCERTAINTIES

Flow Set Point ($kg/m^2/s$)	Estimated Percent Error (± %)
0.61	0.40
0.57	0.10
0.49	0.20
0.41	0.40
0.33	0.70
0.24	0.01

Ambient and exhaust temperatures are measured within ± 0.5 C, while the ambient and exhaust relative humidities are estimated within ±3% even though the relative humidity sensors were calibrated and the estimated values were fit to linear functions of the measured values. The absolute humidity values depend on the measured temperature and relative humidity, and they are estimated to be within ±7%.

Thermal energy consumption estimates depend on the enthalpy difference of the drying air and the ambient air, the mass flow rate of the drying air, the sampling time measurement, and the mass of the malt. The main source of uncertainty in the energy estimate was the resolution of the scale when the malt was at low moisture contents, since at low moisture contents it took about 20 minutes for a change in the scale's weight reading to occur. This made a significant moisture content uncertainty, causing the energy estimate uncertainty to typically be about 2.5%, or .056 MJ/kg. The thermal energy consumption due to drier heat loss appears to be about 6% of the total consumption for each of the airflow reduction experimental tests. The loss levels were calculated considering the difference between the thermal energy of the heated drying air and of the drier exhaust air. Since the loss level appears to be a fixed percentage of the total thermal energy used for drying, the experimental energy comparisons in Chapter VI are not affected by drier heat loss.

The next chapter considers the malt drying experimental procedure and the quality and thermal energy consumption results. All tests described were run with the experimental drier considered in this chapter.

CHAPTER VI

MALT DRYING TESTS

To demonstrate that changes in typical airflow and temperature drying schedules result in thermal energy savings, deep-bed malt drying experiments were made. These experiments were performed at a laboratory in the Mechanical Engineering Department of Portland State University. Various drying temperatures were used for successive experimental batches. Two varieties of two-row malt, Crystal and Harrington, were used. Barley grows either in stalks of two or six rows, and the two-row varieties are generally larger than the six-row ones. It is suspected that two-row barley-malts dry differently than six-rows due to the size difference. Two-rows were preferred, since "model one," Bala's (1983) model, is based on two-row malts. Malt quality test results determined the maximum experimental drying temperature that produced acceptable quality.

The maximum drying temperature, previously determined, was used with model one to obtain drying schedule ideas for thermal energy savings (see Chapter IV). Model one approximated diffusion-controlled drying, which made it useful in estimating the relative thermal-energy saving potential of various airflow reduction methods. The simplest successful airflow reduction techniques learned from model one were performed experimentally using the maximum experimental drying temperature.

DRYING TEST DESCRIPTION

Both Harrington and Crystal malts were obtained from GWM, and drying tests were started within seven hours of removal from the germination facilities. Malt was transported in plastic bags to minimize moisture loss after the initial moisture content estimates were made. The malt was dried in batches initially weighing 36.3 kg, with a bed depth of 0.81 m, using the research malt drier. While the drier was being filled, the malt was compressed to achieve the same initial density of wet malt in each batch. The first sets of drying tests were run at the same, constant, airflow rate and at constant temperatures. Drying temperatures varied from 63.3 C to 86.7 C for the successive tests in each set.

The equilibrium moisture content of the malt at the various drying temperatures and ambient humidities was unknown. Equilibrium moisture content is the moisture content a substance reaches after it is dried at constant temperature and humidity for an infinite (or very long) time. Practically, after a certain drying time, the moisture content change in a substance occurs at a very slow rate. In order to achieve a final moisture content that was close to the equilibrium moisture content, it was decided to dry each batch until a minimum moisture content change of 0.2% d.b. per hour was not achieved. This criterion for drying termination was also used with the drying model, to be consistent with the experiments. The fact that the ambient air humidity was not controlled did not affect the comparison of the experimental results with the model results, since each model test was run, after the experiment, using the same ambient air relative humidity and temperature as the experiment.

All drying tests using the research drier were done without mixing the malt during drying, although mixing is typically done in industry. Initial moisture content estimates of the 'green,' or wet, malt in almost every experiment proved inconsistent with the final moisture content given the amount of water evaporated from the malt. This problem occurred when the green malt and the dried malt were thoroughly mixed before sampling for moisture content analysis, and it was always such that the initial moisture content estimate was above (typically by 1-2% w.b.) what the final moisture content estimate and the total evaporated mass of water would have indicated. Final moisture content measurements were made at GWM's laboratory using a standard oven drying method. It was assumed that the final moisture content was more accurate than the initial moisture content, since the final value is used when selling the malt to a customer. Thus, the final moisture content was used as the reference point in all the estimated moisture content data, and the moisture content at a particular time was estimated using the weight of water evaporated from that time until the end of the experiment.

Drying data graphs for the experimental batches are included in the Appendix. Experimental batches 1, 7, 8, 16-19, and 23 were not included in the data due to drier problems and atypical malt samples. Each graph contains a moisture content estimate ('Mcdb'), grain temperatures (at '.1 m', '.3 m', '.5 m', and '.7 m' height in the bed), and ambient air temperature ('Tamb') and absolute humidity ('Wamb') where the descriptions shown in single quotes are the labels used in the graphs.

Energy saving tests were performed after the constant temperature and airflow tests. Batch 20 was a baseline test for comparison with batches 21 and 22. It used a drying schedule with an airflow of 0.57 $kg/m^2/s$ at 71 C for eight hours, and 0.29 $kg/m^2/s$ at 82 C for the remaining 7 hours. Batches 21 and 22 reduced airflow after the constant-rate period ended in order to save energy.

The duration of the constant-rate period was estimated from previous experiments. In batch 21, airflow was reduced from 0.57 to 0.24 kg/ m^2 /s over a four hour period, and in batch 22 the same airflow reduction was made over a one hour period. The temperature schedule for batches 21 and 22 was 71 C for 10 hours, and 82 C for the final 6 hours. Figures 13 to 17 show the airflow and temperature schedules used in batches 20-22, 23 and 24. Batches 20-22 did not produce acceptable malt qualities. Thus, batches 24 and 25 were run with less drying time at 82 C. Batch 24 had the same airflow reduction as batch 21. Batch 25, the baseline case for batch 24, had an abrupt reduction from 0.57 kg/ m^2 /s to 75% of that after eight hours, which is one method used in industry.

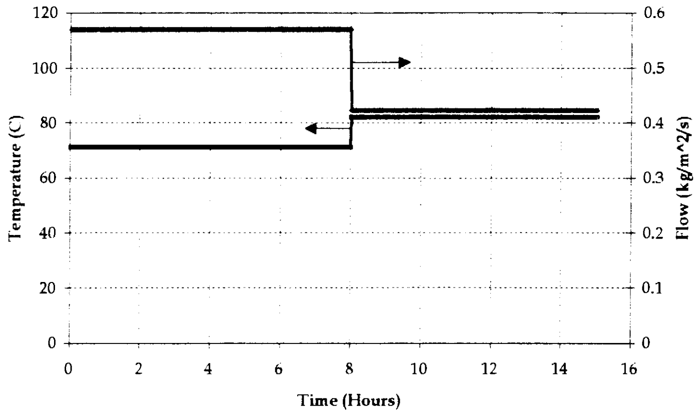


Figure 13. Batch 20 Airflow And Temperature Schedule.

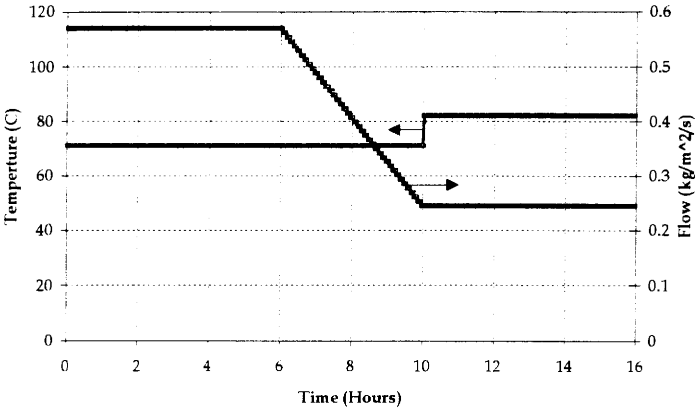


Figure 14. Batch 21 Airflow And Temperature Schedule.

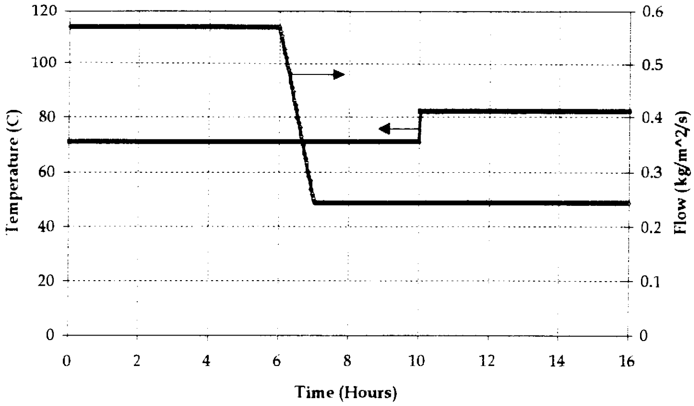


Figure 15. Batch 22 Airflow And Temperature Schedule.

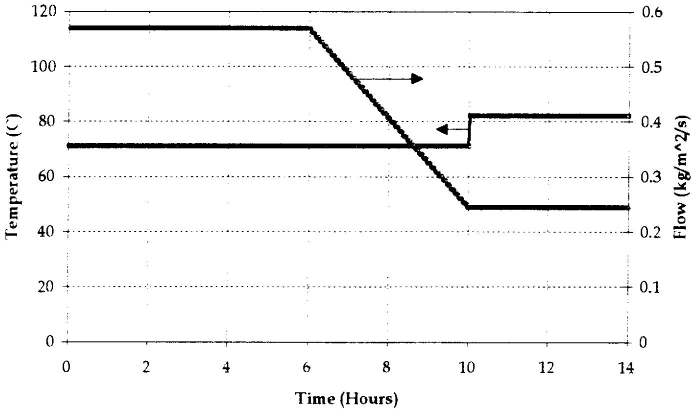


Figure 16. Batch 24 Airflow And Temperature Schedule.

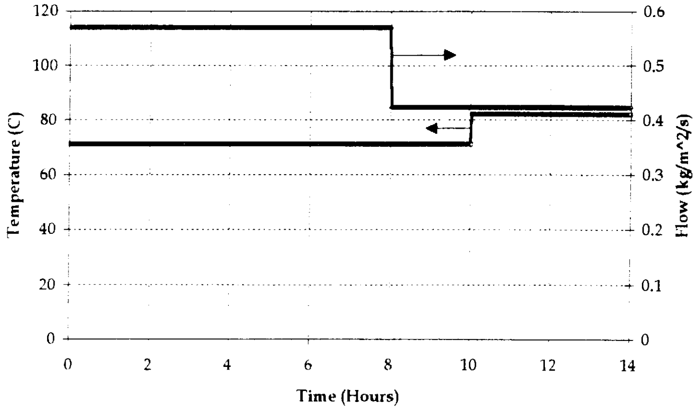


Figure 17. Batch 25 Airflow And Temperature Schedule.

DRYING TEST RESULTS

The energy and quality results for the drying tests are given here as a means of measuring the benefits of, and disadvantages to, the various methods of energy efficiency improvements. Experimental energy consumption in the energy saving tests is greater than the average energy consumption measured for the two-deck kiln at GWM. However, it is not possible to make a direct comparison between the two energy estimates, because two-deck driers are typically more thermally efficient than one-deck driers such as the one used in this research. It is possible that the thermal efficiency of a two-deck drier may be improved using the same method as in this work.

Energy per Ton

The thermal energy consumption refers to the thermal energy used in heating the ambient air to the drying air temperature. It was calculated using eq. (27) from Chapter IV, which is repeated here.

$$Q = \sum_{t=0}^{t_1} \dot{m}_{air} \cdot (h_a - h_{ambient\,air}) \cdot \Delta t .$$

Thermal energy efficiency comparisons were made among the tests in batches 2-6 and batches 9-12. The comparisons were set on an equal basis by considering only the thermal energy required to dry from the minimum initial to the maximum final moisture content found in each set of batches. This comparison method was necessary because higher drying temperatures result in lower final moisture contents. The resulting thermal energy per batch was normalized by dividing by the weight of the batch at the maximum final moisture content of the set. This method may err due to transient heating of the malt bed and drier at the start-up time for the batch with the minimum initial moisture content. This is because the batches with higher initial moisture content already had passed some of the transient stage by the time they reached the minimum initial moisture content of the set. However, evaporation was occurring even during start-up, and thus the effect of the start-up period was disregarded in the energy analysis.

Normalized results for thermal energy usage for Crystal and Harrington malts are shown in Figures 18 and 19, respectively. It is very clear that energy consumption drops about 20% by drying at 70 C rather than 63 C. Increasing Crystal or Harrington drying temperatures above 70 C does not show much efficiency gain.

Thermal energy usage for batches dried with airflow reduction was normalized based on the final weight of the finished malt. Final moisture contents were all within 0.27% d.b., which makes the normalization technique reasonable. The final weight technique is more accurate than using the maximum final moisture content method, because the moisture content estimates for batches 20-22 were accurate only to within 0.5% d.b. Total thermal energy was calculated for the drying time between 78.6% d.b. and the finished moisture content.

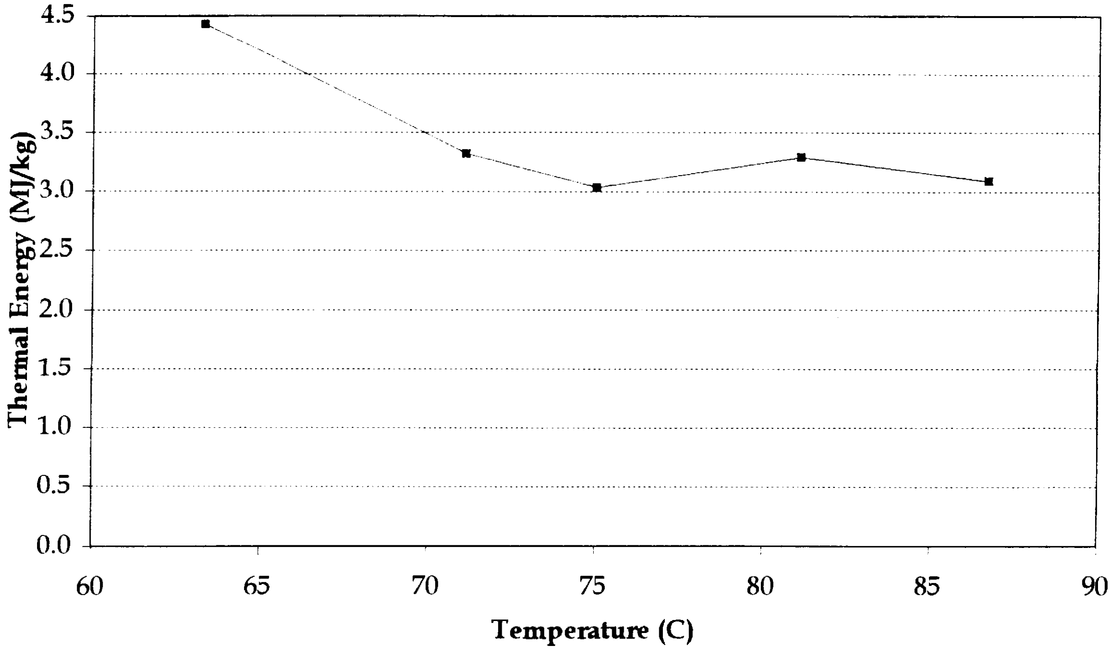


Figure 18. Normalized Thermal Energy to Dry Crystal Malt from 80.1 to 5.7% M.c. D.b.

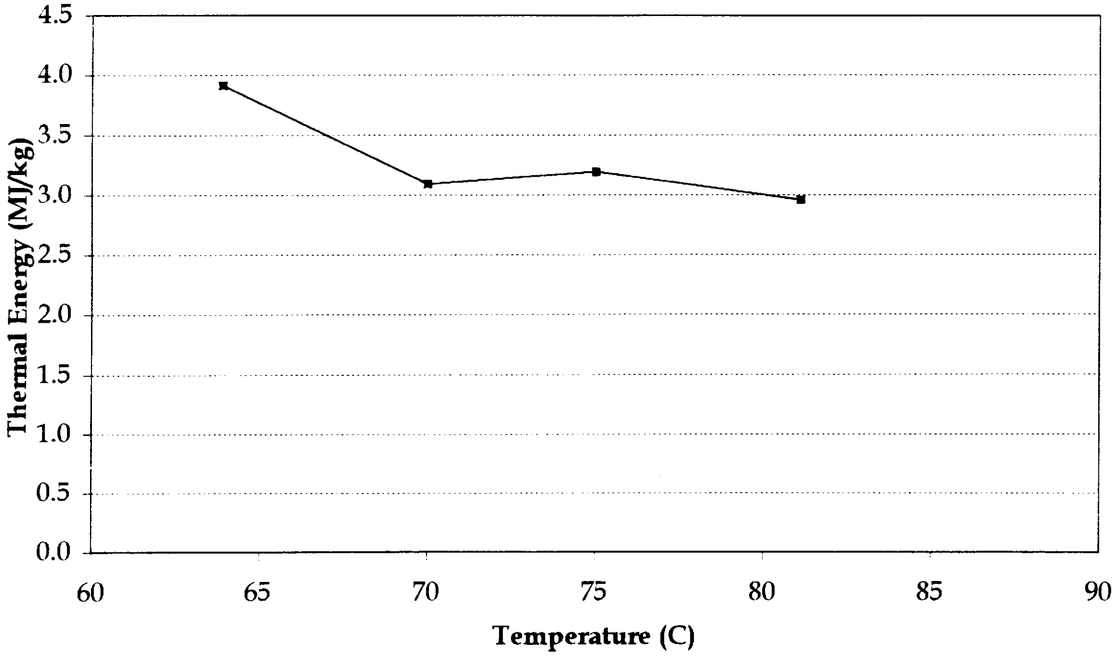


Figure 19. Normalized Thermal Energy to Dry Harrington Malt from 84.6 to 6.3% M.c. D.b.

Normalized results for the thermal energy for batches 20-22, 24 and 25 are shown in Figure 20. The thermal energies shown are higher than those from the other sets because these energies were based on final moisture contents around 4% w.b., which require much more energy to achieve than final moisture contents around 6% w.b. Batches 20, 21, and 22 show a clear trend of thermal energy reduction for schemes with airflow reduction. Batches 24 and 25 show thermal energy savings that would be more realistic for an industrial one-deck kiln (about 20%), since the final moisture contents of the malt are very close to the typical production goal of 4% w.b., and the final malt quality was very close to commercial requirements.

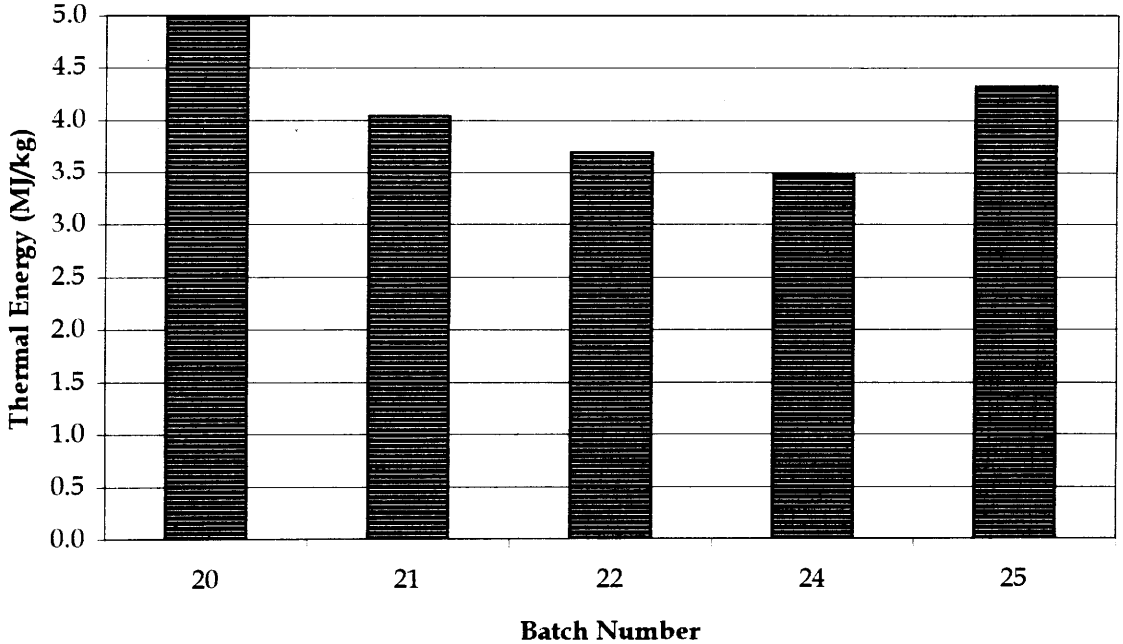


Figure 20. Normalized Thermal Energy to Dry Harrington Malt from 78.6% to Terminal M.c. D.b. for Airflow Reduction.

Malt Quality

Quality results for diastatic power and malt color are emphasized here because they show marked trends with temperature, whereas some other quality factors do not. Table II lists experimental malt quality results, which were measured in GWM's Vancouver laboratory using standard malt analysis techniques. Figure 21 shows quality results for batches 2-6. Diastatic power shows a monotonic decrease with temperature, with 75 C being the highest constant drying temperature for an acceptable value. Acceptable diastatic power values range from about 130 to 150 degrees Lintner. Color increases with temperature, and 75 C also is the highest constant drying temperature with an acceptable value. Acceptable color values are 2 degrees Lovibond, or less.

The diastatic power for batches 9-12 has an undefined trend, with 64 C the highest temperature with an acceptable value. The malt color definitely increases with temperature (Figure 22). The experimentally determined maximum constant-drying temperature for Crystal and Harrington malts appears to be 75 C (167 F). This is the highest drying temperature that produced acceptable malt quality, disregarding the diastatic power for batches 9-12, However, 70 C was considered a safer temperature for tests with a final roasting stage, since the enzyme levels fall and the malt color rises at a faster rate at higher temperatures.

Figures 23 and 24 show no notable trends for color and diastatic power since batches 20-22, 24 and 25 all vary in their temperature and airflow schedules with no particular sequence. Batches 24 and 25 were dried at 82 C for shorter times than batches 20-22. Thus batches 24 and 25 ended with higher diastatic power and lower malt color than batches 20-22, and batches 24 and 25 met all industrial pale ale malt quality requirements. Sulfur dioxide, often used in

TABLE II

EXPERIMENTAL MALT QUALITY RESULTS

Batch No.	Variety	Drying Temperature (C)	Total Dry Time (Hr)	Initial MC (% w.b)	Final MC (% w.b.)	Soluble Protein (%)	Diastatic Power Deg. Lintner	Alpha-Amalyse	Extract Fine Grind % Dry Base	Color (Degrees Lovibond)	Clarity	Viscosity (cs)
2	ID Crystal	63.3	14.5	44.47	5.46	5.35	180	57.2	79.5	1.26	3	1.43
3	ID Crystal	71.1	14	45.18	4.72	5.98	158	43.9	79.8	1.87	5	1.45
4	ID Crystal	75.0	13	46.16	4.32	5.69	148	48.9	79.9	1.90	3	1.45
5	ID Crystal	81.1	14	45.96	3.84	5.92	106	50.3	80.2	3.51	3	1.43
6	ID Crystal	86.7	13	45.90	3.29	5.93	54	40.8	79.4	7.66	2	1.47
9	NW Harrington	63.9	13	46.31	5.87	5.03	130	58.4	78.8	1.23	4	1.42
10	NW Harrington	70.0	13	45.83	5.01	5.13	109	50.8	79.0	1.32	4	1.47
11	CN Harrington	75.0	13	46.35	5.78	4.99	116	45.3	79.3	1.54	3	1.40
12	CN Harrington	81.1	12	46.22	4.25	5.87	117	53.8	78.2	2.59	3	1.39
20	ID Harrington	71.1 (8hr) 82.2 (7hr)	15	44.96	3.56	6.95	105	58.8	80.6	5.27	2	1.40
21	NW Harrington	73.3 (10hr) 83.3 (6hr)	16	46.48	3.78	6.58	106	55.4	80.4	3.71	2	1.38
22	CN Harrington	72.2 (10hr) 83.3 (6hr)	16	47.75	3.90	5.92	124	60.0	79.5	2.55	2	1.33
24	MT Harrington	72.8 (10hr) 83.3 (4hr)	14	45.08	4.07	5.50	133	58.0	81.9	2.12	3	1.43
25	MT Harrington	72.8 (10hr) 84.4 (4hr)	14	43.99	3.84	5.59	132	58.3	81.8	2.03	2	1.44

Abbreviations: CN = Canadian, ID = Idaho, MT = Montana, NW = Northwest.

industrial malt drying, was not used in the experiments. It is often added to kiln air to bleach malt, and to reduce the pH and increase the levels of soluble nitrogen in worts made from the malt.

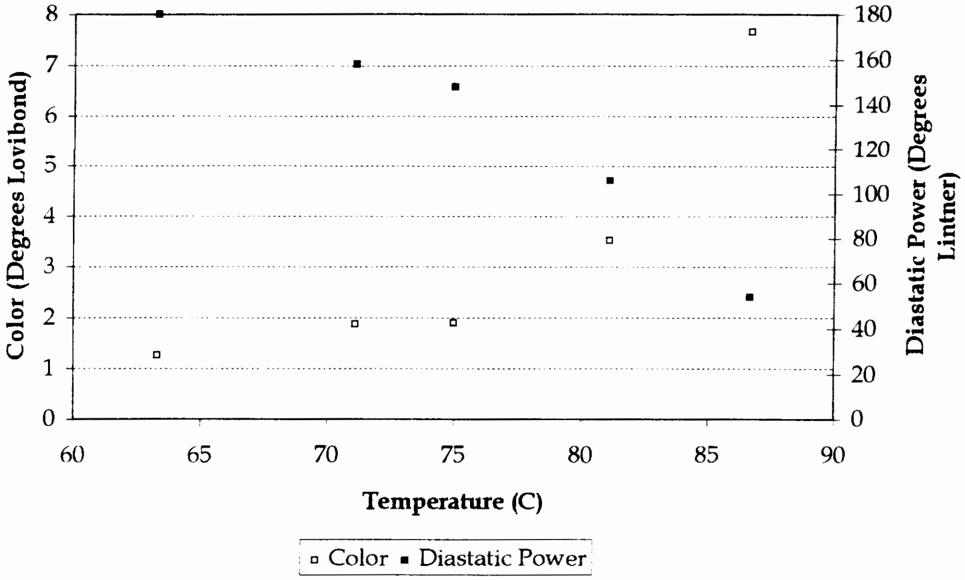


Figure 21. Crystal Malt Quality Indicators Versus Drying Temperature.

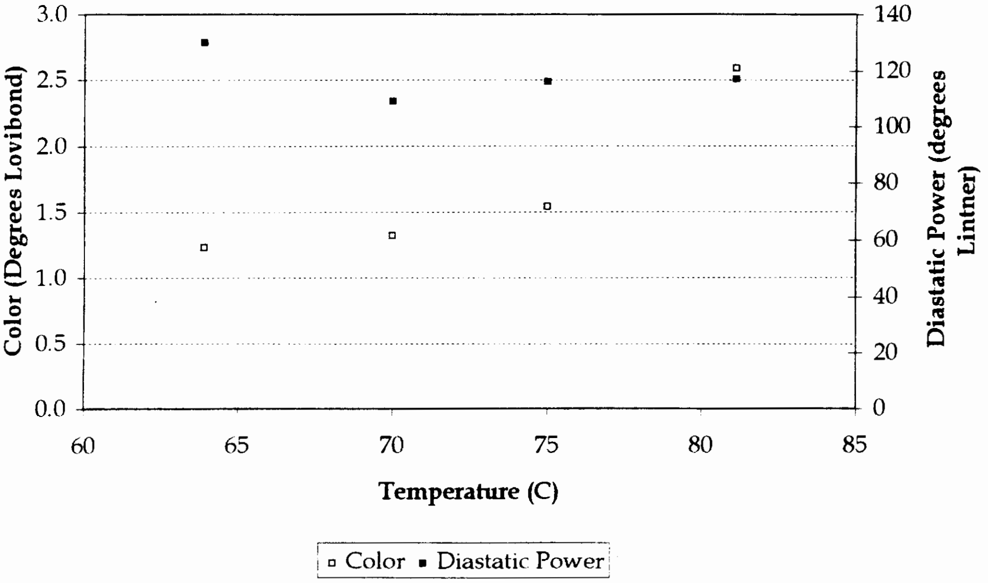


Figure 22. Harrington Malt Quality Indicators Versus Drying Temperature.

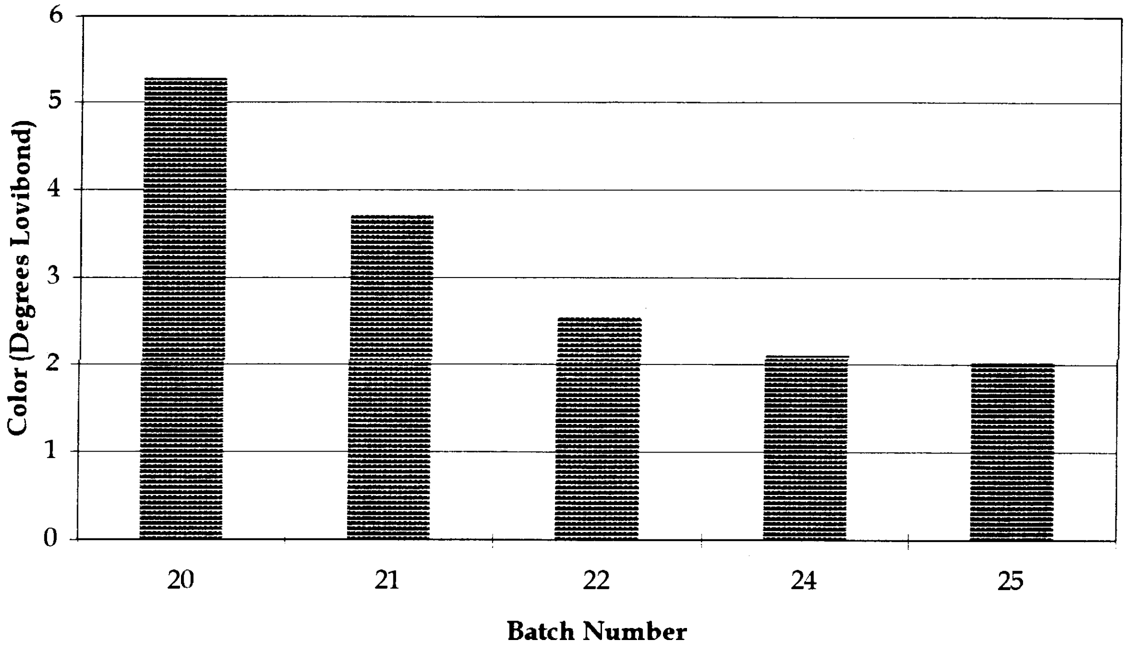


Figure 23. Harrington Malt Color for Airflow Reduction Tests.

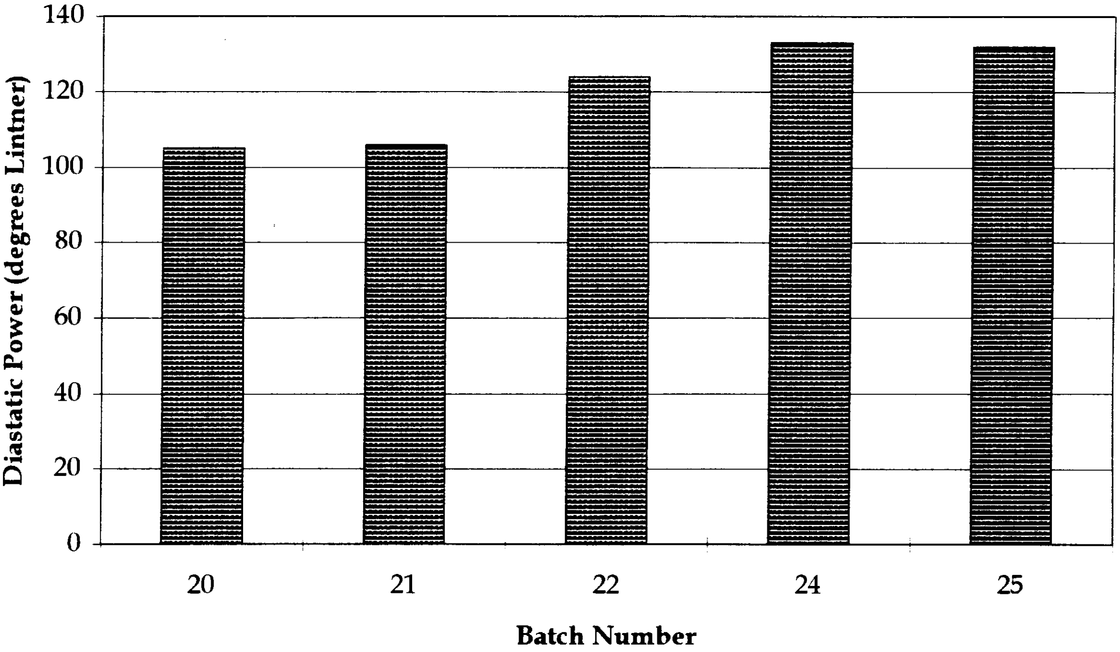


Figure 24. Harrington Malt Diastatic Power for Airflow Reduction Tests.

MALT DRYING TEST SUMMARY

It was determined that the maximum constant drying temperature among the several temperatures tested for Crystal and Harrington malts is 75 C (160 F). This limit is due to malt quality requirements. Thermal energy consumption values for the total energy required to heat the drying airflow were estimated. Thermal energy consumption drops about 20% by increasing drying temperature from 63 C (145 F) to 70 C (160 F). However, it is necessary to do final drying above 75 C (167 F), at least for several hours, to reach a final moisture content close to 4% w.b.

Experimental tests using airflow reduction methods were performed. These tests included at least four hours of 83 C (180 F) drying to achieve final moisture contents around 4% w.b. Results indicate that thermal energy savings of 20% can be achieved by using more aggressive airflow reduction techniques than industry typically uses. Malt quality tests show that the energy saving schedules can produce perfectly acceptable malt.

Chapter VII compares the experiments of Chapter VI with simulations of the experiments using Bala's model one (1983). The validity of the model for testing thermal energy reduction methods is explored.

CHAPTER VII

MODEL VERSUS EXPERIMENTAL DATA COMPARISON

Each experimental batch was simulated with model one for comparison of the results. The model batches were run after the experimental batches with the same initial values for moisture content, average malt temperature, dry bulk density (the bone dry malt weight divided by the total volume of moist malt), and bed depth. The ambient temperature, relative humidity, and airflow values recorded in the experiment were used with the model. The model drying air temperature was taken from the maximum grain temperature levels recorded in the experiment, since the actual drying air temperature sometimes differed up to 2 C from the set point. The experimental drying termination criterion, the minimum moisture content change limit, was also used with the model.

COMPARISON RESULTS

Figures for the model versus experimental data that are not cited in the text are in the Appendix. The data show the model and experimental estimates for the average bed moisture content and grain temperature (denoted by height in the bed, '.1 m', etc.). 'Exp' and 'mod' are abbreviations for experimental and model, respectively.

Constant-Temperature Crystal Malt

A representative example for the first set of data of Crystal malt, batches 2-6, is shown in Figure 25. For batches 2-6, average moisture content values fit well at the higher moisture contents, but the model average moisture content dropped at a higher rate than the experimental values. The faster decrease in the model moisture content compared to the experiment caused all model tests to end earlier than the experiments ended. Grain temperature agreement is better at the bottom of the bed, and becomes poorer in each case as the height of the measurement increases. The shape of the grain temperature curves is very close, except during the initial temperature rise above the wet-bulb temperature of the drying air.

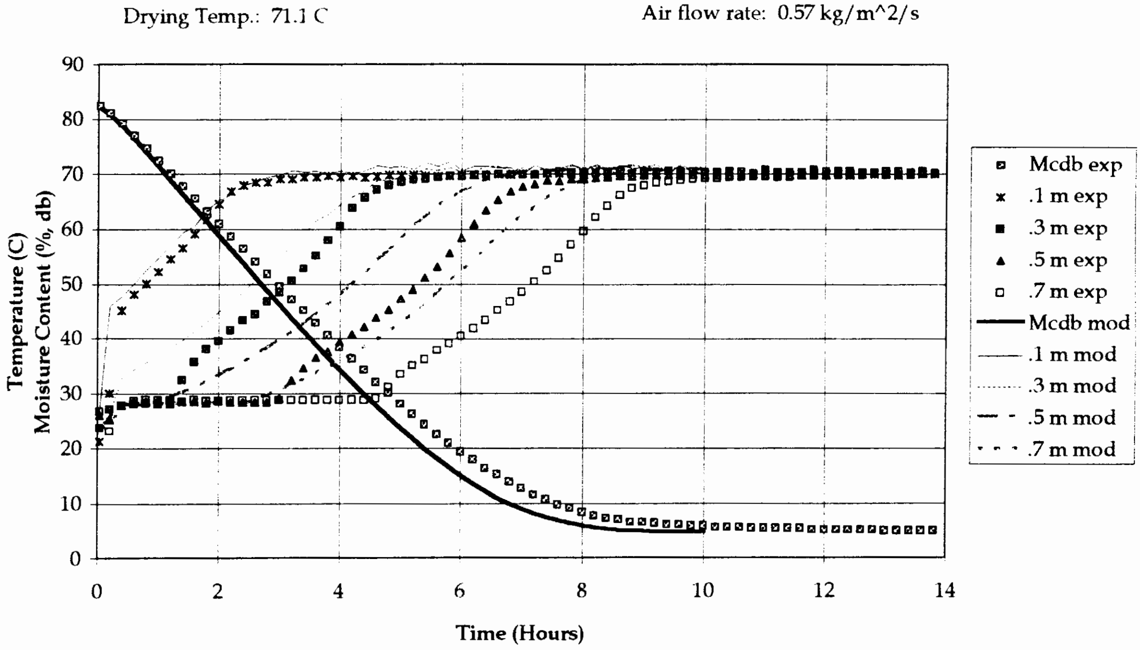


Figure 25. Batch 3 Model Versus Experimental Data for Crystal Malt.

Constant-Temperature Harrington Malt

Model and experimental moisture contents for the second set of data (Harrington malt) in batches 9-12 are in better agreement than they were in batches 2-6. However, the model moisture content still dipped below the experimental value at lower moisture contents. The comparison worsens for each case as the drying temperature increases. Figure 26 is a representative example of the second set of data. Grain temperatures for the model versus experiment exhibit the same trend as with the Crystal set; they fit better at lower heights. The shape of the grain temperature curves is not as close as it is in the Crystal comparisons.

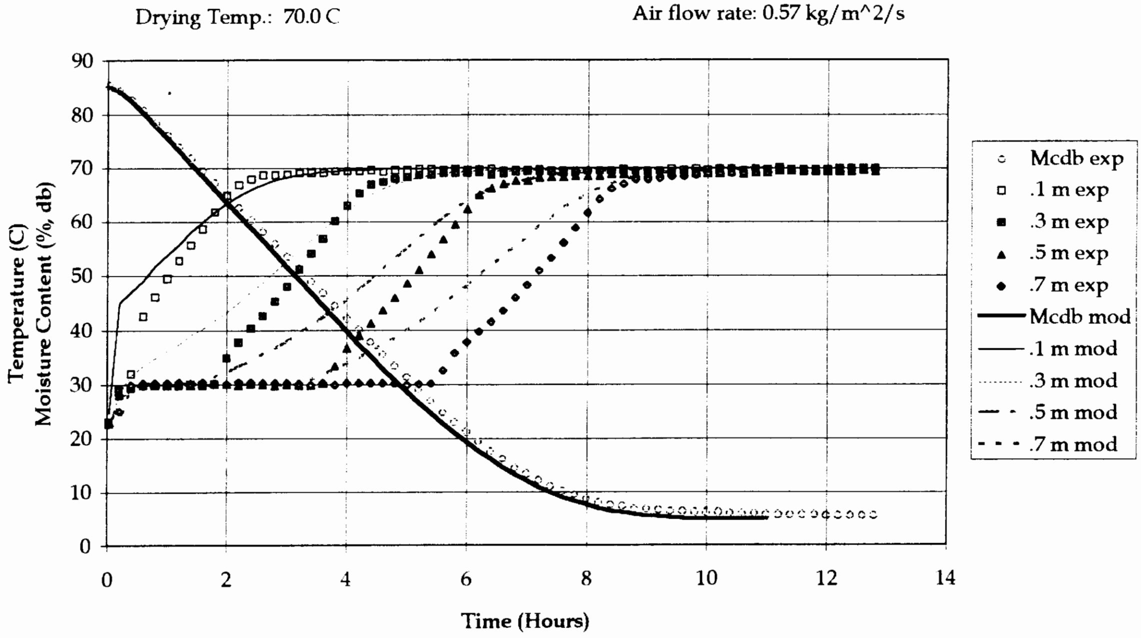


Figure 26. Batch 10 Model Versus Experimental Data for Harrington Malt.

Drier Insulation Tests

Batches 13 and 14, tests for drier improvement due to better insulation, clearly show better moisture content agreement than is seen in their counterparts, batches 2 and 3. Figure 27 shows the typical temperature and moisture content comparison for batches 13 and 14. Not all of the grain temperature data are available for 13 and 14 due to faulty thermocouple wires. The grain temperature agreement appears very similar to batches 2 and 3. It is not inconsistent that the average bed moisture content curves agree better and the grain temperature curves show the same agreement after adding insulation, since the insulation most affects the grain temperature close to the drier chamber's inside wall. The drying rate of malt close to the inside wall increases with the increase in grain temperature, while the grain temperature measurements along the drier chamber's centerline are affected to a much lesser extent.

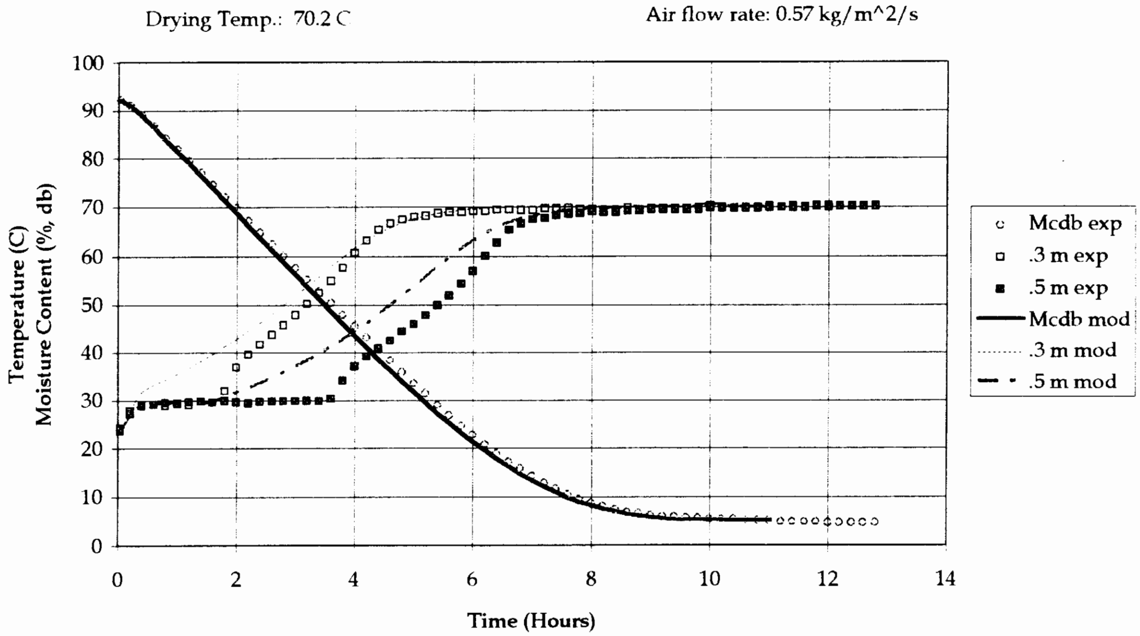


Figure 27. Batch 14 Model Versus Experimental Data for Crystal Malt.

Airflow Reduction Tests

Batches 20-22 and model batches 20-22 show moisture content and temperature agreement similar to the agreement between batches 13 and 14 and model batches 13 and 14. Apparently the model again over predicted drying rates compared to the experiment. The model terminated at the minimum moisture content change limit after only 2-3 hours, once the temperature went up to 82-83 C. The experiment required 6-7 hours under the same conditions. Typical results for batches 20-22 are seen in Figure 28. In batch 22, the model inter-grain air temperature prediction at 0.7 m height accurately exhibited a plateau between hours 6 and 7, although there is a large difference in the temperatures at 0.7 m between the model and experiment.

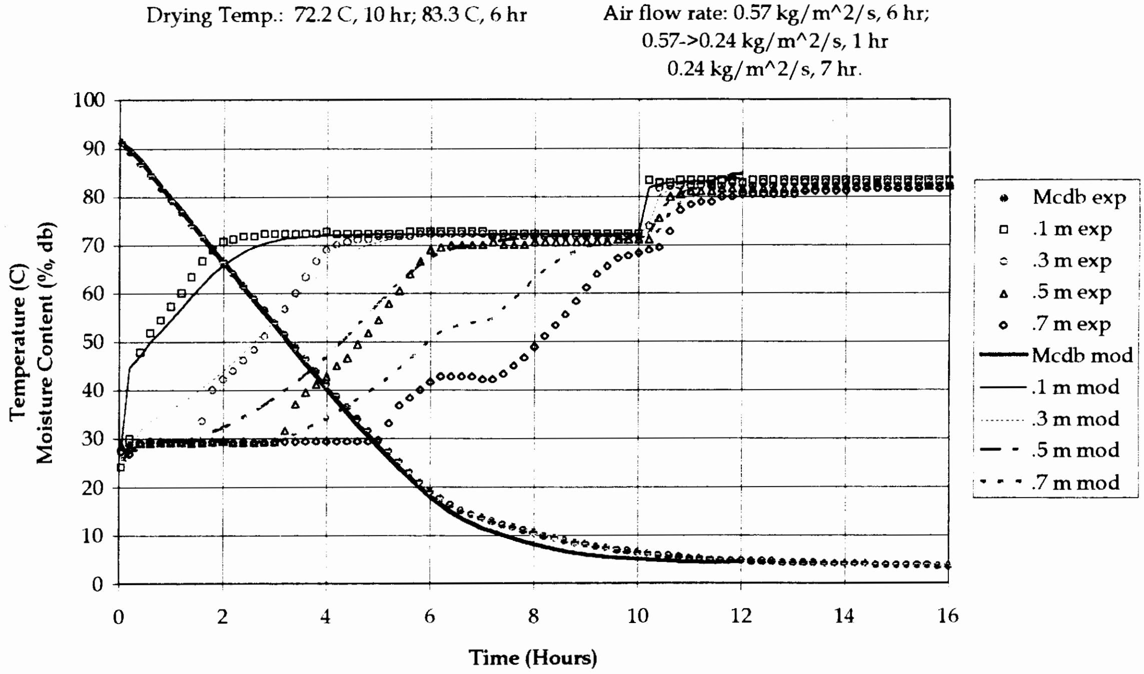


Figure 28. Batch 22 Model Versus Experimental Data for Harrington Malt.

Batches 24 and 25 are also very similar to batches 13 and 14 in their moisture content agreement. Inter-grain air temperature agreement appears better than average compared to all other batches, as seen in Figure 29, which is representative of batches 24 and 25. The model's tendency to over predict drying rate compared to the experiment is apparent, and it resulted in the model reaching the end criterion even before the drying temperature set point went from 72.8 to 83-84 C.

To check how well model one predicts thermal energy savings due to airflow reduction, the thermal energy was calculated and normalized for model batches 20-25, just as in experimental batches 20-25. The relative changes in the energy consumption appear similar, as seen in Figure 30.

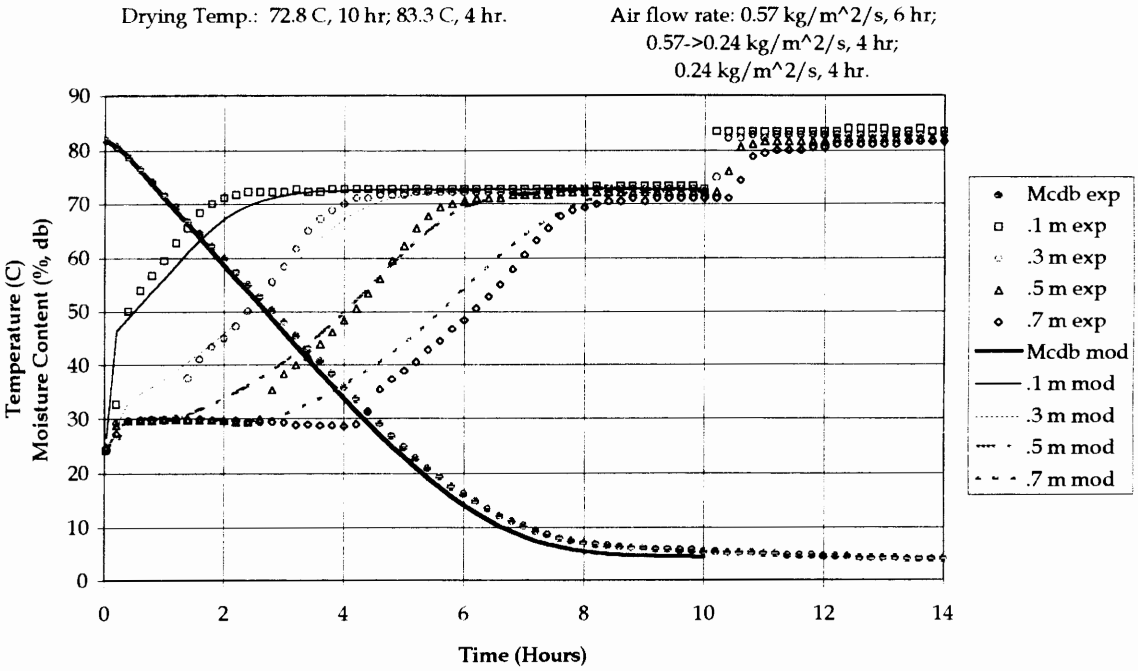


Figure 29. Batch 24 Model Versus Experimental Data for Harrington Malt.

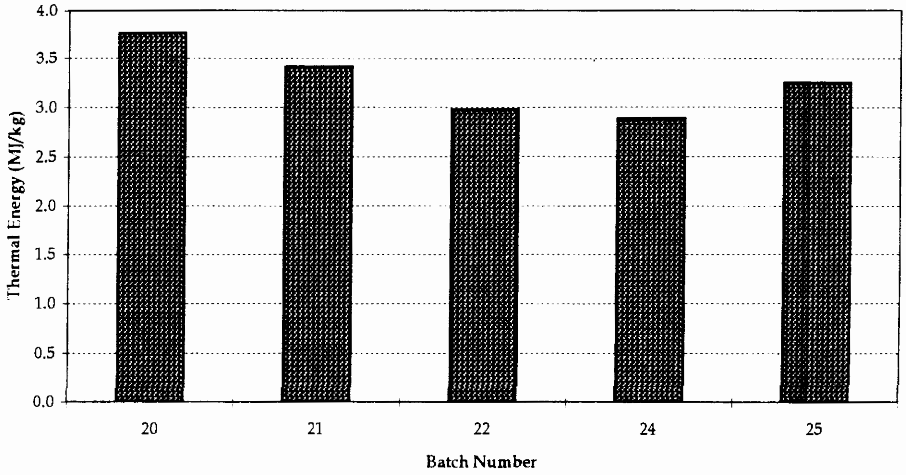


Figure 30. Normalized Thermal Energy to Dry Malt from 78.6% to Terminal Moisture Content for Model Airflow Reduction.

The actual model energy reductions are smaller than in the experiment. Model batch 24, compared to model batch 25, the baseline case, only reduced the energy consumption by 11%, whereas batch 24 reduced its energy consumption by 20% compared to batch 25. This resulted from the more rapid drying predicted by the model at lower moisture contents, which caused the model to spend less energy (when the drier spends more energy) at reduced airflows. Whatever the reason for the discrepancy, the model shows a smaller energy reduction than the experiment.

Overall Comparisons

Looking at all the model and experimental comparisons, one sees that the model accurately predicts the evaporative cooling effect on the grain temperatures. The grain continues to be cooled by evaporation until its surface is no longer completely saturated with water, and then the grain temperature rises continuously toward the drying air temperature.

The model's moisture content and temperature curves have very similar shapes to the experimental ones. The model's exhaust air temperature starts rising (typically more than one hour) before the experimental measurement. This time difference indicates that the model's prediction of the exhaust air temperature may not be good for model-based control scheme tests that apply to industrial driers. The airflow reduction experimental data shows a larger temperature difference between the top and bottom of the bed than the tests with no airflow reduction. This indicates that the heat loss from the drier chamber walls has a greater effect on malt temperature uniformity at lower airflows, and drier insulation becomes increasingly important for the success of airflow reduction schemes.

CHAPTER VIII

RESULTS AND CONCLUSIONS

The thermal efficiency improvements found in this thesis apply to one-deck malt driers, though similar improvements may occur in two-deck driers. A 20% thermal efficiency improvement was experimentally found in constant-temperature drying tests at 70 C (160 F) rather than 63 C (145 F). The quality of the resulting malt was acceptable by industry standards. Drying temperatures above 70 C did not show significant efficiency improvements. The highest constant drying temperature, found experimentally, with acceptable final malt quality was 75 C. However, an initial drying temperature of 70 C is recommended to avoid damaging quality during the high temperature stage typically used at the end of drying.

More aggressive airflow reduction schedules were experimentally found to save about 20% of the thermal energy to heat drying air. Diffusion-based drying model (Bala 1983) simulations of the same airflow reduction schedules showed about an 11% reduction in thermal energy consumption. These results are based on comparisons with airflow schedules similar to those typically used in industry. The temperature schedules were the same for each schedule in the comparisons. The source of the energy saving discrepancy between the experiments and the simulations has not been determined. Final malt quality for the energy saving experiments was perfect, and the drying time was one hour, at the most, greater than the typical industrial airflow schedules. These energy savings can be made with no heat recovery equipment additions to typical industrial malt kilns. Heat loss may cause more thermal non-uniformity in the drier cross-section at low airflows compared to higher airflows, thus requiring better drier insulation. Drier control by exhaust humidity measurements may be useful to reduce the testing required to implement the airflow reduction schedules.

FUTURE WORK

Improvements to the experimental drier used in this research are suggested to make the exhaust air temperature and relative humidity measurements more accurate. The suggestions include adding a constriction at the top of the drier exhaust tube. This would keep outside air from falling into the tube by increasing the exhaust velocity out of the drier. Adding an aluminum foil lining to the inside walls of the exhaust tube would also improve the temperature measurement by reducing the radiation heat loss from the exhaust thermocouple to the walls. Drier heat loss through the walls by radial conduction could be thoroughly investigated, once the exhaust air measurements are improved, by comparing the energy of the drying air going into the malt with the energy of the drier exhaust air plus the sensible heat change of the malt itself.

More research to develop a more accurate grain drying model would be useful. Complex diffusion-based models, such as the one developed by Bruce (1985), might allow use of direct simulation methods to minimize the thermal energy consumed in drying. This could improve on the trial-and-error simulation methods used in this research. The model could be used for further improvements in deep-bed drier operation. It could also be used to investigate counter-flow driers and other drying methods that push the thermal efficiency limit higher than possible with deep-bed driers.

REFERENCES

American Society of Mechanical Engineers (A.S.M.E.). Fluid Meters, Their Theory and Applications. 6th ed. NY., NY.: A.S.M.E., 1971.

Bala, B. K. "Deep Bed Drying of Malt." Diss. U. of Newcastle upon Tyne, U. K., 1983.

Bala, B. K. "Simulation of Deep Bed Malt Drying." Journal of Agricultural Engineering Research 30 (1984): 235-244.

Bonneville Power Administration (B.P.A.) Adjustable Speed Drives Workshop, Jantzen Beach, OR, 4 March 1992.

Briggs, D. E., Hough, J. S., Stevens, R., and Young, T. W. Malting and Brewing Science. Vol. 1. NY., NY.: Chapman and Hall Ltd., 1981.

Bruce, David M., and Sykes, R. A. "Apparatus for Determining Mass Transfer Coefficients at High Temperatures for Exposed Particulate Crops, with Initial Results for Wheat and Hops." Journal of Agricultural Engineering Research 28 (1983): 385-400.

Bruce, David M. "Exposed-Layer Barley Drying: Three Models Fitted to New Data up to 150 C." Journal of Agricultural Engineering Research 32 (1985): 337-347.

Chirife, Jorge. "Fundamentals of the Drying Mechanism During Air Dehydration of Foods." Advances in drying. Ed. Mujumdar, Arun S. Washington, D.C.: Hemisphere Publishing Corporation; 1983: 73-102. 2nd v.

Cuti, John G. Private conversation. Great Western Malting Company, Vancouver, WA. October 31, 1995.

Geankoplis, Christie J. Transport Processes and Unit Operations. Newton, MA: Allyn and Bacon, 1983.

Grofton, Peter. Mastering Serial Communications. Berkeley, CA: Sybex, 1986.

Kuntze, Tomi M., Saxen, Henrik. "Simulation of Deep-Bed Kilning of Malt." Industrial and Engineering Chemistry Research 33 (2) (1994): 321-328.

McEwen, E., Simmonds, W. H. C., Ward, G. T. "The Drying of Wheat Grain. Part III: Interpretation in Terms of Biological Structure." Trans. Instn. Chem. Engrs. 32 (1954): 115-120.

Miller, Richard W. Flow Measurement Engineering Handbook. NY., NY.: McGraw-Hill, 1983.

Perry, Robert, and Green, Don. Eds. Perry's Chemical Engineer's Handbook. 6th ed. NY., NY.: McGraw-Hill Book Co., 1984.

Smith, Carlos A., and Corripio, Armando B. Principles and Practice of Automatic Process Control. NY., NY.: John Wiley, 1985.

Stefani, Raymond T., Savant, C. J., Shahian, B., and Hostetter, G. Design of Feedback Control Systems. NY., NY.: Saunders College Publishing, 1994.

APPENDIX A

DRYING AIR PROPERTY EQUATIONS

The goal of this section is to estimate the drying rate of each bed in a two-deck kiln. Calculations are necessary to approximate the drying air conditions at each level of the two-deck kiln, shown in Figure 1 in the text. Data, from the Compartment House PLC control system at Great Western Malting Company, for the thermal consumption of the heat exchanger, and the temperature and relative humidity at the positions shown in Figure 1, is also necessary.

LOWER DECK DRYING RATE

To calculate the lower deck drying rate, it is necessary to find the humidity at points 2 and 3 in Figure 1. The mass flow rate of air through the heat exchanger is also needed. Then a mass balance on the moisture in the air flowing through the lower deck is made, which yields the lower deck's drying rate.

Humidity Calculation at Point 2

Given T, air temperature (F), and rh, relative humidity (%), at 1, H, humidity (lbm water/lbm dry air), can be found at point 2 because it is equal to H at point 1. To find H at 1, first calculate p_{wsat}, the saturated water vapor pressure (atm), at 1. Setting

$$T_{k1} = \frac{5}{9}\cdot(T_1 - 32) + 273.16 \tag{27}$$

and

$$\theta_1 = \frac{273.16}{T_{k1}} \tag{28}$$

p_{wsat1} can be found from the equation

$$\log_{10}(p_{wsat1}) = 10.80 \cdot (1-\theta_1) + 5.028 \cdot \log_{10}(\theta_1) + 1.505 \times 10^{-4} \cdot (1 - 10^{-8.297 \cdot [\frac{1}{\theta_1} - 1]}) + 4.287 \times 10^{-4} \cdot (10^{4.770 \cdot (1-\theta_1)} - 1) - 2.220. \tag{29}$$

The actual vapor pressure, p_w (atm), is given by

$$p_{w1} = \frac{rh_1 \cdot p_{wsat1}}{100} \tag{30}$$

and H at 1 is found from

$$H_1 = 0.6219 \cdot \frac{p_{w1}}{1 - p_{w1}}. \tag{31}$$

Humidity Calculation at Point 3

Given T and rh at 4, h_3, air enthalpy at 3, can be found by assuming it equals h_4, where h_4 is given by

$$h_4 = 0.24 \cdot T_4 + H_4 \cdot (1061 + 0.444 \cdot T_4). \tag{32}$$

To find H_4, follow the steps for the Humidity Calculation at Point 2, replacing the subscript 1 with 4. Then H_3 is given by

$$H_3 = \frac{h_3 - 0.24 \cdot T_3}{1061 + 0.444 \cdot T_3}. \tag{33}$$

Air Flow Rate Through Heat Exchanger

The air mass flow rate through the heat exchanger is found from an energy balance on the heat exchanger air and water. Given $\dot{q}$, the heat exchanger thermal usage rate (therm/minute), and h_2 and h_1, the enthalpy of the air downstream and upstream of the heat exchanger (Btu/lbm dry air), $\dot{m}_{air,htx}$, the mass flow rate of air (lbm/minute) can be found by

$$\dot{m}_{air,htx} = \frac{\dot{q} \cdot 10^5}{h_2 - h_1}. \tag{34}$$

h_1 and h_2 are found with eq. (32), by replacing 4 with 1 and 2, respectively.

Moisture Mass Balance on the Drying Air

The actual drying rate of the lower deck is estimated by a simple moisture mass balance on the air through the lower deck. Since any airflow around the lower deck has no change in H, humidity, that airflow does not show up in the calculation. The drying rate, $\dot{m}_{water}$ (lbm water/minute), is given by

$$\dot{m}_{water} = \dot{m}_{air,htx} \cdot (H_2 - H_1). \tag{35}$$

UPPER DECK DRYING RATE

The upper deck drying rate is found similarly to the lower deck. Since H at 3 and H at 4 are already known from equations (33) and (31) using the analysis described above, it is only necessary to find $\dot{m}_{air,upper}$, the mass flow rate of air through the upper bed (lbm dry air/minute). Then a moisture mass balance may be used to find the upper deck drying rate.

$\dot{m}_{air,upper}$ is found by doing an energy balance on the airflow through the heat exchanger, through the cold-air bypasses, and through the upper deck. The analysis results in the equation

$$\dot{m}_{air,upper} = \dot{m}_{air,htx} \cdot \frac{h_2 - h_1}{h_3 - h_1}. \tag{36}$$

Then $\dot{m}_{water,upper}$, the upper deck drying rate (lbm water/minute) is found by the equation

$$\dot{m}_{water,upper} = \dot{m}_{air,upper} \cdot (H_4 - H_3). \tag{37}$$

APPENDIX B

WETTED-SURFACE MODEL CODE

1. Variable definitions

dmair, dmairini: mass flow of air, lb/min
dmevap: increment of water evaporated, lb/min
energy: energy supplied to heat drying air, Btu
flowred: reduction factor for air flow
HABop: % opening of hot air bypasses
hamb: enthalpy of ambient air, Btu/lb
hmA: mass transfer coefficient * grain surface area, cfm
hon: enthalpy of air on, Btu/lb
invsolid: 1/(solid percentage, dec., green malt)
m: lb dry grain
mcin: initial moisture content of green malt % wb
mdiff: difference in dmevap: dmair(Wex-Wao)- hmA(den,w,surf - den,w, air)
mevap: total mass of water evaporated, lb
psatTsurf: saturated vapor pressure for Tsurf of malt
psatwb: partial saturation pressure of water at wet bulb temp, atm
psurf: grain surface vapor pressure, atm
pwexold, pwex: partial pressure of water in exhaust air, atm
rhamb: ambient relative humidity, %
rhamb: relative humidity of ambient air, %
rhave: average relative humidity in equilibrium with average malt mc
rhs: equilibrium relative humidity at grain surface, decimal
Tamb: ambient air temp, F
Tex: temperature of exhaust air, F
Texold, Tex: exhaust air temperature, F
time: time, minutes
Ton: air on temperature, F
Tsold, Ts: grain surface temperature, F
tstep: time step for drying analysis
Twboldk, Twbk, Twb: wet bulb temperature, (K, K, & F)
wdenex: water vapor density of exhaust air
wdenon: water vapor density of air on
wdens: water vapor density of malt surface
wdifflm: log-mean vapor density difference between air on and air off and bed
Wex: absolute humidity of exhaust air
Won: absolute humidity of air on

2. Excel 4.0 Macro Code for Mass Transfer Model

```
mod2

Ton1=145                                              input variables
Ton1_2=155
Ton1_3=180
time_1=230
time_2=470
Tamb= 63
rhamb= 70
```

```
hmAini=1417383
m=320616
mcini1= 13
mcini2= 47
HABop= 0.75
dmairini=34294
flowred= 0.61
tstep= 10

mc1= mcini1                                              initialize variables
mc2= mcini2
dmair1=(1- HABop)*dmairini
dmair2= dmairini
hmA1= (1- HABop)^0.49*hmAini
hmA2= hmAini
invsolid1= 1/(1-mcini1/100)
invsolid2= 1/(1-mcini2/100)
mevap1= 0
mevap2= 0
time=0
energy= 0
                                                         calculate Wamb and hamb
pwamb='C:\CHKILN\MACRO2.XLM'!pwrh(Tamb,rhamb)
Wamb= 0.6219* pwamb/(1- pwamb)
hamb= 0.24*Tamb + Wamb*(1061+ 0.444*Tamb)

Won1= Wamb
hon1= 0.24*Ton1 + Won1*(1061+ 0.444*Ton1)

Twb= 'C:\CHKILN\MACRO2.XLM'!twb(hon1)                    iterate to find Twbon1
psatwb=(hon1-0.24*Twb)/(659.83+0.036124*Twb+hon1)        psat at Twb, atm
pwon1= Won1/(0.6219 + Won1)                              pw, air on, atm


                                                         initial exhaust and surface conditions
Tex1=Twb
Tex2=Twb

                                                         initialize equilibrium rh of surfaces
=IF( mc1 < 30)
   x= 19.2/30
   mcx= mc1*x                                            mc mapped from 6.3 to 30 to 6.3 to 19.2
   rhave1= (-0.0272*(mcx)^3 + 0.7561*(mcx)^2 + 0.3735*(mcx)
+ 0.9431)/100
   rhs1= (mc1/40+ 0.25)*rhave1
=ELSE()
   rhs1=1
=END.IF()
=IF( mc2 < 30)
   x= 19.2/30
   mcx= mc2*x                                            mc mapped from 6.3 to 30 to 6.3 to 19.2
   rhave2= (-0.0272*(mcx)^3 + 0.7561*(mcx)^2 + 0.3735*(mcx)
+ 0.9431)/100
   rhs2=(mc2/40+0.25)*rhave2
=ELSE()
```

```
    rhs2= 1
 =END.IF()
pwex1= 0.98*psatwb                                                  initial pwex1 guess at t=0
pwex2= 0.98*psatwb                                                  initial pwex2 guess at t=0

 =WHILE(mc1>4)
     Tex1last= 0
     psurf1last= 1
     iter1=0
     iter2=0

     Ts1= 'C:\CHKILN\MACRO2.XLM'!Tsurf(hon1,rhs1)
      psurf1= (hon1-0.24*Ts1)/(659.83+0.036124*Ts1+hon1)           pw
      psatTs1= psurf1/rhs1

=     WHILE(AND(OR(ABS(Tex1last-Tex1)>0.5, ABS((psurf1last-        iterate to find psurf and Tex at time t
psurf1)/psurf1last)> 0.002), iter1<100))
        mevap1last= mevap1
        Tex1last= Tex1
         psurf1last= psurf1
         iterp1= 0
         pwexold= 1
          x= 0.24 + 0.036124* pwex1
         Tex1R= (hon1 - (hon1 + 659.836)*pwex1)/x + 459.7
         wdenex1= pwex1*24.676/Tex1R                               density of water vapor, exhaust
         wdens1= psurf1*24.676/(Ts1 + 459.7)                       density of water vapor, grain surface
=         IF(wdenex1> wdens1)
            pwex1= 0.98*Tex1R*psurf1/(Ts1 + 459.7)
            x= 0.24 + 0.036124* pwex1
           Tex1R= (hon1 - (hon1 + 659.836)*pwex1)/x + 459.7
           wdenex1= pwex1*24.676/Tex1R                             density of water vapor, exhaust
=        END.IF()

=        WHILE(AND( ABS(pwexold-pwex1)>0.00000001,                 iterate to find pwex using Newton-Raphson
iterp1<100))
           x= 0.24 + 0.036124* pwex1
           Tex1R= (hon1 - (hon1 + 659.836)*pwex1)/x + 459.7
           wdenex1= pwex1*24.676/Tex1R                             density of water vapor, exhaust
=           WHILE(wdenex1> wdens1)
                pwex1=(pwex1+ pwexold)/2
                x= 0.24 + 0.036124* pwex1
               Tex1R= (hon1 - (hon1 + 659.836)*pwex1)/x +
459.7
               wdenex1= pwex1*24.676/Tex1R                         density of water vapor, exhaust
=           NEXT()
           pwexold= pwex1
           wdenon1= pwon1*24.676/(Ton1 + 459.7)                    density of water vapor, air on
           wdens1= psurf1*24.676/(Ts1 + 459.7)                     density of water vapor, grain surface
           wdiff1= wdenex1 - wdenon1
           wdiff2= LN( (wdens1 - wdenon1)/(wdens1 - wdenex1) )
```

```
          wdifflm= wdiffl/wdiff2                              log-mean water vapor density difference
                                                              doesn't work because data from 6/25/94
                                                              grave has pwex > psurf, so log-mean gives
                                                              an infinite result
          hevapl= hmAl*wdifflm
          wevapl= dmairl*( 0.6219*pwexl/(1- pwexl) - Wonl)
          f= wevapl - hevapl
          difr= LN( (wdensl -wdenonl)/(wdensl - wdenexl))
          dTexlR= (-0.276124*honl - 158.361)/x^2
          dwdenexl= (TexlR - pwexl*dTexlR)*24.676/TexlR^2
          ddifr= dwdenexl/( wdensl - wdenexl )
          ddiflm= (dwdenexl *difr -(wdenexl -wdenonl)* ddifr)/
difr^2
          df= 0.6219*dmairl/(1 -pwexl)^2 - hmAl*ddiflm
          pwexl= pwexl - f/df
          iterpl =iterpl+ 1
=      NEXT()

=        IF(iterpl=100)
=          FORMULA("Didn't converge on pwexl")
=          RETURN()
=        END.IF()

         Texl= (honl - (honl+ 659.836)*pwexl)/(0.24 +          Tex, F
0.036124*pwexl)
         Wexl=0.6219*pwexl/(l-pwexl)                           Wex
         dmevapl= dmairl*(Wexl- Wonl)
         mevapllast= mevapllast+ dmevapl*tstep
         mcl= (m*(invsolidl- 1) -mevapllast)/(m*invsolidl-     mc % wb
mevapllast)*100

=         IF(mcl < 30)
            iterl= 1
            iter2= iter2 + 1
            x= 19.2/30
            mcx= mcl*x                                         mc contracted from 0 - 30 to 0 - 19.2
            rhavel= (-0.0272*(mcx)^3 + 0.7561*(mcx)^2 +
0.3735*(mcx) + 0.9431)/100
            rhsl= (mcl/40+ 0.25)*rhavel
=         END.IF()
=iter2
=         IF(iter2=100)
=           FORMULA("Didn't converge on rhsl recalculations")
=           RETURN()
=         END.IF()

          Tsl= 'C:\CHKILN\MACRO2.XLM'!Tsurf(honl,rhsl)
          psurfl= (honl-0.24*Tsl)/(659.83+0.036124*Tsl+honl)   pw
          psatTsl= psurfl/rhsl

          iterl= iterl + 1
```

```
=    NEXT()                                                    end of iterate for Ts & Tex loop

=       IF(iter1=100)
=          FORMULA("Didn't converge on abs(Tex1-Tex) and
abs((psurf1- psurf)/psurf)")
=          RETURN()
=       END.IF()

   Wex1=0.6219*pwex1/(1-pwex1)                                 Wex
   dmevap1= dmair1*(Wex1- Won1)
   mevap1= mevap1+ dmevap1*tstep
   mc1= (m*(invsolid1- 1) -mevap1)/(m*invsolid1-mevap1)*100    mc % wb
   rhex1= 'C:\CHKILN\MACRO2.XLM'!calcrh(Tex1,Wex1)             calculate rh exhaust
   mdiff1= f                                                   check dmair(Wex-Wao)= hmA(den,s-
                                                               den,air)
   time= time+ tstep

   hex1= 0.24*Tex1 + 0.6219*pwex1/(1-pwex1)*(1061+
0.444*Tex1)
   energy= energy + dmair2*(hon1- hamb)*tstep
   hsurf1= 0.24*Ts1 + 0.6219*psurf1/(1-psurf1)*(1061+
0.444*Ts1)

   col1= COLUMN(ACTIVE.CELL())
=    FORMULA(time)                                             print out values on active sheet
=    SELECT(OFFSET(ACTIVE.CELL(),0,1))
=    FORMULA(Ton1)
=    SELECT(OFFSET(ACTIVE.CELL(),0,1))
=    FORMULA(Won1)
=    SELECT(OFFSET(ACTIVE.CELL(),0,1))
=    FORMULA(hon1)
=    SELECT(OFFSET(ACTIVE.CELL(),0,1))
=    FORMULA(psurf1/(Ts1+459.7)*24.676)                        water vapor density, surface of grain
=    SELECT(OFFSET(ACTIVE.CELL(),0,1))
=    FORMULA(Ts1)
=    SELECT(OFFSET(ACTIVE.CELL(),0,1))
=    FORMULA(Tex1)
=    SELECT(OFFSET(ACTIVE.CELL(),0,1))
=    FORMULA(Wex1)
=    SELECT(OFFSET(ACTIVE.CELL(),0,1))
=    FORMULA(rhex1)
=    SELECT(OFFSET(ACTIVE.CELL(),0,1))
=    FORMULA(rhs1*100)
=    SELECT(OFFSET(ACTIVE.CELL(),0,1))
=    FORMULA(pwex1/(Tex1+ 459.7)*24.676)                       water vapor density, exhaust air
=    SELECT(OFFSET(ACTIVE.CELL(),0,1))
=    FORMULA(hex1)
=    SELECT(OFFSET(ACTIVE.CELL(),0,1))
=    FORMULA(dmevap1)
=    SELECT(OFFSET(ACTIVE.CELL(),0,1))
=    FORMULA(mc1)
=    SELECT(OFFSET(ACTIVE.CELL(),0,1))
=    FORMULA(mdiff1)
```

```
=    SELECT(OFFSET(ACTIVE.CELL(),0,1))
=    FORMULA(hsurf1)
=    SELECT(OFFSET(ACTIVE.CELL(),0,1))
=    FORMULA(energy/10^5)
=    SELECT(OFFSET(ACTIVE.CELL(),1, col1-
COLUMN(ACTIVE.CELL())))

=  IF(time = time_2)                                  Calculate increased air on temperature
      Ton1= Ton1_3
      dmair1= flowred* dmairini
      hmA1= (flowred^0.49)*hmAini
      pwon1= Won1/(0.6219 + Won1)
=  ELSE.IF(time = time_1)
      Ton1= Ton1_2
      pwon1= Won1/(0.6219 + Won1)
=  END.IF()
   hon1= 0.24*Ton1 + Won1*(1061+ 0.444*Ton1)

=  IF(mc1 < 30)
      x= 19.2/30
      mcx= mc1*x                                      mc mapped from 6.3 to 30 to 6.3 to 19.2
      rhave1= (-0.0272*(mcx)^3 + 0.7561*(mcx)^2 +
0.3735*(mcx)  + 0.9431)/100
      rhs1= (mc1/40+ 0.25)*rhave1
      psurf1= rhs1*psatTs1
=  END.IF()

=NEXT()

=RETURN()
```

3. Macro functions used in Excel code

a. Calculate relative humidity given absolute humidity and temperature

```
Function to calculate relative humidity given W and T
calcrh
=RESULT(1)                                   return number
=ARGUMENT("tf",1)                            argument for fahrenheit temperature
=ARGUMENT("w",1)                             argument for absolute humidity
=IF(tf=0, RETURN(H17))
=IF(w=0, RETURN(H17))
=(tf-32)*5/9+273.16                          calculate tf in kelvin
=w/(0.6219 +w)                               pw
=273.16/G8                                   z=273.16/T
=10.796*(1-G10)                              p1
=5.0281*LOG10(G10)                           p2
=-8.2969*((1/G10)-1)                         a1
=0.00015047*(1-10^G13)                       p3
=4.7696*(1-G10)                              a2
=0.0004287*(10^G15-1)                        p4
=G11+G12+G14+G16-2.2196                      lp
```

```
=10^G17                                               ps
=G9/G18*100                                           rh
=RETURN(G19)
```

b. Calculate partial pressure of water vapor given temperature and relative humidity

```
Function to calculate pw given T and rh
pwrh
=RESULT(1)                                            return number
=ARGUMENT("tf",1)                                     argument for fahrenheit temperature
=ARGUMENT("rh",1)                                     argument for relative humidity
=IF(tf=0, RETURN(H39))
=IF(rh=0, RETURN(H39))
Tk=(tf-32)*5/9+273.16                                 calculate tf in kelvin
z=273.16/Tk                                           z=273.16/T
pa=10.796*(1-z)                                       pa
pb=5.0281*LOG10(z)                                    pb
aa=-8.2969*((1/z)-1)                                  aa
pc=0.00015047*(1-10^aa)                               pc
ab=4.7696*(1-z)                                       ab
pd=0.0004287*(10^ab-1)                                pd
lp=pa+pb+pc+pd-2.2196                                 lp
psat=10^lp                                            ps
pw=psat*rh/100
=RETURN(pw)
```

c. Calculate wet bulb temperature given enthalpy

```
function to calculate wet bulb temperature given h
twb
=RESULT(1)
=ARGUMENT("hao",1)
=IF(hao=0, RETURN(0))
iter= 1                                               iterate to find twb
Twbold= 0
Twbnew= 60
=WHILE(AND( ABS(Twbold-Twbnew)>0.5, iter<100))
    Twbold= Twbnew
    Twboldk= (Twbold-32)*0.555555 + 273.16            twbold (K)
    pw= (hao-0.24*Twbold)/(659.83+0.036124*Twbold+hao) pw
    aa= 5.02808*LOG10(273.16/Twboldk)
    b= 0.000150474*(1-10^(-8.29692*(Twboldk/273.16-1)))
    d= 0.00042873*(10^(4.76955*(1-273.16/Twboldk)) -1)
    Twbk= 10.79586*273.16*(10.79586-LOG10(pw) +aa +b + d -   twbnew K
2.2195983)^(-1)
    Twbnew= (Twbk-273.16)*1.8+32                      twbnew F
    iter= iter+ 1
=NEXT()
=RETURN(Twbnew)
```

d. Calculate grain surface temperature given enthalpy and relative humidity at grain surface

function to calculate grain surface temperature using Newton-Raphson given hon and rhs

```
Tsurf
=RESULT(1)
=ARGUMENT("hao",1)
=ARGUMENT("rhs",1)
=IF(hao=0, RETURN(0))
=IF(rhs=0, RETURN(0))
iter= 1                                                                   iterate to find twb
Tsurfold= 1
Tsurf= -90.9091*rhs + 170.9

=WHILE(AND( ABS((Tsurfold-Tsurf)/Tsurfold)>0.001, iter<100))
    Tsurfold= Tsurf
    Tsurfk= (Tsurf-32)*5/9 + 273.16                                       twbold (K)
    pw= (hao-0.24*Tsurf)/(659.83+0.036124*Tsurf+hao)                      pw
    aa= 5.02808*LOG10(273.16/Tsurfk)
    b= 0.000150474*(1-10^(-8.29692*(Tsurfk/273.16-1)))
    d= 0.00042873*(10^(4.76955*(1-273.16/Tsurfk)) -1)
    psatTsurf= pw/rhs
    x= (10.79586-LOG10(psatTsurf) +aa +b + d -2.2195983)
    f= Tsurfk- 10.79586*273.16/x                                          twbnew K
    aa= 9/5*(0.24*(659.83+ 0.036124*Tsurf + hao) + 0.036124*(hao-
0.24*Tsurf))/(2.30259*(hao- 0.24*Tsurf)*(659.83+ 0.036124*Tsurf +hao))
    bb= -5.02808/2.30259/Tsurfk
    cc= -0.000150474*10^(-8.29692*(Tsurfk/273.16 -1))*(-8.29692/273.16)*2.30259
    dd= 0.00042873*4.76955*273.16*2.30259/Tsurfk^2*10^(4.76955*(1- 273.16/Tsurfk))
    df= 1+ 10.79586*273.16/x^2*(aa+ bb+ cc+ dd)
    Tsurfk= Tsurfk - f/df
    Tsurf= (Tsurfk-273.16)*1.8+32                                         twbnew F
    iter= iter+ 1
=NEXT()
=RETURN(Tsurf)
```

APPENDIX C

MODEL ONE CODE

```
/* Program name:        Model1 header file                  */
/* Purpose:             Consolidates function prototypes    */
/* File:                model1.h                            */
/* Date:                17/3/95                             */

int airinit(double *, double *, double *, double *, double *,
        int *, float *);

void arrayinit(double *, float, float, double *, double *, double *, double *, double *, int, float);

double *dvector(int, int);

float equilrh(float, float);

float frhcalc(float, float, float, float, float, float, float, float, double, float, float, float, float, float,
        float, float, float *, float *, float *, float, float *);

int getvalues(float *, float *, float *, float *, float *, double *, double *, float *, double *, float *,
        float *, float *, float *, float *, int *, int *, float *, float *, int *, int *, float *);

int htxinput(float, float *, float *, float *, float *, int, double *, double *, double *, double *,
        double *);

int liter(double *, double *, double *, double *, double *, double *, double, int, float, float, float,
        float *, float, float, float, float, float, float, float, float, float, float, int);

FILE *openout(char *);

void prlaydat(float, float, float, float, int, double *, double *, double *, double *, FILE *, int);

void prtimdat(float, float, float, float, float, double *, double *, float, FILE *, int, double *, float);

int rootfind(float, float *, float, float *, float, float, float, float, float *, float, float, float, double,
        float, float, float, float, float, float, float, float *, float *, float, int);

float satpr(float);

int titer(float, double *, double *, double *, double *, double *, double *, float, float, double, int,
        float, double, double, double *, double *, double *, double *, int, double *, float, float,
        float, float, float, float, float, int, float, float, int, int, float);
```

```
/* Purpose:         Initializes drier input airflow
                    properties                       */
/* File:            airinit.cpp                      */
/* Date:            17/3/95                          */

/* Inputair.dat file format (include at least everything shown!):

The first line must start with time = 0 min
                    0   72  0.38   161   7.1
                    2   72  0.38   161   7.1
*/
```

```
#include <stdio.h>
#include <stdlib.h>
#include "model1.h"

int airinit(double *time, double *tatm, double *rhat, double *htxtemp, double *G, int *N, float
        *tml)
{
        double *temp;
        int check=5, i=1;
        FILE *fin;

        fin=fopen("inputair.dat", "r");
        if (fin==NULL)
        {
                printf("\n\nCouldn't open inputair.dat for reading"
                        "\n");
                return -1;
        }
        fscanf(fin, "%*s %*s %*s %*s %*s %*s %*s %*s %*s %*s");

        while ((i<=*N) && (check==5))
        {
                check=fscanf(fin, "%lf %lf %lf %lf %lf", time+i,
                        tatm+i, rhat+i, htxtemp+i, G+i);
                tatm[i]=.55556*(tatm[i]-32.0);
                htxtemp[i]=.55556*(htxtemp[i]-32.);
                G[i]=4.8824*G[i];
                i++;
        }
        if (i==*N+1)
        {
                check =fscanf(fin, "%lf", temp);
                if (check!=EOF)
                {
                        printf("\nNumber of air input data exceeds"
                                "maximum limit set in model1.dat.\n"
                                "Increase the maximum in model1.dat to the"
                                " number of air input\ndata time steps");
                        return -1;
                }
        }

        fclose(fin);
        i-=2;
        *tml=time[i];
        *N= i;

        return 1;
}
```

```
/* Program name:                Malt property initializer          */
```

```
/* Purpose:                    Sets initial values of malt arrays */
/* File:                       arrayini.cpp                       */
/* Date:                       20/3/95                            */

#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#include "model1.h"

void arrayinit(double *rh, float mcini, float tgini, double *mcdb, double *tg, double *ta, double
        *rt,  double *hum, int nz, float apr)
{
        int i;
        float rhtemp, pvs, pv, humtemp;

        rhtemp=equilrh(mcini, tgini);
        pvs=satpr(tgini);
        pv=rhtemp*pvs;
        humtemp=.622*pv/(apr-pv);
        for(i=1; i<=nz; i++)
        {
                rh[i]=rhtemp;
                mcdb[i]=mcini;
                tg[i]=tgini;
                ta[i]=tgini;
                rt[i]=0.0;
                hum[i]=humtemp;
        }
}
```

```
/* Program name:               Vector allocator                   */
/* Purpose:                    Allocates double type arrays       */
/* File:                       dvector.cpp                        */
/* Date:                       17/3/95                            */

#include <stdio.h>
#include <stdlib.h>
#include "model1.h"

double *dvector(int nl, int nh)
{
        int j;
        double *v;

        v=(double *)malloc((unsigned)(nh-nl+1)*sizeof(double));
        if(!v)
        {       printf("Allocation failure in dvector()");
                exit(1);
        }
        v-=nl;

        for(j=nl; j<=nh; j++)
```

```
			v[j]=0.0;

		return v;
}
```

```
/* Program name:	Equilibrium relative humidity function		*/
/* Purpose:		Find malt's equilibrium rh=f(mc,tg)		*/
/* File:		arrayini.cpp					*/
/* Date:		20/3/95						*/

float equilrh(float mc, float tg)
{
		float mcwb, rh;

		mcwb=mc/(mc+1);
		rh=exp((-37357.912/(8.315*(tg+273.15)))*exp(-29.9857*
			mcwb));
		return rh;
}
```

```
/* Program name:	RH Function Calculator		*/
/* Purpose:		Finds value of rh-rhmax		*/
/* File:		frhcalc.cpp			*/
/* Date:		25/3/95				*/

#include <stdio.h>
#include <stdlib.h>
#include "model1.h"

float frhcalc(float cpa, float cpv, float cpl, float huma, float dm, float dendry, float dz, float Gx,
		double dt, float a, float yy, float ht, float f, float b, float tda, float apr, float *dtg, float
		*dta, float *h, float rhmax, float *rha)
{
		float e, ge, top, bb, bot, t, ps, p, frh;

		e=cpa+cpv*(huma-(dm*dendry*dz/(Gx*dt)));
		ge=Gx*e;
		top=dendry/dt*dm;
		top=a+top*((2.*yy/ht)+f*dz/ge);
		bb=b+cpl*dm;
		bot=1.+dendry/dt*(2.*b/ht+dz*bb/ge);
		*dtg=top/bot;
		*dta=-dendry*dz/(Gx*dt*e)*((*dtg)*bb-dm*f);
		t=tda+(*dta);
		ps=satpr(t);
		*h=huma-dm*dendry*dz/(Gx*dt);
		p=(*h)*apr/(.622+(*h));
		*rha=p/ps;
		frh=(*rha)-rhmax;

		return frh;
```

```
}
```

```
/* Program name:     Data scanner                        */
/* Purpose:          Scans input from model1.dat         */
/* File:             getvalue.cpp                        */
/* Date:             17/3/95                             */

/* Model1.dat file format:

 Leave a space on both sides of each value after the =

 Specific heat of grain= .39466 Btu/lbm/F
 Specific heat of water vapor= .444 Btu/lbm/F
 Specific heat of water liquid= 1.0 Btu/lbm/F
 Specific heat of air= .24 Btu/lbm/F
 Moisture content limiter (0 = goal, 1 = change limit)= 0
 Moisture content goal= .1 dry basis, ratio
 Moisture content change limit (>=.1, <=10%, d.b.)= .2
 Moisture content change period (>= 5, <=60min)= 60
 Density of dry grain= 21.12 lbm/ft^3
 Dry wt./area= 56.31 lbm/ft^2
 Bed depth= 32 in
 Time step= 2 min
 Time limit criterion= 1.667e-4 min
 RH root criterion= 1.0e-4 rh, decimal
 Max airoff rh= .98 decimal
 Grain temperature, initial= 86.0 F
 Moisture content, initial= .8868 dry basis, decimal
 Max No. of ambient input steps= 5
 No. of layers= 150
 Print layer results each 3 time steps
 Print layer results each 1 layers
 Kiln bed surface area= 5760 ft^2
 Total inlet area of fans= 143.1 ft^2
 Fan efficiency= .638 ratio
 Cost per kWhr= .03 $
 Cost per therm= .34 $

*/

#include <stdio.h>
#include <stdlib.h>
#include "model1.h"

int getvalues(float *cpg, float *cpv, float *cpl, float *cpa, float *mcgol, double *dendry, double
        *dwa, float *z, double *dt, float *epsi, float *eps, float *rhmax, float *tgini, float *mcini,
        int *N, int *nz, float *kwhcost, float *thermcost, int *endcrit, int *mcchamin, float
        *mcchalim)
{
        int check;
        FILE *fin;
```

```
fin=fopen("model1.dat","r");
if(fin==NULL)
        printf("\n\nCouldn't open file for reading\n");

fscanf(fin, "%*s %*s %*s %*s %*s %*s %*s %*s %*s %*s %*s"
        " %*s");
check=fscanf(fin, "%*s %*s %*s %*s %f %*s", cpg);
check+=fscanf(fin, "%*s %*s %*s %*s %*s %f %*s", cpv);
check+=fscanf(fin, "%*s %*s %*s %*s %*s %f %*s", cpl);
check+=fscanf(fin, "%*s %*s %*s %*s %f %*s", cpa);
check+=fscanf(fin, "%*s %*s %*s %*s %*s %*s %*s %*s %*s"
 " %*s %i", endcrit);
check+=fscanf(fin, "%*s %*s %*s %f %*s %*s %*s", mcgol);
check+=fscanf(fin, "%*s %*s %*s %*s %*s %*s %*s %f",
 mcchalim);
check+=fscanf(fin, "%*s %*s %*s %*s %*s %*s %*s %i",
 mcchamin);
check+=fscanf(fin, "%*s %*s %*s %*s %lf %*s", dendry);
check+=fscanf(fin, "%*s %*s %lf %*s", dwa);
check+=fscanf(fin, "%*s %*s %f %*s", z);
check+=fscanf(fin, "%*s %*s %lf %*s", dt);
check+=fscanf(fin, "%*s %*s %*s %f %*s", epsi);
check+=fscanf(fin, "%*s %*s %*s %f %*s %*s", eps);
check+=fscanf(fin, "%*s %*s %*s %f %*s", rhmax);
check+=fscanf(fin, "%*s %*s %*s %f %*s", tgini);
check+=fscanf(fin, "%*s %*s %*s %f %*s %*s %*s ", mcini);
check+=fscanf(fin, "%*s %*s %*s %*s %*s %*s %i", N);
check+=fscanf(fin, "%*s %*s %*s %i", nz);
check+=fscanf(fin, "%*s %*s %*s %f %*s", kwhcost);
check+=fscanf(fin, "%*s %*s %*s %f %*s", thermcost);

fclose(fin);

if(check!=21)
{   printf("\nData not read in properly\n");
        return 0;
}

printf("\n\ncpg= %6.3f\t\tcpv= %6.3f", *cpg, *cpv);
printf("\ncpl= %6.3f\t\tcpa= %6.3f\t\tend criterion= %s",
 *cpl, *cpa, ((*endcrit==0) ? "goal":"change limit"));
if (*endcrit==0)
        printf("\nmcgol = %5.3f ratio, d.b.", *mcgol);
else
        printf("\nm.c. change limit = %5.2f %% d.b.\nm.c."
         " change time = %i min", *mcchalim, *mcchamin);
printf("\ndendry= %6.3lf\t\tdwa= %6.3lf", *dendry,
        *dwa);
printf("\nz= %6.3f\t\tdt= %6.3lf\t\tepsi= %g", *z, *dt,
        *epsi);
printf("\neps= %g\t\trhmax= %6.3f\t\ttgini= %6.3f", *eps,
        *rhmax, *tgini);
printf("\nmcini= %6.3f\t\tN= %3i\t\t\tnz= %3i", *mcini,
```

```
                *N, *nz);

        *cpg=4.1868*(*cpg);
        *cpv=4.1868*(*cpv);
        *cpl=4.1868*(*cpl);
        *cpa=4.1868*(*cpa);
        *mcchalim /= 100.;
        *dendry=16.0184*(*dendry);
        *dwa=4.8824*(*dwa);
        *z=.0254*(*z);
        *tgini=.55556*(*tgini-32.0);

        return 1;
}
```

```
/* Program name:            Heat exchanger i/o properties           */
/* Purpose:                 Interpolates air properties for htx     */
/* File:                    htxinput.cpp                            */
/* Date:                    20/3/95                                 */

#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#include "model1.h"

int htxinput(float et, float *Tat, float *rha, float *htxair, float *Gx, int N, double *time, double
        *tatm, double *rhat, double *htxtemp, double *G)
{
        int i=1;
        float frac; /* weight fraction for interpolation */

        while (i<=N && et>(time[i]-.0001))
                i++;

        if(i==N)
                if(et > time[i])
                {
                        printf("\n\nDrying time exceeds drying input"
                        " time data.\nShorten run time/increase input"
                        " time steps.");
                        return -1;
                }

        if(fabs(et-time[i]) < 1.0e-3)
        {
                *Tat=tatm[i];
                *rha=rhat[i];
                *htxair=htxtemp[i];
                *Gx=G[i];
        }

        else
```

```
        {
                frac=(et-time[i-1])/(time[i]-time[i-1]);
                *Tat=tatm[i-1]+frac*(tatm[i]-tatm[i-1]);
                *rha=rhat[i-1]+frac*(rhat[i]-rhat[i-1]);
                *htxair=htxtemp[i-1]+frac*(htxtemp[i]-htxtemp[i-1]);
                *Gx=G[i-1]+frac*(G[i]-G[i-1]);
        }

        return 1;
}
```

```
/* Program name:        Malt drying layer solver module         */
/* Purpose:             Executes sequence of layer steps        */
/* File:                liter.cpp                               */
/* Date:                23/3/95                                 */

#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#include "model1.h"


int liter(double *rh, double *mcdb, double *tg, double *ta, double *rt, double *hum, double dt,
        int nz, float apr, float htxair, float Gx, float *mcmean, float rhda, float huma, float dz,
        float rhmax, float cpg, float cpv, float cpl, float cpa, float dendry, float eps, int maxit)
{
        int i;
        float a, b, f, e, ge, yy,
                top, bot, bb, /* intermediate calculation values */
                dk, /* drying constant */
                dm, /* water mass change at step */
                dta, /* air temperature change */
                dtg, /* grain temperature change */
                eqmcwb, /* equilibrium mc, wb, ratio */
                eqmcdb, /* equilibrium mc, db, ratio */
                frh, /* function to limit rha to rhmax */
                h, /* humidity variable for search functions */
                ht, /* heat transfer coefficient */
                lmv, /* latent heat of malt moisture */
                p, /* water vapor pressure, atm */
                ps, /* water vapor sat. pr., atm */
                tda=htxair; /* drying air temperature */

        ht=175.07*pow(Gx,.6906);

        for(i=1;i<=nz;i++)
        {
                dk=11961456.*exp(-6819.5249/(273.16+tda));
                if(rhda>rhmax)
                        rhda=rhmax;
                eqmcwb=(10.5283-log(-8.315*(tda+273.16)*log(
                        rhda)))/29.9957;
```

```
        eqmcdb=eqmcwb/(1.-eqmcwb);
        dm=-dk*dt*(mcdb[i]-eqmcdb)/(1.+dk*dt*.5);
        a=2.*(tda-tg[i]);
        b=cpg+cpl*mcdb[i];
        f=cpv*tda+2501.61-tg[i]*cpl;

        lmv=2501.61*(1.+.5704*exp(-13.67*mcdb[i]));
        yy=cpv*tda+lmv-cpl*tg[i];
        frh= frhcalc(cpa, cpv, cpl, huma, dm, dendry,
            dz, Gx, dt, a, yy, ht, f, b, tda, apr,
            &dtg, &dta, &h, rhmax, &rhda);

        if (frh>eps)
            if(rootfind(frh, &dm, rhmax, &rhda, cpa, cpl,
                cpv, huma, &h, dendry, dz, Gx, dt, yy, ht,
                f, b, a, tda, apr, &dtg, &dta, eps, maxit)
                ==-1)
            {
                printf("\n\nlayer= %i", i);
                printf("\nHit enter to end");
                getchar();
                return -1;
            }

        tg[i]+=dtg;
        tda+=dta;
        ta[i]=tda;
        mcdb[i]+=dm;
        rh[i]=rhda;
        hum[i]=huma=h;
        rt[i]=dm/dt;
        *mcmean+=mcdb[i];
    }

    *mcmean/=nz;

    return 1;
}
```

```
/* Program name:    Output file opener                          */
/* Purpose:         Opens an output file for program results    */
/* File:            Openout.cpp                                 */
/* Date:            17/3/95                                     */

#include <stdio.h>
#include <stdlib.h>
#include "model1.h"

FILE *openout(char *xx)
{
    int i=1, c;
    char *f= "layerout.01";
```

```
        FILE *fp, *fpin;

        fp=fopen(f, "r");

        while ((i<10) && (fp != NULL))
        {
                fclose(fp);
                f[10] = (char)(i+48);
                fp=fopen(f,"r");
                i++;
        }

        while ((i>=10) && (i<100) && (fp != NULL))
        {
                fclose(fp);
                f[9]=(char)(i/10+48);
                f[10]=(char)(i%10+48);
                fp=fopen(f,"r");
                i++;
        }

        if (fp!=NULL)
        {
                printf("\nAll timeout.* (1-99) are used.  Change"
                        "directories!");
                return NULL;
        }

        else
        {
                fclose(fp);
                fp=fopen(f, "w");
                xx[8]=f[9];
                xx[9]=f[10];
                printf("\n\nOutput file:  %s", xx);
        }

        fpin=fopen("model1.dat", "r");
        if (fpin==NULL)
        {
                printf("\n\nModel1.dat can't be opened in openout");
                return NULL;
        }

        return fp;
}
```

```
/* Program name:      Results printint module          */
/* Purpose:           Prints time and layer results    */
/* File:              prtimdat.cpp                     */
/* Date:              23/3/95                          */
```

```
void prlaydat(float et, float mcmean, float Gx, float htxair, int nz, double *mcdb, double *ta,
        double *tg, double *hum, FILE *flayer, int layint)
{
        int i;

        fprintf(flayer, "\n\n\nTime= %3.0f min\tAve M.C.= %4.1f %"
                " w.b.", et, mcmean*100);

        fprintf(flayer, "\nG= %5.2f lbm/(ft^2*min)\tHtxair= %3.0f"
        " F", Gx/4.8824, htxair*1.8+32.);

        fprintf(flayer, "\n\nMalt    M.C.    Air    Grain    "
        "Air\nLayer   D.B.   Temp.   Temp.   Humidity\nNo."
        "    %      F      F      lbm/lbm");
        fprintf(flayer, "\n______________________________________"
                "______");

        for(i=layint;i<=nz;i+=layint)
                fprintf(flayer,"\n%3i     %4.1f    %5.2f    %5.2f"
                        "    %6.5f", i, mcdb[i]*100, ta[i]*1.8+32,
                        tg[i]*1.8+32, hum[i]);
}
```

```
/* Program name:      Results printint module              */
/* Purpose:           Prints time and layer results        */
/* File:              prtimdat.cpp                         */
/* Date:              23/3/95                              */

#include <stdio.h>
#include "model1.h"

void prtimdat(float et, float Tat, float huma, float htxair, float Gx, double *ta, double
        *hum, float mcmean, FILE *ftime, int nz, double *tg, float htxen)
{
        fprintf(ftime, "\n%-4.0f  %5.3f         %5.1f  %5.1f"
        " %8.6f %5.1f %8.6f %5.1f %6.2f        %5.1f %5.1f %5.1f "
        "%5.1f", et, Gx/60, htxair, Tat, huma, ta[nz],
        hum[nz], mcmean*100, htxen, tg[nz/8], tg[nz*3/8], tg[nz*5/8],
        tg[nz*7/8]);

}
```

```
/* Program name:      Condensation procedure solver        */
/* Purpose:           Finds value of dm for rha=rhmax      */
/* File:              rootfind.cpp                         */
/* Date:              23/3/95                              */

#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#include "model1.h"
```

```
int rootfind(float frh, float *dm, float rhmax, float *rha, float cpa, float cpl, float cpv, float huma,
        float *h, float dendry, float dz, float Gx, double dt, float yy, float ht, float f, float b, float
        a, float tda, float apr, float *dtg, float *dta, float eps, int maxit)
{
        int i=1;
        float xl, xh, xav, fl, fh, fx, dx, rts;

        /* bracketing */
        xl= *dm;
        fl=frh;
        xh=xl+.0006;
        fh=frhcalc(cpa, cpv, cpl, huma, xh, dendry, dz, Gx, dt,
                a, yy, ht, f, b, tda, apr, dtg, dta, h, rhmax, rha);

        while(fl*fh>0.0 && (i++)<=100)
        {
                xl=xh;
                fl=fh;
                xh+=.0006;
                fh=frhcalc(cpa, cpv, cpl, huma, xh, dendry, dz, Gx, dt,
                        a, yy, ht, f, b, tda, apr, dtg, dta, h, rhmax, rha);
        }

        if (fl*fh>0.0)
        {
                printf("\n\nrh= %4.3f root not bracketed in ROOTFIND",
                        rhmax);
                printf("\ni= %i", i);
                printf("\nfrhfin= %f", fh);
                printf("\ndmini= %f", *dm);
                printf("\ndmfin= %f", xh);
                return -1;
        }

        for(i=1;i<=5;i++)
        {
                xav=(xl+xh)/2.;
                frh=frhcalc(cpa, cpv, cpl, huma, xav, dendry, dz, Gx, dt,
                a, yy, ht, f, b, tda, apr, dtg, dta, h, rhmax, rha);
                if(fl*frh>0.)
                {
                        xl=xav;
                        fl=frh;
                }

                else if(fl*frh<0.0)
                {
                        xh=xav;
                        fh=frh;
                }
                else
                {
```

```
                        *dm=xav;
                        return 1;
                }
        }

        /* SECANT METHOD */

        if (fabs(fl)<fabs(fh))
        {
                rts=xl;
                xl=xh;
                fx=fl;
                fl=fh;
        }
        else
        {
                rts=xh;
                fx=fh;
        }

        for(i=1;i<=maxit;i++)
        {
                dx=(xl-rts)*fx/(fx-fl);
                xl=rts;
                fl=fx;
                rts+=dx;
                fx=frhcalc(cpa, cpv, cpl, huma, rts, dendry, dz, Gx,
                        dt, a, yy, ht, f, b, tda, apr, dtg, dta, h, rhmax,
                        rha);

                if((fabs(dx)<eps) | | (fx==0.0))
                {
                        *dm=rts;
                        return 1;
                }
        }

        printf("\n\nMaximum number of iterations exceeded in"
                "Rootfind");
        return -1;
}
```

```
/* Program name:            Saturation Pressure           */
/* Purpose:                 Calculate water saturation
                                    pressure, atm         */
/* File:                    arrayini.cpp                  */
/* Date:                    20/3/95                       */

float satpr(float tg)
{
        float a, b, c, d, /* constants for sat. press. curve-fit
                                    equ's    */
```

```
                t,          /* inverse of abs. temp (K) * 273.16 */
                s;          /* saturated vapor pressure */

        t=273.16/(273.16+tg);
        a=10.79586*(1-t);
        b=5.02808*log10(t);
        c=1.50474e-4*(1-pow(10,-8.29692*(1/t-1.)));
        d=4.2873e-4*(pow(10,4.76955*(1.-t))-1);
        s=pow(10, a+b+c+d-2.2195983);

        return s;
}
```

```
/* Program name:            Malt drying time solver module*/
/* Purpose:                 Executes sequence of time steps*/
/* File:                    titer.cpp                     */
/* Date:                    17/3/95                       */

#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#include <conio.h>
#include "model1.h"

int titer(float mcin, double *rh, double *mcdb, double *tg, double *ta, double *rt, double *hum,
        float z, float tml, double dt, int nz, float mcgol, double dendry,  double dwa, double
        *timein, double *tatm, double *rhat, double *htxtemp, int N, double *G, float apr, float
        rhmax, float cpg, float cpv, float cpl, float cpa, float eps, int maxit, float kwhcost, float
        thermcost, int endcrit, int mcchamin, float mcchalim)
{
        float airflow,      /* htx airflow, cfm */
                dz=z/nz,            /* length of depth increment, m */
                dp,         /* pressure drop through bed */
                et=0.0,  /* elapsed time */
                fancost, /* cost of energy used by fans, $ */
                fanenergy=0, /* kwh used by fans */
                Gx,                 /* htx airflow at et */
                htxair,  /* air temp after htx at et */
                htxcost, /* cost of energy used by htx, $ */
                htxen=0.0, /* cumulative heat energy to dry malt, MJ/m^2 */
                huma,   /* atmospheric humidity ratio at et */
                iamb, /* enthalpy of ambient air */
                ihtxair, /* enthalpy of air after htx */
                mciniwb,            /* initial mc, wb, ratio */
                mcmean=mcin, /* average bed mc at et, ratio, D.B. */
                mcmeanlast=mcin,        /* mcmean at mcchamin minutes before
                                        current mcmean */
                mcmeanwb,       /* mean mc, wb, ratio */
                mccha=100.,     /* percent change in moisture content over mcchamin */
                pv,             /* water vapor press., atm */
                rha,            /* atmospheric rh at et, ratio */
                rhda,   /* drying air rh, ratio */
```

```
          Tat,              /* atmospheric temp at et */
          totcost, /* total fan and htx costs */
          vbed,             /* velocity of air through bed, ft/min */
          vex, /* specific air volume of exhaust, lbm/ft^3 */
          vfan,             /* velocity of air through fan, ft/min */
          vhtx,    /* specific air volume htx, lbm/ft^3 */
          zini=z;  /* initial bed depth, m */

int j;
FILE *flayer, *ftime, *fpin;
char *xx="timeout.1 ", /* time step output file string */
                  c; /* copy char for inputair.dat */

clrscr();
flayer=openout(xx);
if (flayer==NULL) return -1;

ftime=fopen(xx, "w");
if (ftime==NULL)
{
          printf("\n\nCouldn't open %s for output", xx);
          return -1;
}

/* Print inputair.dat and model1.dat to timeout.xx */

fprintf(ftime,"INPUTAIR.DAT\n\n");
fpin=fopen("inputair.dat", "r");
while((c=fgetc(fpin))!=EOF)
          fputc(c, ftime);
fclose(fpin);
fpin=fopen("model1.dat", "r");
fprintf(ftime,"\n\nMODEL1.DAT\n\n");
while((c=fgetc(fpin))!=EOF)
          fputc(c, ftime);
fclose(fpin);

mciniwb=mcmean/(1.+mcmean)*100;

fprintf(ftime, "\n\nMin   Flow (kg/m^2/s)  Aotemp  Tamb  "
 " Humamb   Tex   Humex    Mcdb  Htxen (MJ/m^2)  Tc1    Tc2    Tc3    "
 "Tc4");
printf("\nWorking...");

_setcursortype(_NOCURSOR);
gotoxy(1, 15);
printf("Elaptime = ");

while (((endcrit) ? (mccha > mcchalim) : (mcmean > mcgol))
 && et <= tml)
{
          gotoxy(12,15);
          printf("%4.0f", et);
```

```
        if (htxinput(et, &Tat, &rha, &htxair, &Gx, N, timein,
                tatm, rhat, htxtemp, G)==-1)
                return -1;

        pv=rha*satpr(Tat);
        huma=.622*pv/(apr-pv);
        rhda=pv/satpr(htxair);

        htxen+=Gx*(htxair-Tat+huma*1.805*(htxair-Tat))*dt
                /1000.;
        fanenergy+=600.*dt/60.*(1.407e-6*Gx*Gx*Gx*Gx-1.272e-4
                *Gx*Gx*Gx+4.64e-3*Gx*Gx-5.626e-2*Gx+.2684);

        mcmean=0.0;
        j=liter(rh, mcdb, tg, ta, rt, hum, dt, nz, apr,
                htxair, Gx, &mcmean, rhda, huma, dz, rhmax, cpg,
                cpv, cpl, cpa, dendry, eps, maxit);
        if(j==-1)
                return -1;

        mcmeanwb=mcmean/(1.+mcmean)*100.;
        z=zini*(1.-.1591*(1.-exp(-.0966*(mciniwb-
                mcmeanwb))));
        dendry=dwa/z;
        dz=z/nz;
        et+=dt;
        if (!(((int)(et +mcchamin)) % mcchamin))
        {
                mccha = mcmeanlast - mcmean;
                mcmeanlast = mcmean;
        }

        prtimdat(et, Tat, huma, htxair, Gx, ta,
                hum, mcmean, ftime, nz, tg, htxen);
}

_setcursortype(_NORMALCURSOR);
/* 145.43 metric tons dry malt per batch */
fancost=fanenergy*kwhcost/145.43/(1.+mcmean);
htxcost=htxen*thermcost/dwa/(1.+mcmean);
totcost=fancost+htxcost;
fprintf(ftime,"\n\nHeat energy (GJ/ton):  %5.3f", htxen/
        dwa/(1.+mcmean));
printf("\n\nHeat energy (GJ/ton):  %5.3f", htxen/dwa/(1.
        +mcmean));
fprintf(ftime,"\n\nFan cost ($/ton)= $%4.2f\nHtx cost "
        "($/ton)= $%5.2f\nTotal cost ($/ton)= $%5.2f", fancost,
        htxcost, totcost);
printf("\n\nFan cost ($/ton)= $%4.2f\nHtx cost "
        "($/ton)= $%5.2f\nTotal cost ($/ton)= $%5.2f", fancost,
        htxcost, totcost);
fprintf(ftime,"\n\nFinal bed depth:  %5.2f in", z*39.37);
printf("\nFinal bed depth:  %5.2f in", z*39.37);
```

```
        if(mcmean<=mcgol)
                printf("\n\nMoisture content goal reached");
        if (mccha < mcchalim)
                printf("\n\nMoisture content change limit reached");
        if (et>tml)
                printf("\n\nTime limit reached");

        return 1;
}
```

```
/* Program name:     Deep bed malt drying U. Michigan      */
/* Purpose:          Executes sequence of program steps    */
/* File:             Model1.cpp                            */
/* Date:             17/3/95                               */

#include <stdio.h>
#include <stdlib.h>
#include <conio.h>
#include "MODEL1.H"

main()
{
        /* N no of ambient temp input values */
        int N, nz, i,
                maxit=50, /* max iterations for secant condensation
                                                procedure */
                endcrit,        /* end criterion:  0= m.c. goal, 1= m.c.
                                                        change limit */
                mcchamin;       /* period of minutes for checking m.c.
                                                        change percent */
        double dendry, dwa, dt, dz, mcmean, *timein, *tatm, *rhat, *mcdb, *ta, *tg, *rt, *hum,
                *rh, *p /* pointer for array malloc */, *G, *htxtemp;
        float apr=1.0, cpg, cpv, cpl, cpa, mcgol, tml, z, epsi, eps, rhmax, tgini, mcini, thermcost,
                kwhcost, mcchalim; /* m.c. change % limit */

        printf("\n\nModel1.c Grain Drying Model\n\n");

        if(!getvalues(&cpg, &cpv, &cpl, &cpa, &mcgol, &dendry, &dwa, &z, &dt, &epsi, &eps,
                &rhmax, &tgini, &mcini, &N, &nz, &kwhcost, &thermcost, &endcrit,
                &mcchamin, &mcchalim))
        {
                getch();
                exit(-1);
        }

        printf("\nHit any key to continue");
        getch();

        p=dvector(1,5*N + 7*nz);

        timein=p;
```

```
        tatm=p+N;
        G=tatm+N;
        rhat=G+N;
        htxtemp=rhat+N;
        mcdb=htxtemp+N;
        rt=mcdb+nz;
        ta=rt+nz;
        tg=ta+nz;
        rt=tg+nz;
        hum=rt+nz;
        rh=hum+nz;

        if (airinit(timein, tatm, rhat, htxtemp, G, &N, &tml)==-1)
                exit (-1);

        arrayinit(rh, mcini, tgini, mcdb, tg, ta, rt, hum, nz,
                apr);

        i=titer(mcini, rh, mcdb, tg, ta, rt, hum, z, tml, dt, nz, mcgol, dendry, dwa, timein, tatm,
                rhat, htxtemp, N, G, apr, rhmax, cpg, cpv, cpl, cpa, eps, maxit, kwhcost,
                thermcost, endcrit, mcchamin, mcchalim);
        if (i==-1) exit (-1);

        return 1;
}
```

APPENDIX D

DRIER CONTROL AND DATA ACQUISITION HARDWARE

1. Neptronic Baby Blue Damper Motor, Model BBM2000.
2. Schaevitz Pressure Transducer, Model P3061.
3. Omega Type-T Hypodermic Needle Thermocouple Probes, Model HYP-0.
4. Kapton 28-gauge Type-J Thermocouple Wires, custom-made at Grant Edgel in Portland, OR.
5. Athena SCR Controller, Model 93Z-48030-A0.
6. Vaisala Relative Humidity Sensor, Model HMP 135Y.
7. Vaisala Relative Humidity Sensor, Model HMW 50U.
8. AND Digital Scale, Model FG-150K.
9. Keithley Series 500 Data Acquisition and Control System.
10. AST 80286 PC-Compatible Computer, Model AST 286.

APPENDIX E

DRIER OPERATION PROCEDURE

Drier Operation and Setup

This procedure covers filling the deep-bed malt drier, running the drying program FLOWCON, emptying the drier, sampling the finished malt, and program operation.

A. FILLING THE DEEP-BED MALT DRIER

- Remove any malt left over in the plenum or in the drying chamber.
- Turn the scale on with only the drier plenum resting on it and wait till 0.0 lb. or kg shows on the scale. If 0.0 lb./kg does not show up, the weight on the scale is above the tare limit. Remove the weight and turn the scale off and on again.
- Disconnect the flexible connector, if necessary, from the drier plenum inlet and rotate the plenum so the flexible connector is not contacting it.
- Put the support bar and aluminum screen on the supports in the drying chamber.
- Put the clean middle gasket on top of the plenum's flange and align the mark on the gasket, facing up, with the flange mark, keeping the bolt holes aligned.
- Wipe the bottom flange of the drying chamber and align the marks on the side of the bottom flange and the mating flange while keeping the bolt holes aligned as you put the drying chamber on the plenum. Bolt the flanges together with the ¼" 1½" long hex-head bolts, washers and wing nuts. Tighten finger-tight.
- Put the top red-rubber gasket on the drier chamber's top flange without aligning it (just to tare the scale), and put the exhaust tube on the flange, resting the bolts in the holes and putting the wing nuts and washers on exhaust tube's flange.
- Without any external connections, push the tare button on the scale.
- Remove the bolts, washers, wing nuts, exhaust tube, and the gasket.
- Technique for filling the drying chamber:
    - Note the weight, before filling the drying chamber with malt, for reference.
    - Refer to Figure 31 for a cut-away side view of the drier when filled with malt.
    - Add 10 lb. of malt and place a grain thermocouple on top of the malt. This type of thermocouple has a perforated pvc cover and measures air temperature between the grains. Bury it just enough so it stays in position in

the center of the drying chamber, and push the wire into the malt, guiding it to the side of the drier closest to the point where the wire will connect above the drier.

- Use a wire twist-tie to keep the thermocouple wire at the side of the drier and connect the wire to the plug above the drier.
- Add enough malt for a 30 lb. total, and pack it down to the 12 in mark, which is on the inside drier wall.
- Repeat the method of adding a thermocouple for the second thermocouple.
- Add enough malt for a 50 lb. total and pack it down to the 20 in mark.
- Repeat the method of adding a thermocouple for the third thermocouple.
- Add enough malt for a 70 lb. total and pack it down to the 28 in mark.
- Repeat the method of adding a thermocouple for the fourth thermocouple.
- Add enough malt for an 80 lb. total and pack it down to the 32 in mark.

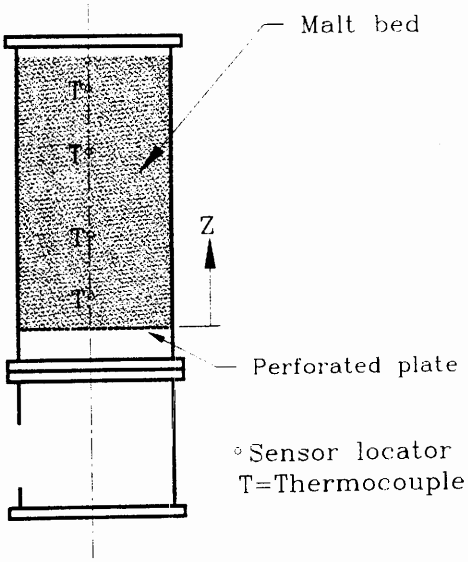


Figure 31. Drier Filling Schematic.

- Record the initial depth of the malt.
- Disconnect each thermocouple's connector above the drier starting with the first, or lowest, initially, and place each successively on top of the malt. Use labels on the thermocouple wires to organize them. The order helps avoid entangling the wires.
- Wipe the top flange of the drying chamber.

- Wipe the top red-rubber gasket and put it on the top flange, aligning the marks and then the bolt holes.
- Wipe the bottom of the exhaust tube, align the exhaust tube's mating mark with the mark on the top gasket, and put the flanges together, with the bolt holes in alignment.
- Bolt the flanges together with the ¼" 1½" long hex-head bolts, washers and wing nuts and tighten.
- Reattach the grain thermocouples above the drier, starting with the last, or highest thermocouple.
- Record the initial weight of the malt.
- Rotate the whole drier so the drier plenum air inlet is aligned with the inlet air duct and attach the flexible connector, adjusting it as necessary to minimize its effect on the scale's reading of the malt's initial weight, and tighten the hose clamp to fix the flexible connector to the inlet duct.
- Record the weight with the flexible connector attached.
- Insert the Vaisala exhaust relative humidity probe in the bottom hole in the exhaust tube and put the small red-rubber gasket on the end of the probe inside the drier, sliding it against the inside drier wall. The general position of the probe is shown in Figure 32. Position the relative humidity probe so its tip is mid-way between the centerline and the wall of the exhaust tube.

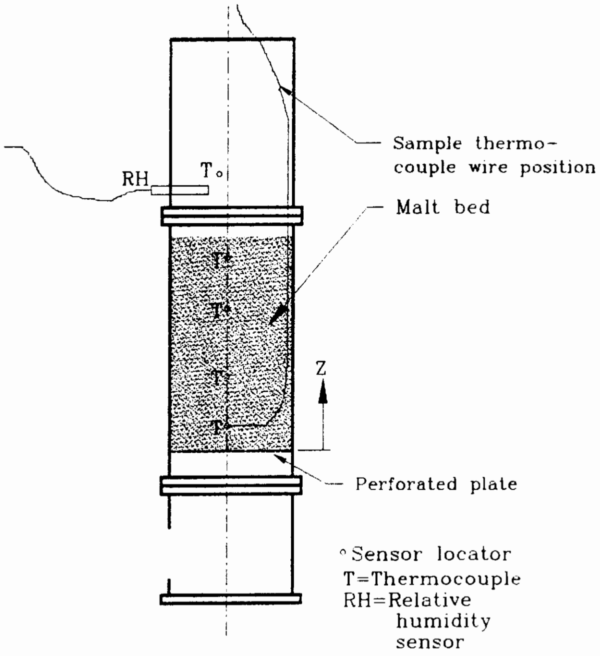


Figure 32. Sensor Positions with Respect to the Drying Section.

- Record the weight with the flexible connector and the exhaust relative humidity probe attached.
- Hang the six inch type-J thermocouple probe from above the drier and position its tip close to the exhaust relative humidity probe's tip.
- Fold the cardboard flap, on the exhaust hood, down and attach it to the flap on the left side of the exhaust hood with a piece of duct tape. The flaps channel the drier exhaust air into the exhaust hood, and the tape holding the front and left flaps together stops the flaps from being sucked against the exhaust tube, which might affect the scale reading.
- Setup the drier control program by deleting or renaming any old 'flow.dat' file. This file contains the drying measurements taken during a batch. All new drying measurements are appended to the 'flow.dat' file, so nothing will be lost. The 'drierinp.dat' file contains the drying schedule data for drier control. Modify it for the drying schedule desired, using 25 or less lines of input. See Figure 33 for an example of the drierinp.dat format. Note that the first time value must be 0. Drying with the target-moisture-content termination option is not recommended, since the moisture content estimate is dependent on the initial moisture content, which is difficult to accurately predict.

```
Time (min)  Flow (lbm total air/ft^2 bed/min)  Temp (F)
0  3 160
120  3  160
180  3  160
240 3 160
300 3 180
420 3  180
480 7 180
```

Figure 33. Drierinp.dat File Format.

- Try the flowcon program without the blower and heater on to see that all the sensors work (use a 10 second save interval).

B. RUNNING FLOWCON

•Steps to run the drier control program after typing 'krun flowcon' at the DOS prompt in the directory with the flowcon.exe program.

1. Check the input data (from 'drierinp.dat') displayed on the screen for errors. Ifthe drying schedule is not what you want, change the 'drierinp.dat' file, and re-run flowcon.
2. If you enter a number incorrectly, the program may crash. Hit <cntr-break> and re-run the program.
3. Controller gains are tuned for the experimental drier as described in the Research Malt Drier chapter of the thesis. They may be re-tuned for better operation or different control equipment so the gains given here are just suggestions. At the prompt "Input flow control proportional gain (>0):" enter '1'.
4. At "Input flow control integral gain (>=0):" enter '0.2'.
5. At "Input heater control proportional gain (>0):" enter '0.5'.
6. At "Input heater integral gain (>=0):" enter '0.01'.
7. At "Input total run time (>0, < 4.29e6) sec:" enter a number of seconds for the maximum drier run time (e.g. enter '54000' for 54000 seconds = 15 hours).
8. At "Input seconds per save data (>0, <65535) sec:" enter the sampling interval for the malt temperature, weight, and inlet and exhaust air conditions, which will be saved as data in 'flow.dat'. Typically, 120 seconds was used.
9. At "Input seconds per print data (>0, <65535) sec:" enter the interval at which flow, heater temperature, and air-on temperature will be printed to the screen. Typically, 5 seconds was used.
10. At "Input initial moisture content (>0, <1.0) wet basis, decimal:" enter the initial moisture content of the malt as estimated from a moisture balance or NIR test, both of which may be available at Great Western Malting Company.
11. At "Input 0 to terminate at a target moisture content, or 1 to terminate at minimum-moisture-content-change limit (0 or 1):" enter the method by which drying will be stopped by the computer.

a. For the target moisture content:

    1. At "Input moisture content goal (>0, <1.0) wet basis, decimal:" enter the final moisture content desired.

b. For the minimum-moisture-content-change limit:

    1. At "Input time for moisture-content-change-limit check (sec, >=30,<=7200):" enter the sampling period over which the change in moisture content will be calculated.
    2. At "Input moisture content change for dryness check (% d.b., >0, <=10):" enter the threshold of change in moisture content at which drying should stop.
    3. At "Input time for preheat before moisture content change limit check (sec, >=5, <=3600):" enter the time required to start drying at a rate which will not cause the moisture content change limit to prematurely stop the drier. This may only be critical when drying malt with a low initial moisture content.

12. At "Input initial weight of malt with no attachments and fan off (lb./kg, >0, <=200):" enter the weight of malt, which you previously recorded, with no attachments to the drier, except the air-on temperature thermocouple.
13. "Weight test = ..." is just a check to ensure the computer and scale are communicating properly. If "Check if scale is on and properly connected" appears, there is a problem with the scale, and the program will terminate. The scale must be connected to COM 1 on the computer with the RS-232 cable. The cable also connects to the side of the scale display console.
14. Turn on the fan, the heater power, and the exhaust fan. As soon as possible, at "Hit 'y' to begin or 'n' to quit:", hit 'y' to begin.

•Record the initial weight with the fan on after about 20 seconds, so the air flow is stable.

C. EMPTYING THE DRIER AND SAMPLING THE FINISHED MALT

•At the termination of drying, the blower should be turned off as soon as possible, because a small airflow leaks past the closed damper, which eventually adds moisture to the malt.

- Record the weight of the drier assembly with the blower off before disconnecting anything.
- Disconnect the exhaust relative humidity probe, and before disconnecting anything else, record the weight of the drier assembly.
- Disconnect the flexible connector from the drier plenum inlet duct. Record the weight, which should be the final weight of the malt.
- Remove the exhaust thermocouple from inside the exhaust tube.
- Disconnect the grain thermocouples from above the drier, starting with the first, or lowest, and proceed in order, dropping each thermocouple connector into the malt.
- Remove the exhaust tube and red-rubber gasket.
- Record the final depth of the malt.
- Unbolt the drying chamber. It may be necessary to rock it from side-to-side to loosen it from the drier-plenum flange.
- Attach the loose ends of the thermcouple wires to the top flange of the drier chamber with a twist-tie.
- Pick up the drier chamber and hold it close to the surface on which you dump the malt. This avoids stretching the thermocouple wires when the malt spills out.
- Remove the twist-tie from the wires, put the drier chamber aside, and gently remove the thermocouples and wires from the malt pile.
- Before sampling the malt for moisture or quality tests, dump it in the middle of a large flat surface, split the pile into quarters, mix the opposite piles together, combine the halves, and repeat the mixing and combining once more to uniformly mix the malt.

D. FLOWCON PROGRAM OPERATION AND KNOWN BUGS

- For the target-moisture-content option, the computer displays the current elapsed drying time (sec), the airflow (lbm total air/ft^2 bed/min.), the airflow set point, the air-on (drying air) temperature (F), the air-on temperature set point, the scale's weight reading (lb./kg), the ambient air temperature (F), the ambient relative humidity (%), the drier exhaust air temperature (F), the exhaust relative humidity (%), the inter-grain air temperature (F) at 4, 12, 20, and 28 in., the moisture content (% dry basis) corrected for the weight due to attachments and airflow, and the heater surface temperature (F), in this order. Figure 34 shows the display.

```
Sec      Flow   FlowSP   Airontemp    AirSP   Weight   Tamb    Rhamb   Tex    Rhex
33360    5.3    5.2      160.3        160.0   48.0     76.5    38.7    154.6 3.9

Talow    Tamed    Tahi     Tahir    Mcdb     Htrtemp
163      163      162      161      10.41    270
```

Figure 34. Flowcon Display Format.

- The minimum-moisture-content-change-limit-option display is the same as in Figure 34, with the addition of '`Mcchange dec.`' after '`Htrtemp.`' This shows the moisture content change as a decimal number over the last moisture-content-change interval.
- Drying may be paused such that the heater is turned off and the damper is closed by hitting the <esc> key at any time. The elapsed-drying-time timer stops until the user hits 'y' at the prompt "Pausing... Continue drying? (y or n):". Hitting 'n' will cause the drying data collected prior to the pause to be saved to 'flow.dat', and the program will stop the current drying run.
- The 'drierinp.dat' file has the format shown in Figure 35.

```
Time (min)   Flow (lbm total air/ft^2 bed/min)   Temperature (F)
0            7.5                                   160
479.98       7.5                                   160
480          5.25                                  160
719.98       5.25                                  160
720          5.25                                  180
```

Figure 35. Drierinp.dat File Format.

The first line of headings is required for flowcon to read the data. Time is the elapsed drying time. The first line of data must start with a time of 0 minutes. Flow set point follows time (spacing is arbitrary) and temperature indicates the desired drying temperature set point. Flowcon interpolates the flow and temperature set points for elapsed drying times between the times entered in 'drierinp.dat'. If the drying time exceeds the last time point in 'drierinp.dat', the last line in 'drierinp.dat' is used until drying ends. The maximum number of input time points in 'drierinp.dat' is 25. More input can be accommodated by increasing the MAXSET variable in *flowcon.c* and recompiling 'flowcon'.

•The screen displays values, for data, which randomly look erroneous or have characters and symbols in place of numbers. There is nothing wrong with the sensors or the actual data values in the computer. It seems there is a programming deficiency, or the computer has difficulty with printing and doing timer interrupts simultaneously. The flowcon display sometimes shows two lines of data beneath the heading rows, which is another bug, but nothing is wrong. The line of data directly below a heading is the most current one.

•For program comments, sensor-to-Keithley connection instructions, and more detailed program explanations, refer to the source code files flowcon.c, interrup.c, function.c, fvector.c, ivector.c, readscal.c, and setupcom.c.

APPENDIX F

ORIFICE PLATE FLOW EQUATION

This section develops the airflow measurement equation used to control the airflow rate in the research malt drier. The sharp-edge orifice plate used in the research drier has a 1.55 in diameter orifice. Referring to Figure 36 and the list below for the nomenclature of the equation, the equation used to calculate the mass flow rate of air, given by Miller (1989), is

$$q = 0.09970190 \cdot \frac{Y_1 \cdot d^2 \cdot C \cdot \sqrt{\Delta h_w \cdot \rho_{f1}}}{\sqrt{1-\beta^4}}, \tag{38}$$

where

q = mass flow rate of air, lbm/s,

Y_1 = adiabatic gas expansion factor,

d = orifice diameter, in. (=1.55 in.),

C = discharge coefficient (true flow rate/theoretical flow rate),

Δh_w = differential pressure, in. w.g.,

ρ_{f1} = density of air at 1, lbm / ft^3,

$\beta = d/D$ (=.55),

D = internal pipe diameter of 3 in. schedule 80 pipe (= 2.864 in.).

Note that a thermal expansion factor was not used in eq. (38), since all flow measurements are assumed to be taken at room temperature (70 F).

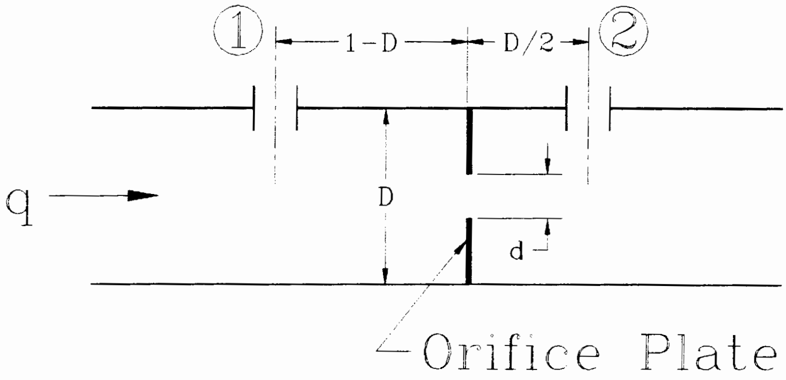


Figure 36. Orifice Plate Schematic.

The adiabatic expansion factor is given by

$$Y_1 = 1 - (0.41 + 0.35 \cdot \beta^4) \cdot \frac{x_1}{\kappa} \tag{39}$$

for downstream pressure taps less than D/2 from the upstream face of the orifice plate. The other variables are given by

$x_1 = 1 - \frac{p_{f2}}{p_{f1}}$,

p_{fa} = fluid static pressure at a (a= 1 or 2),

and

κ = isentropic exponent (=1.4 for air).

Assuming p_{f1} = 5 in. w.g., then

$$p_{f1} = 14.696 \text{ psi} + 5 \text{ in. w.g.} \times \frac{1 \text{ psi}}{27.6807 \text{ in w.g.}}.$$
$$= 14.8766 \text{ psia} = 411.7956 \text{ in. water}$$

Also,

$$x_1 = \frac{\Delta h_w}{411.796}$$

$$\frac{x_1}{\kappa} = \frac{\Delta h_w}{576.514}.$$

$$Y_1 = 1 - (0.41 + 0.35 \cdot (0.55)^4) \cdot \frac{\Delta h_w}{576.514}$$
$$= 1 - 7.667 \times 10^{-4} \cdot \Delta h_w.$$

$\Delta h_w \approx 5$ in. w.g., under typical experimental conditions, so

$7.667 \times 10^{-4} \cdot \Delta h_w \approx 3.83 \times 10^{-3}$.

Thus the term $7.667 \times 10^{-4} \cdot \Delta h_w$ is negligible compared to 1.0, and we will assume $Y_1 = 1.0$.

The discharge coefficient is given by

$$C = C_\infty + \frac{b}{R_D^n}, \quad R_D > 4000, \tag{40}$$

where R_D is the Reynolds number based on the internal pipe diameter. For D and D/2 pressure taps,

$$C_\infty = 0.5959 + 0.0312 \cdot \beta^{2.1} - 0.184 \cdot \beta^8 + 0.0391 \cdot \frac{\beta^4}{1-\beta^4} - 0.0158 \cdot \beta^3,$$

$$b = 91.71 \cdot \beta^{2.5},$$

$$n = 0.75.$$

Assuming $\rho_{\text{airflow}} = 0.0741 \ \text{lbm} / \text{ft}^3$ (at 70 F and 50% relative humidity),

$$R_D = \frac{4q}{\pi D \nu \rho} = 426153 \cdot q,$$

where q is given in lbm/s.

$C_\infty(\beta = 0.55) = 0.604549$, so

$$C = C_\infty + \frac{b}{R_D^n} = 0.604549 + \frac{1.23353 \times 10^{-3}}{q^{0.75}}.$$

The average value of q for the experimental conditions is about 0.1062 lbm/s, so

$$\frac{1.23353 \times 10^{-3}}{q^{0.75}} \approx 6.632 \times 10^{-3}.$$

Thus $\frac{b}{R_D^n}$ is only 1.1% of the C_∞ term, and it will be neglected. This leaves us with C = 0.604549.

Assuming $\rho_{f1} = 0.0741\ \mathrm{lbm/ft^3}$,

$$q = 4.2705 \times 10^{-2}\sqrt{\Delta h_w}\ . \tag{41}$$

Equation (41) errs from the result given by eq. (38) by -1.8%, if $\rho_{f1} = 0.0714$ $\mathrm{lbm/ft^3}$, and by 1.9%, if $\rho_{f1} = 0.0769\ \mathrm{lbm/ft^3}$.

APPENDIX G

EXPERIMENTAL DRYING DATA

GWM piece #: C1272
Variety: Idaho Crystal
Dry date: 11 July 1995

Airon Temp: 63.3 C
Air flow rate: .594 kg/m^2/s

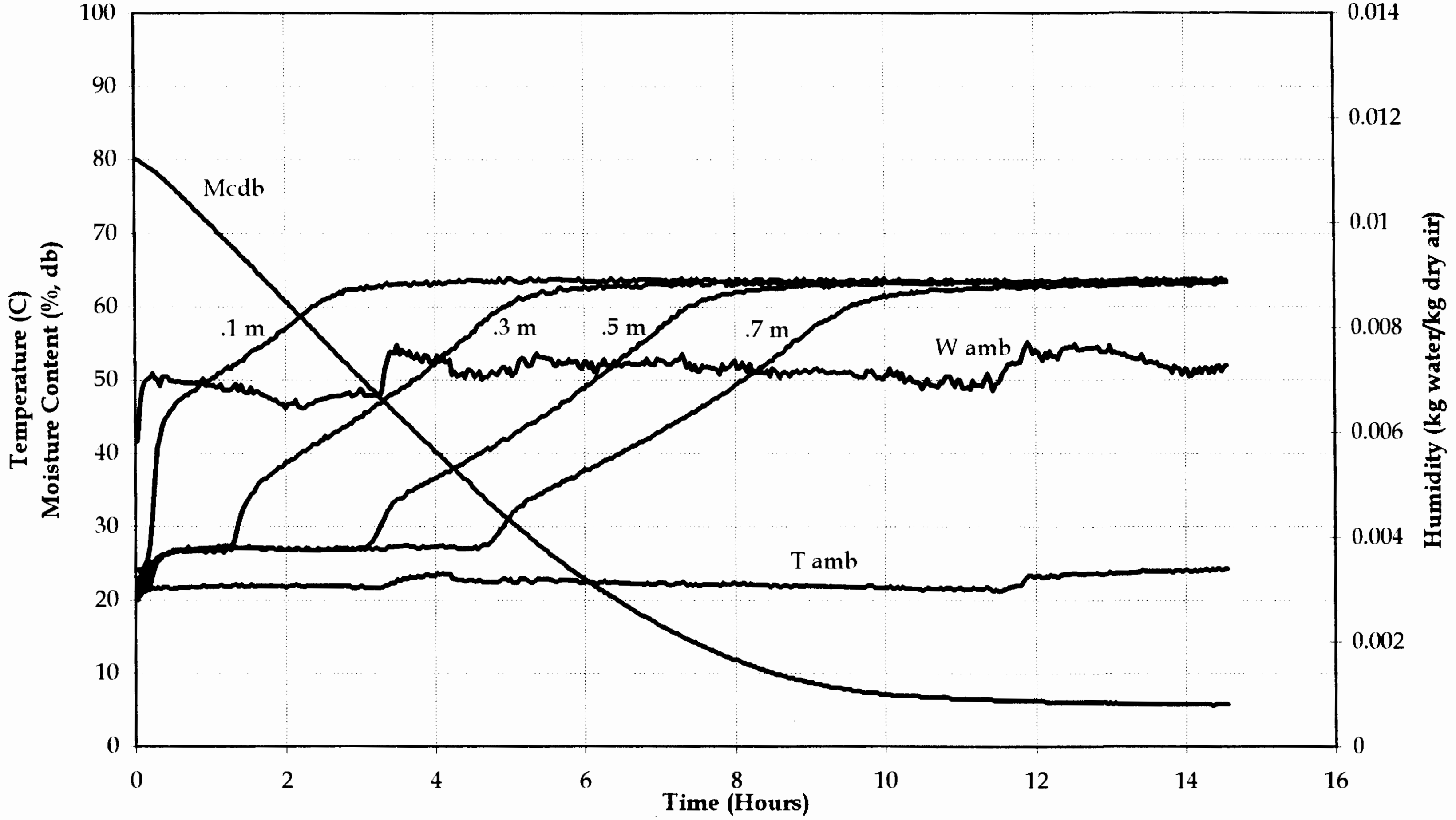
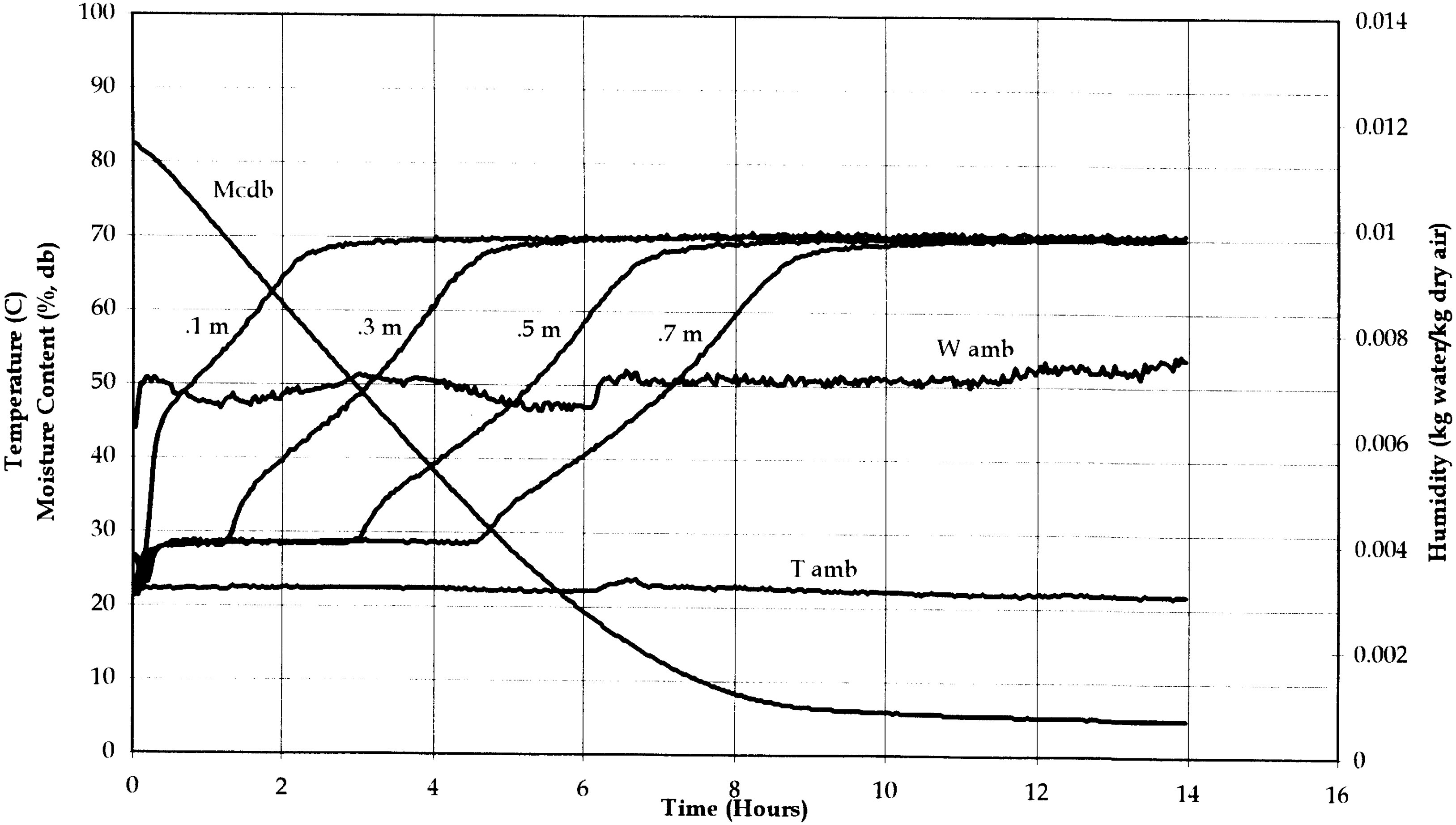


Figure 37. Experimental Batch 2.


GWM piece #: C1275
Variety: Idaho Crystal
Dry date: 12 July 1995

Airon Temp: 71.1 C
Air flow rate: .57 kg/m^2/s

Figure 38. Experimental Batch 3.

GWM piece #: C1276
Variety: Idaho Crystal
Dry date: 13 July 1995

Airon Temp: 75 C
Air flow rate: .57 kg/m^2/s

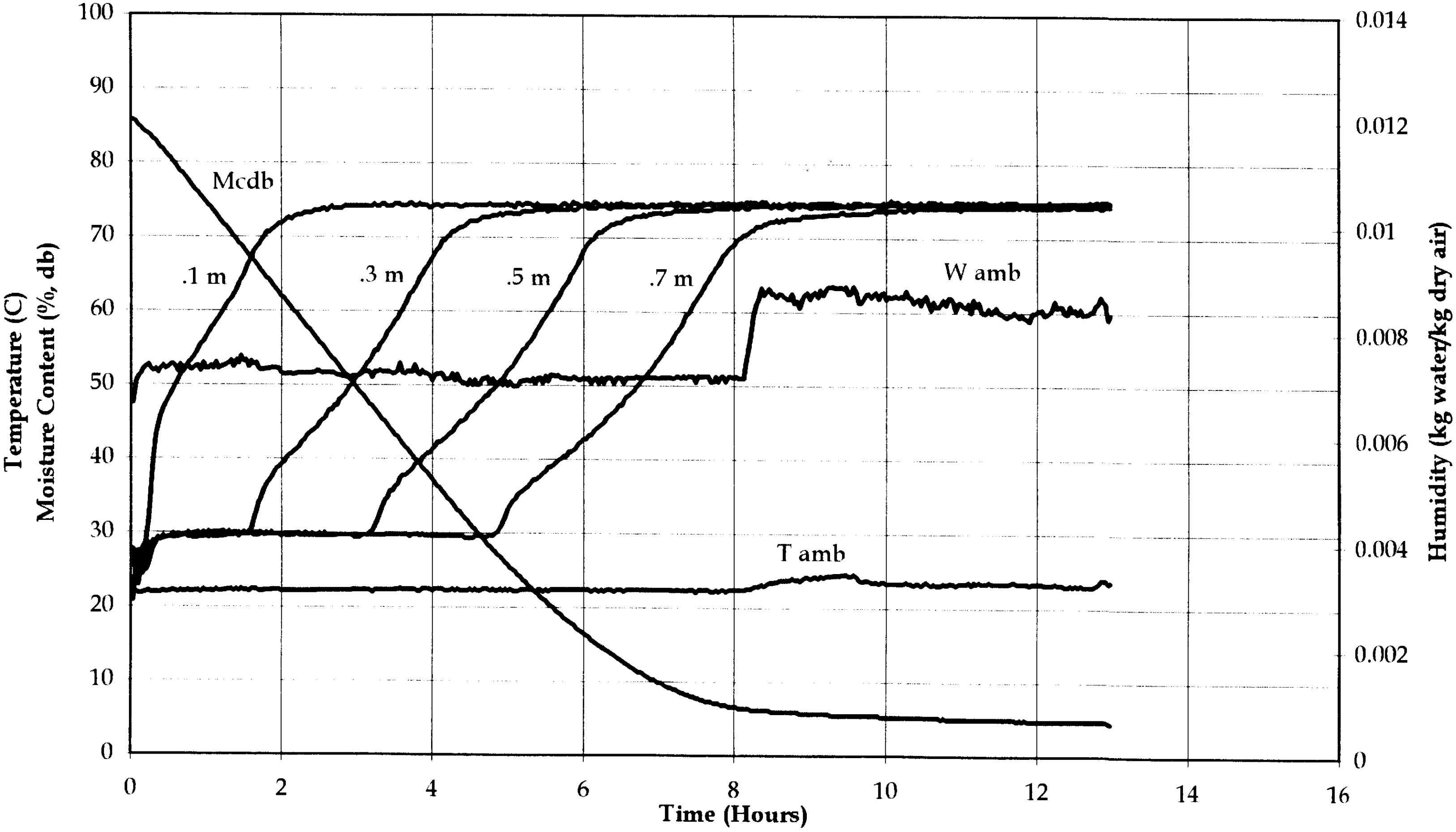


Figure 39. Experimental Batch 4.

GWM piece #: C1277
Variety: Idaho Crystal
Dry date: 14 July 1995

Airon Temp: 81.1 C
Air flow rate: .57 kg/m^2/s

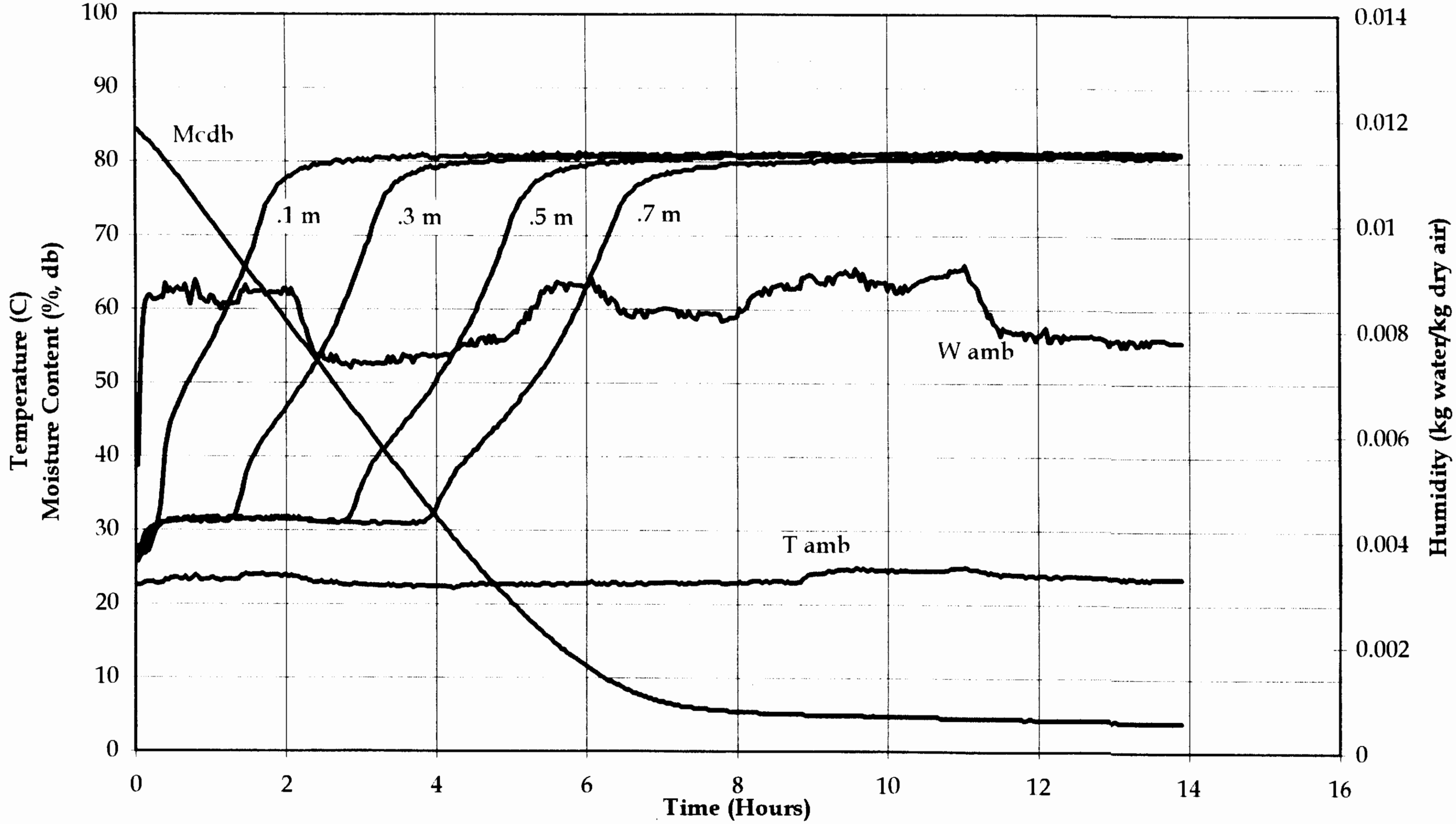


Figure 40. Experimental Batch 5.

GWM piece #: C1278
Variety: Idaho Crystal
Dry date: 14 July 1995

Airon Temp: 86.7 C
Air flow rate: .57 kg/m^2/s

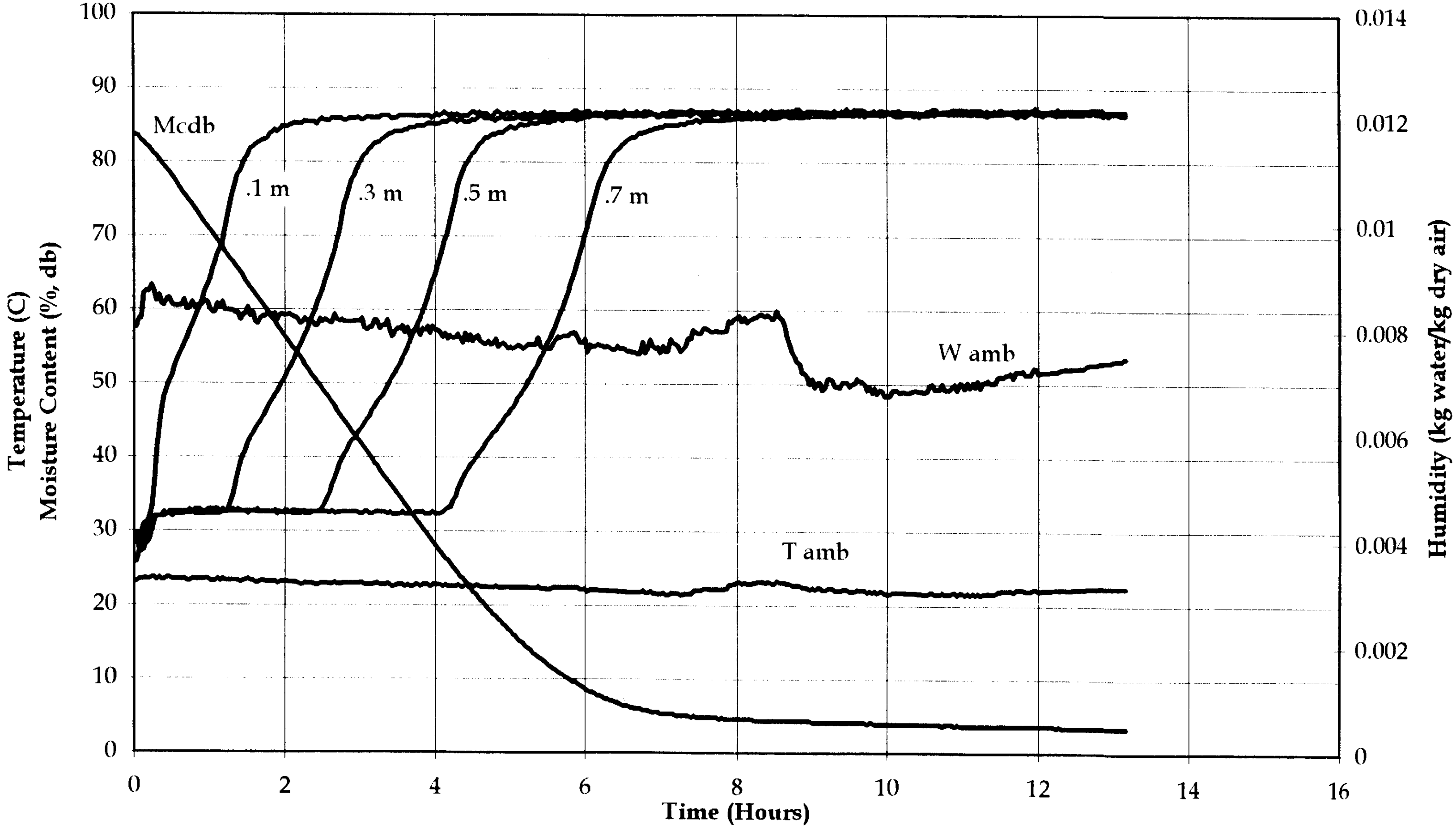


Figure 41. Experimental Batch 6.

GWM piece #: F2704
Variety: NW Harrington
Dry date: 22 July 1995

Airon Temp: 63.9 C
Air flow rate: .57 kg/m^2/s

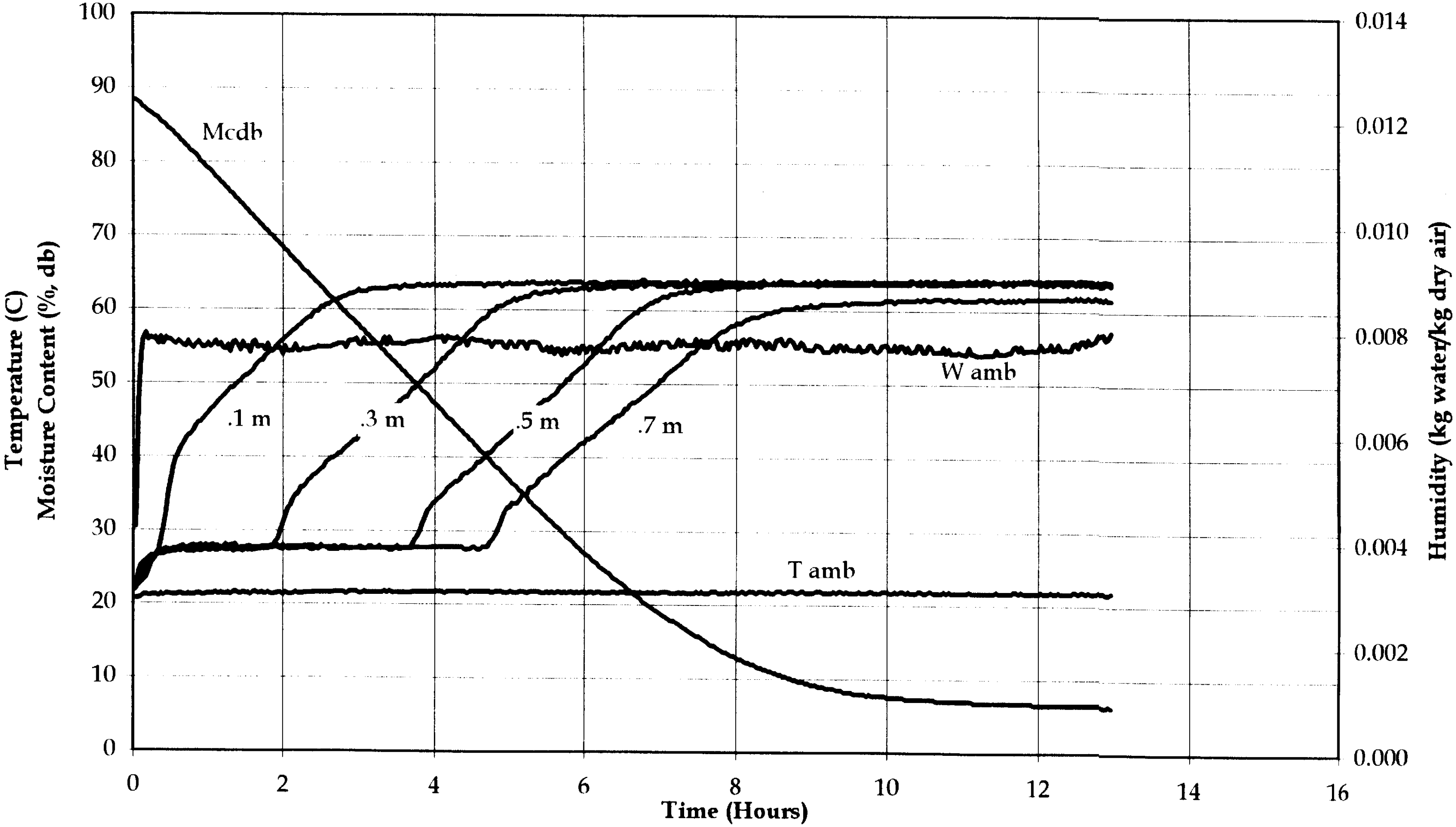


Figure 42. Experimental Batch 9.

GWM piece #: F2705
Variety: NW Harrington
Dry date: 22 July 1995

Airon Temp: 70.0 C
Air flow rate: .57 kg/m^2/s

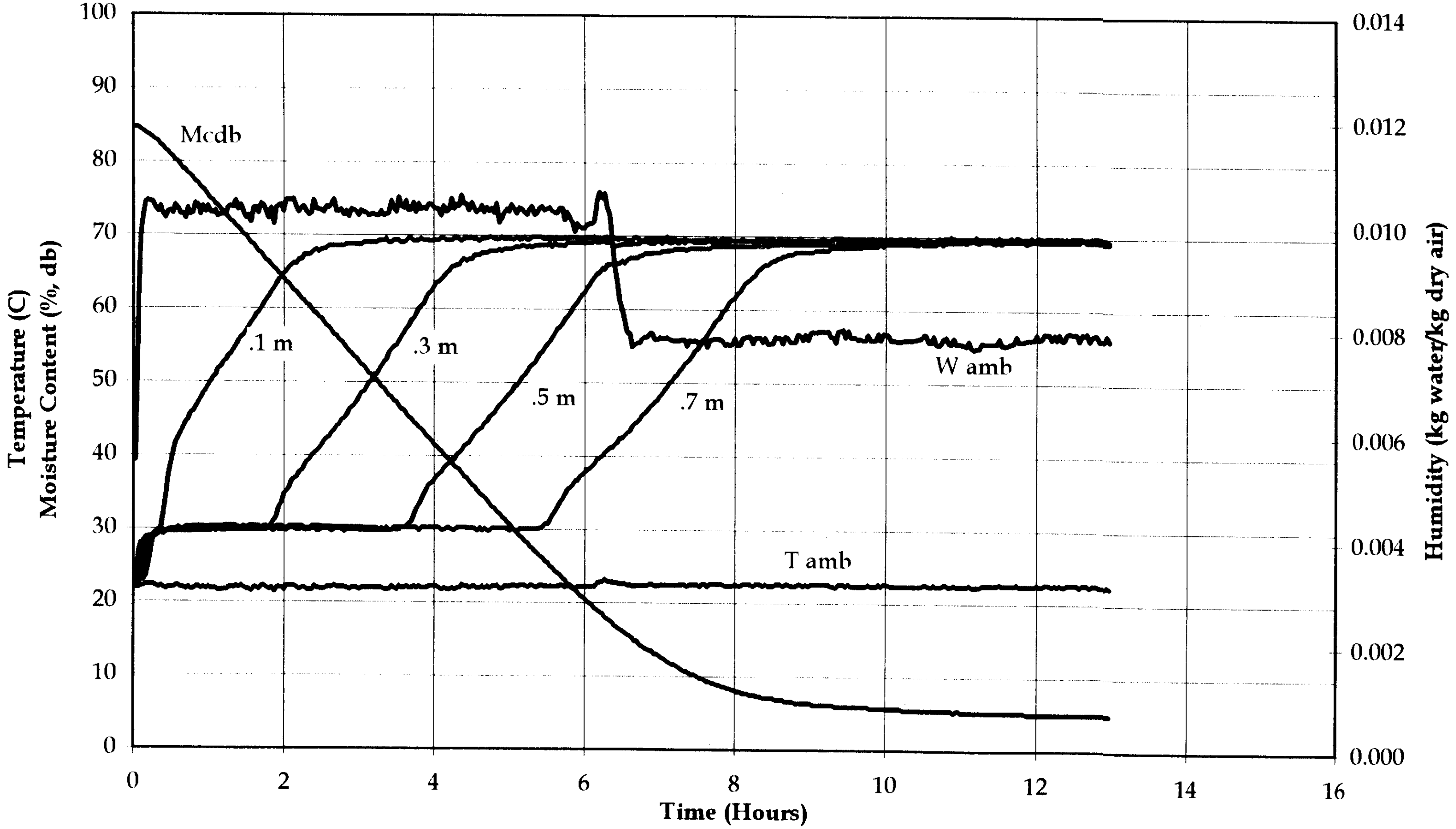
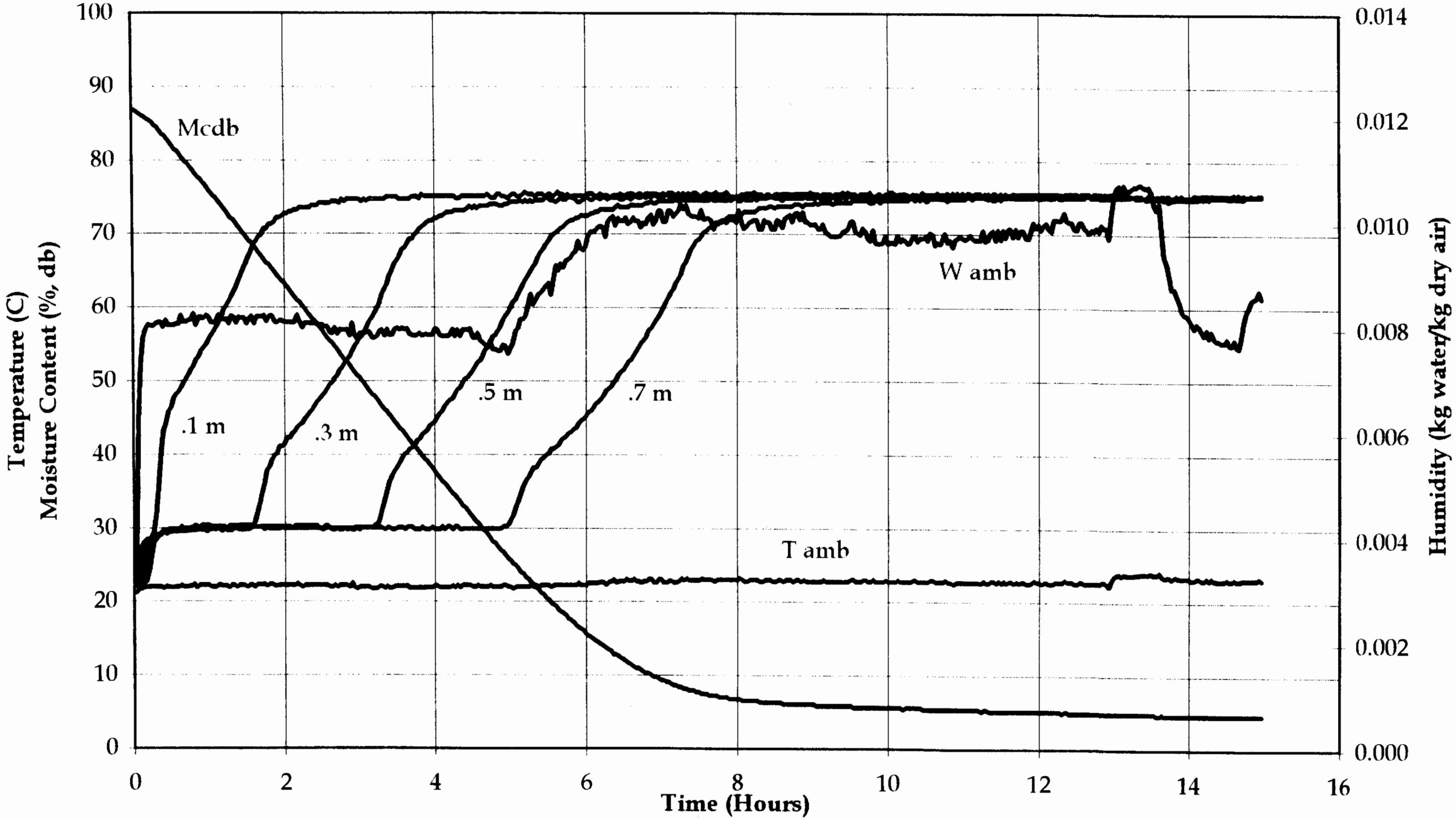


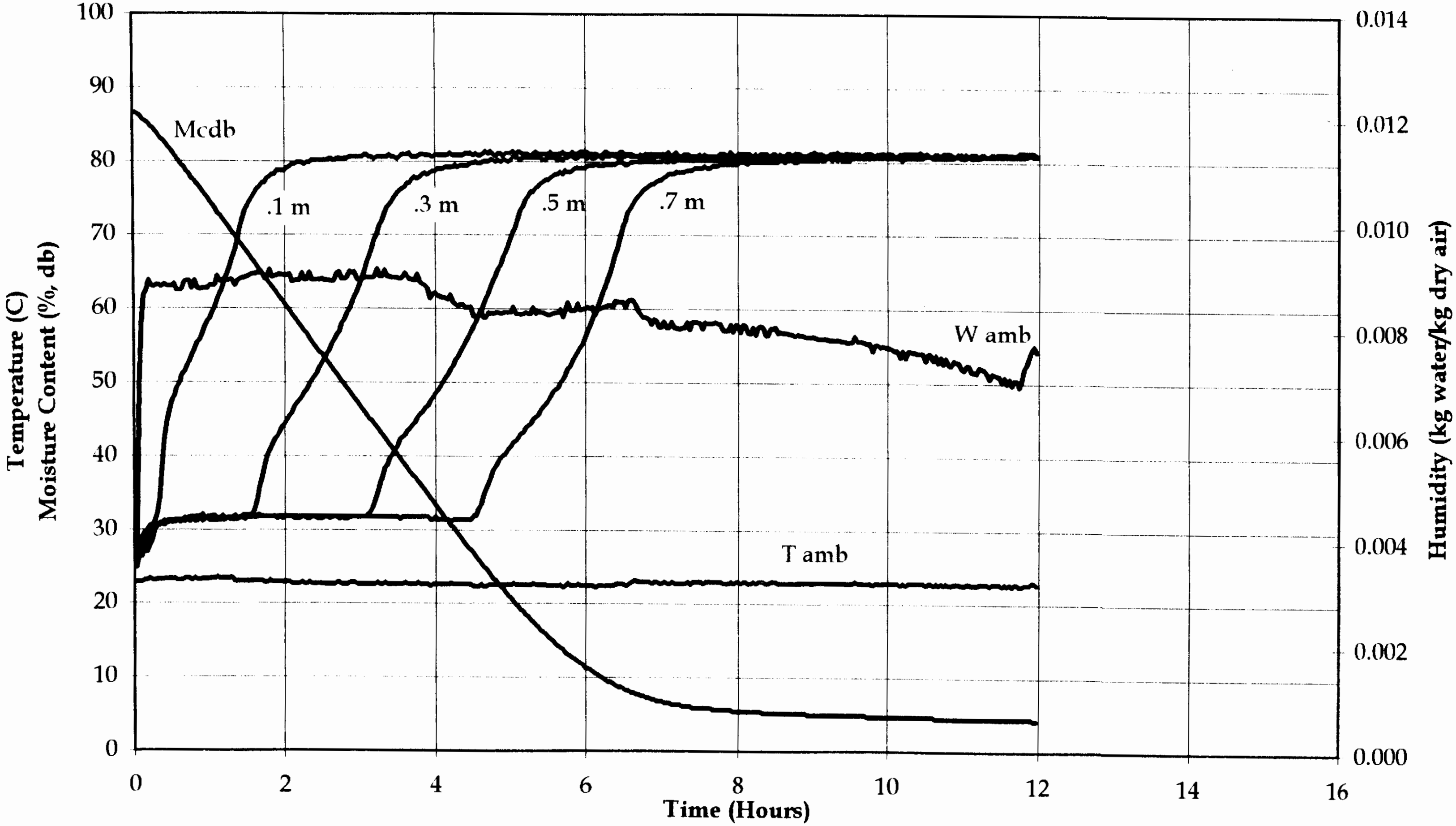
Figure 43. Experimental Batch 10.



GWM piece #: F2706
Variety: CN Harrington
Dry date: 23 July 1995

Airon Temp: 75.0 C
Air flow rate: .57 kg/m^2/s

Figure 44. Experimental Batch 11.



GWM piece #: F2706
Variety: CN Harrington
Dry date: 24 July 1995

Airon Temp: 81.1 C
Air flow rate: .57 kg/m^2/s

Figure 45. Experimental Batch 12.

GWM piece #: C1317
Variety: Idaho Crystal
Dry date: 9 August 1995

Airon Temp: 65.3 C
Air flow rate: .57 kg/m^2/s

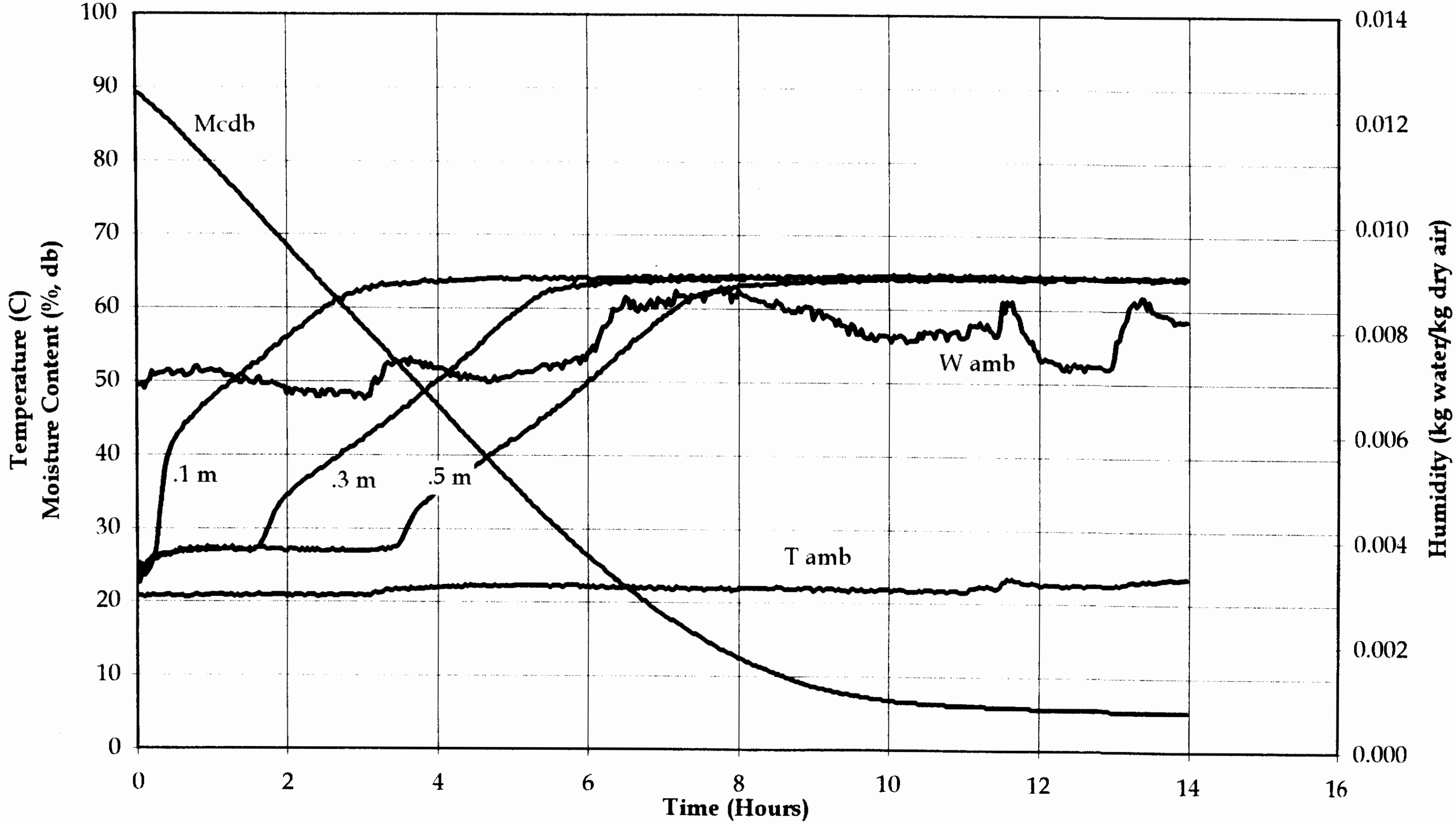


Figure 46. Experimental Batch 13.

GWM piece #: C1318
Variety: Idaho Crystal
Dry date: 10 August 1995

Airon Temp: 70.2 C
Air flow rate: .57 kg/m^2/s

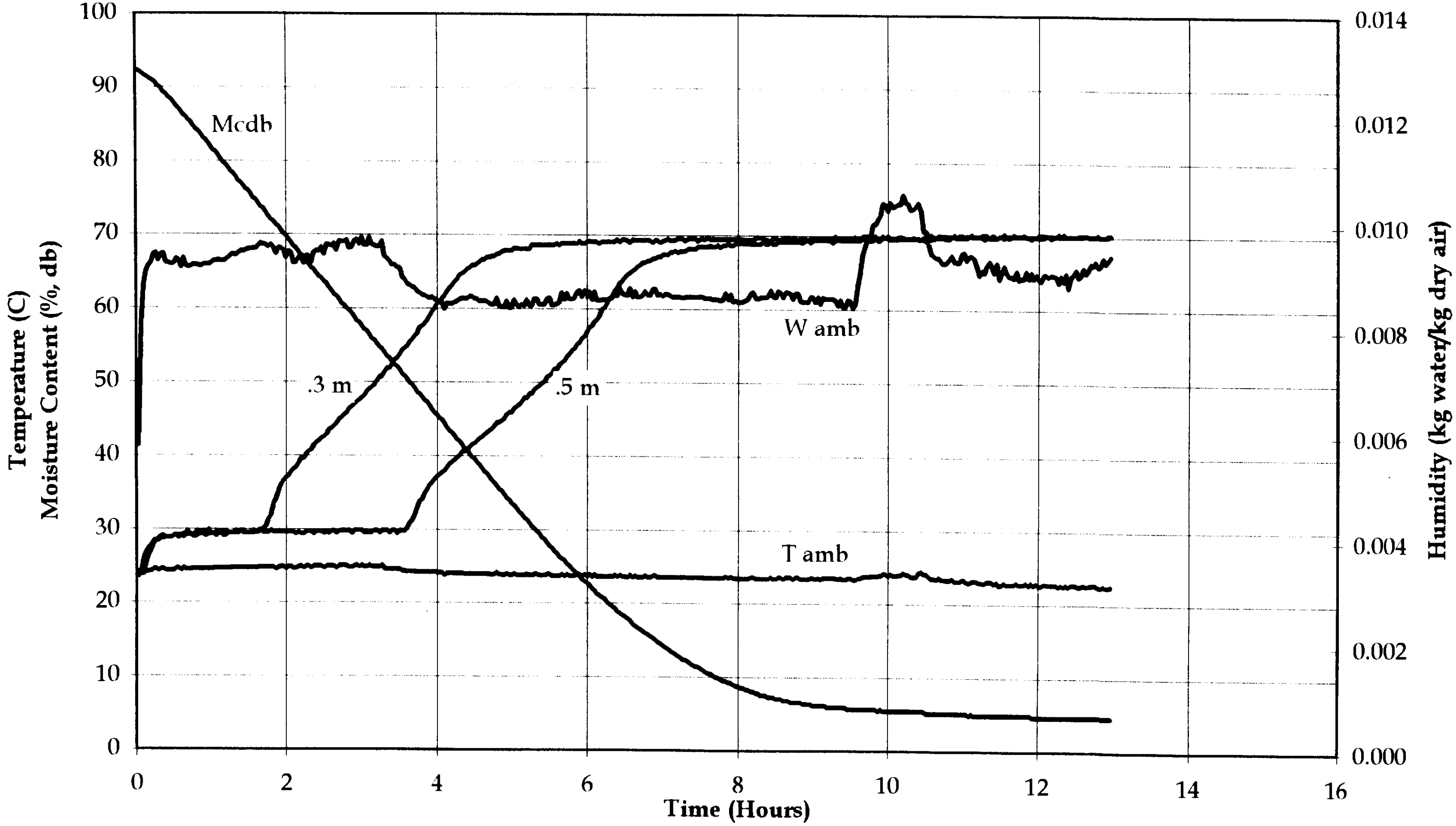


Figure 47. Experimental Batch 14.

GWM piece #: F2757
Variety: NW Harrington
Dry date: 13 September 1995

Airon Temp: 71.1 C, 8 hr; 82.2 C, 7 hr.
Air flow rate: .57 kg/m^2/s, 8 hr;
.43 kg/m^2/s, 7 hr.

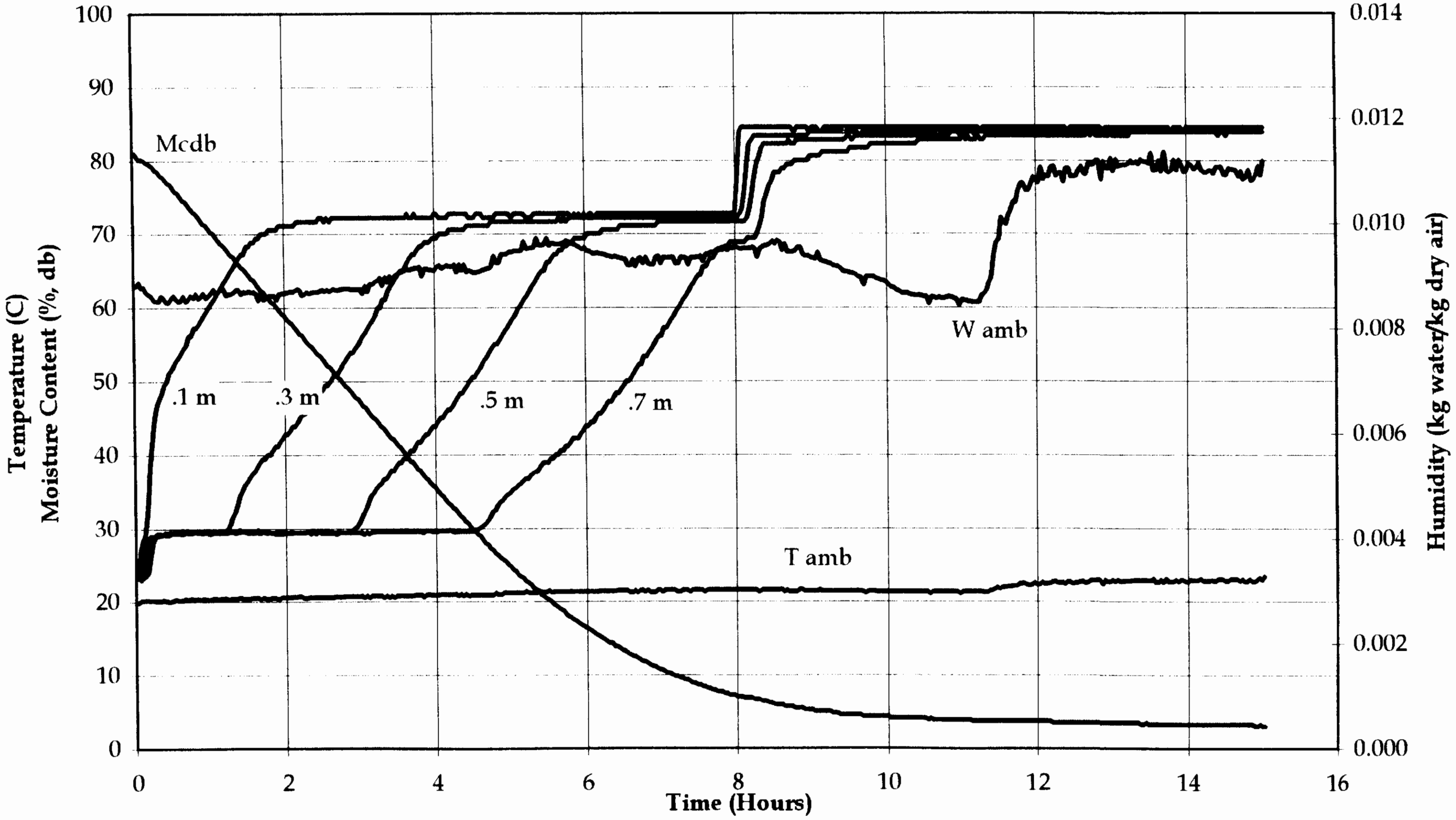


Figure 48. Experimental Batch 20.

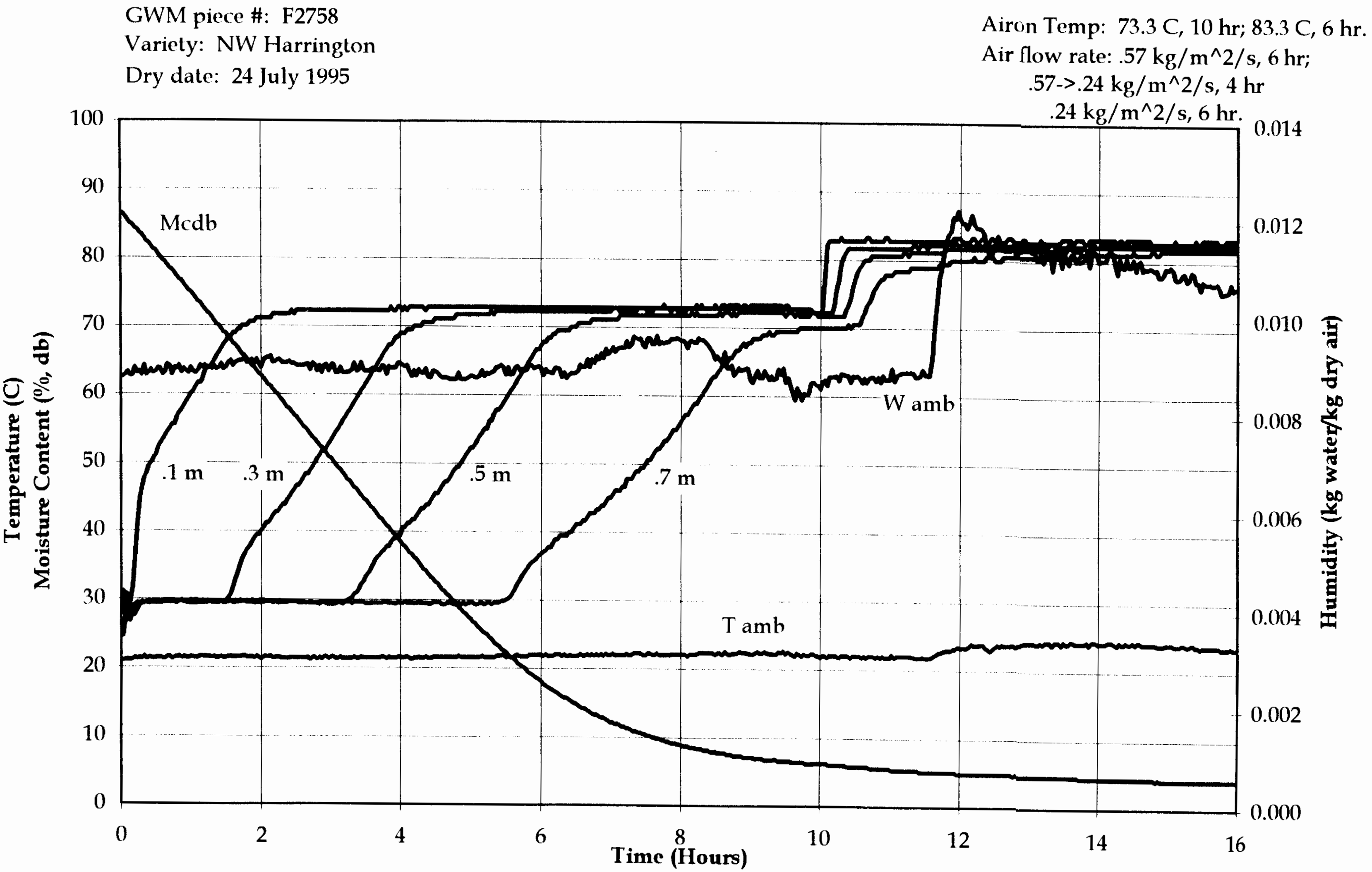
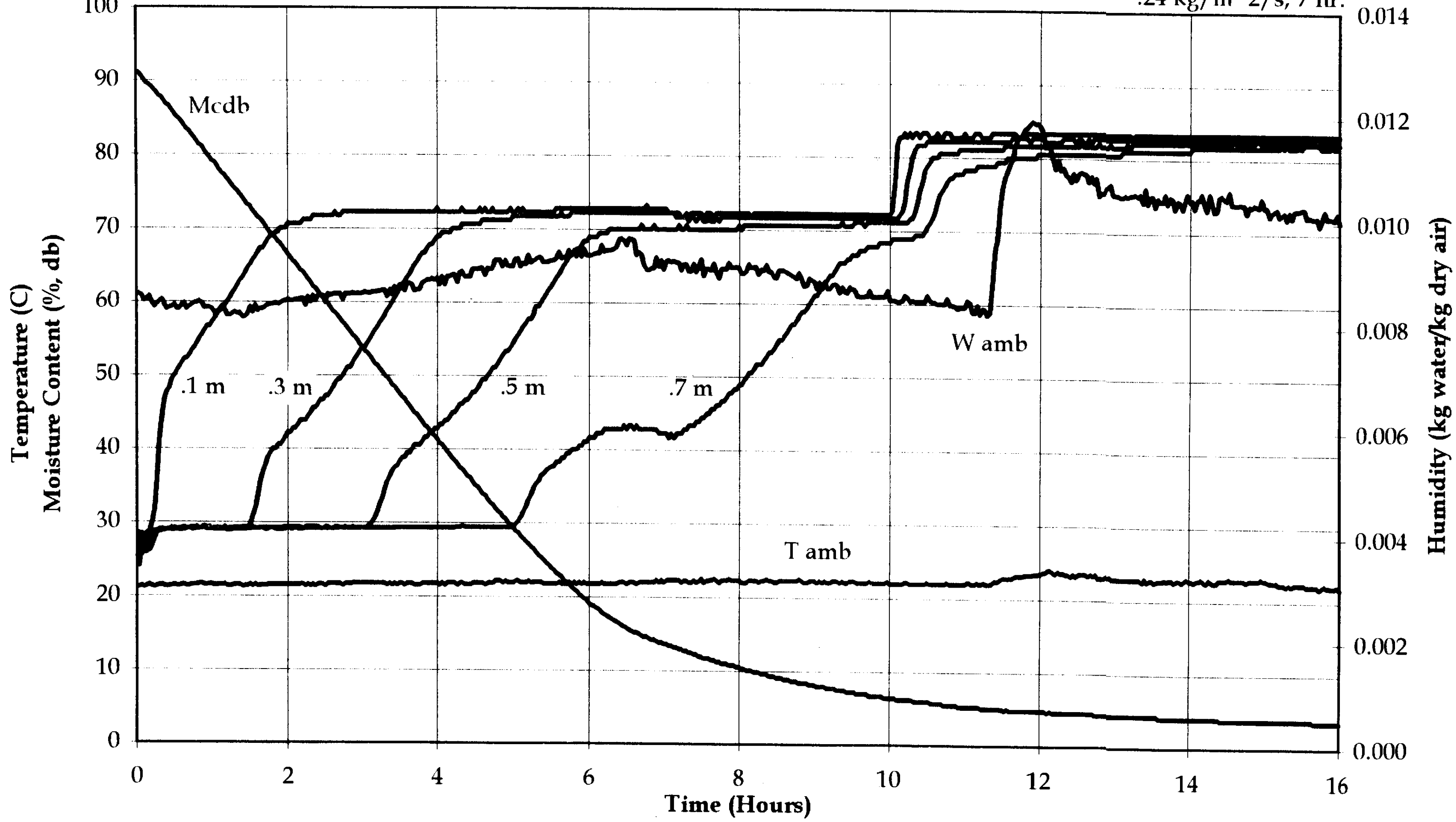


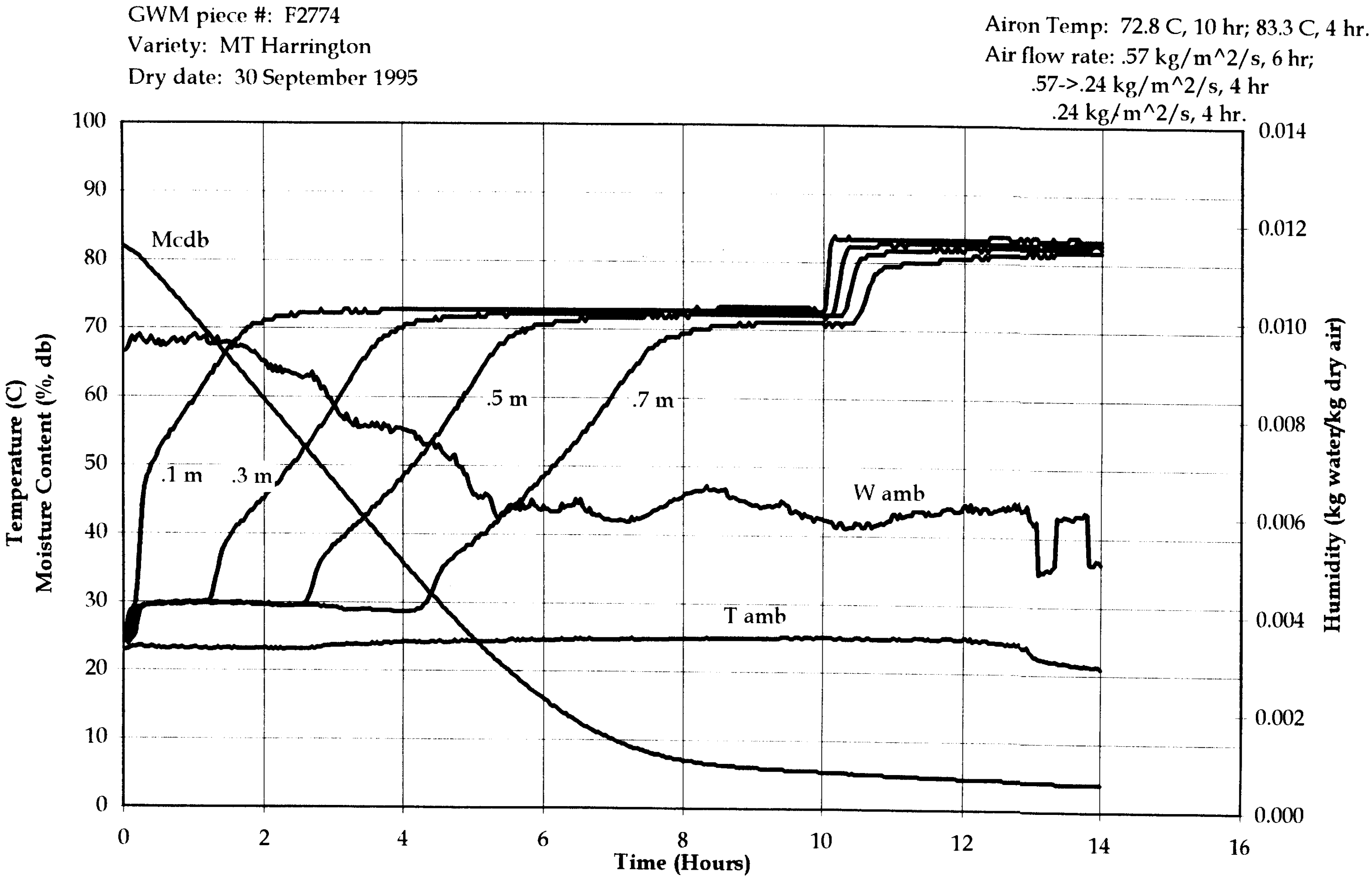
Figure 49. Experimental Batch 21.



GWM piece #: F2759
Variety: CN Harrington
Dry date: 15 September 1995

Airon Temp: 72.2 C, 10 hr; 83.3 C, 6 hr.
Air flow rate: .57 kg/m^2/s, 6 hr;
.57->.24 kg/m^2/s, 1 hr
.24 kg/m^2/s, 7 hr.

Figure 50. Experimental Batch 22.



GWM piece #: F2774
Variety: MT Harrington
Dry date: 30 September 1995

Airon Temp: 72.8 C, 10 hr; 83.3 C, 4 hr.
Air flow rate: .57 kg/m^2/s, 6 hr;
.57->.24 kg/m^2/s, 4 hr
.24 kg/m^2/s, 4 hr.

Figure 51. Experimental Batch 24.

GWM piece #: F2775
Variety: MT Harrington
Dry date: 1 October 1995

Airon Temp: 72.8 C, 10 hr; 84.4 C, 4 hr.
Air flow rate: .57 kg/m^2/s, 8 hr;
.43 kg/m^2/s, 6 hr.

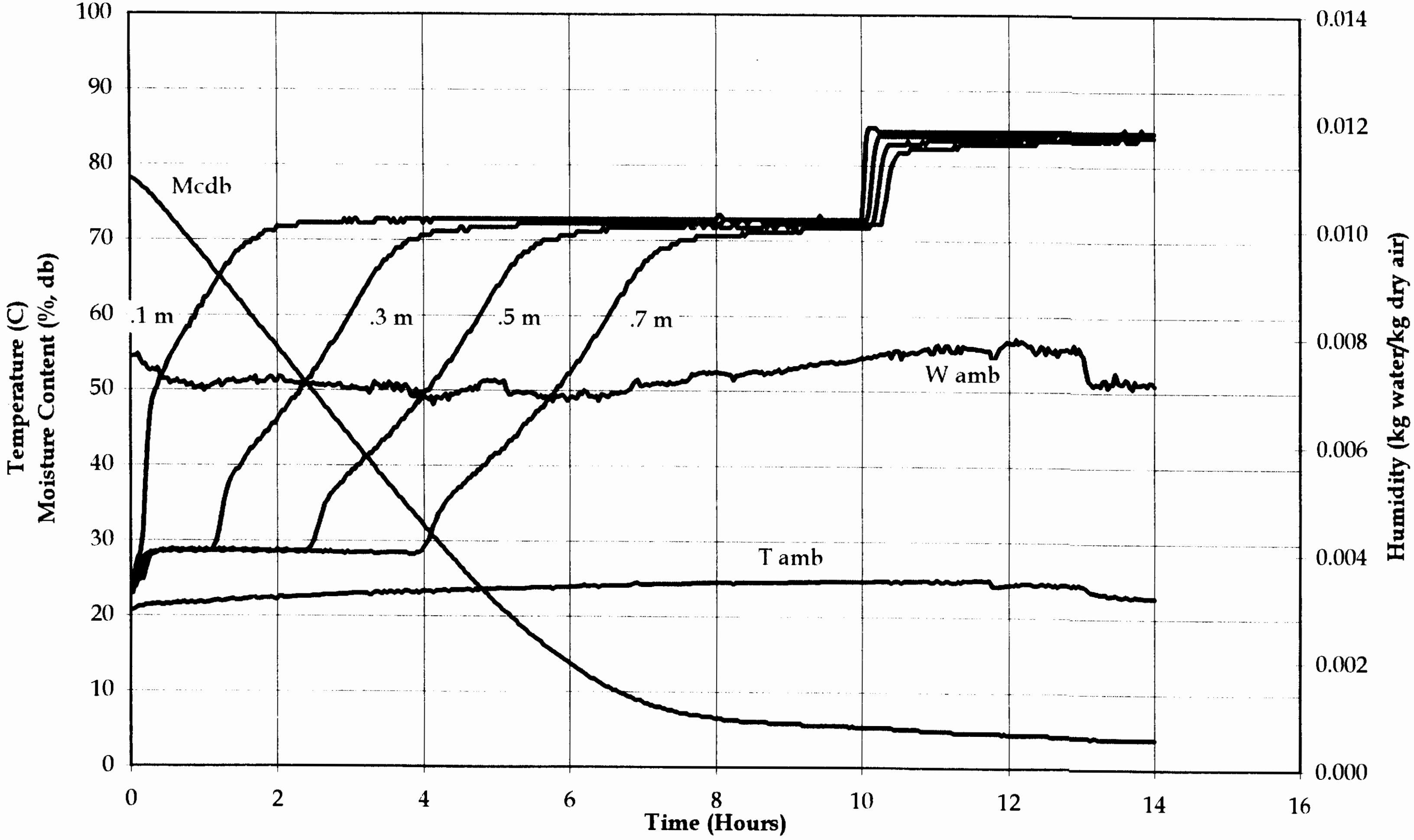


Figure 52. Experimental Batch 25.

APPENDIX H

MODEL VERSUS EXPERIMENTAL DATA COMPARISON

GWM piece #: C1272
Variety: Idaho Crystal
Dry date: 11 July 1995

Airon Temp: 63.3 C
Air flow rate: .594 kg/m^2/s

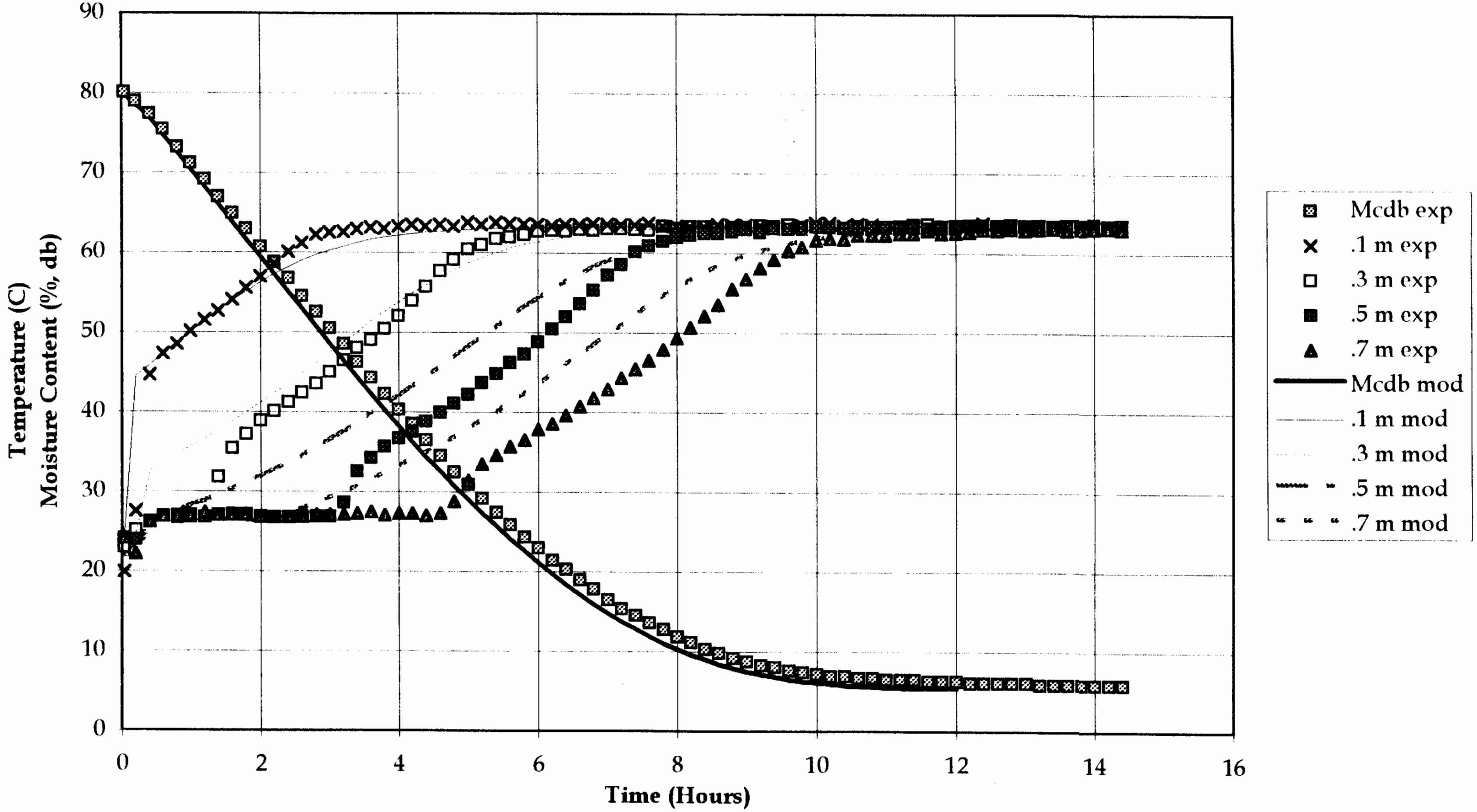


Figure 53. Batch 2 Model vs. Experimental Data.

GWM piece #: C1275
Variety: Idaho Crystal
Dry date: 12 July 1995

Airon Temp: 71.1 C
Air flow rate: .57 kg/m^2/s

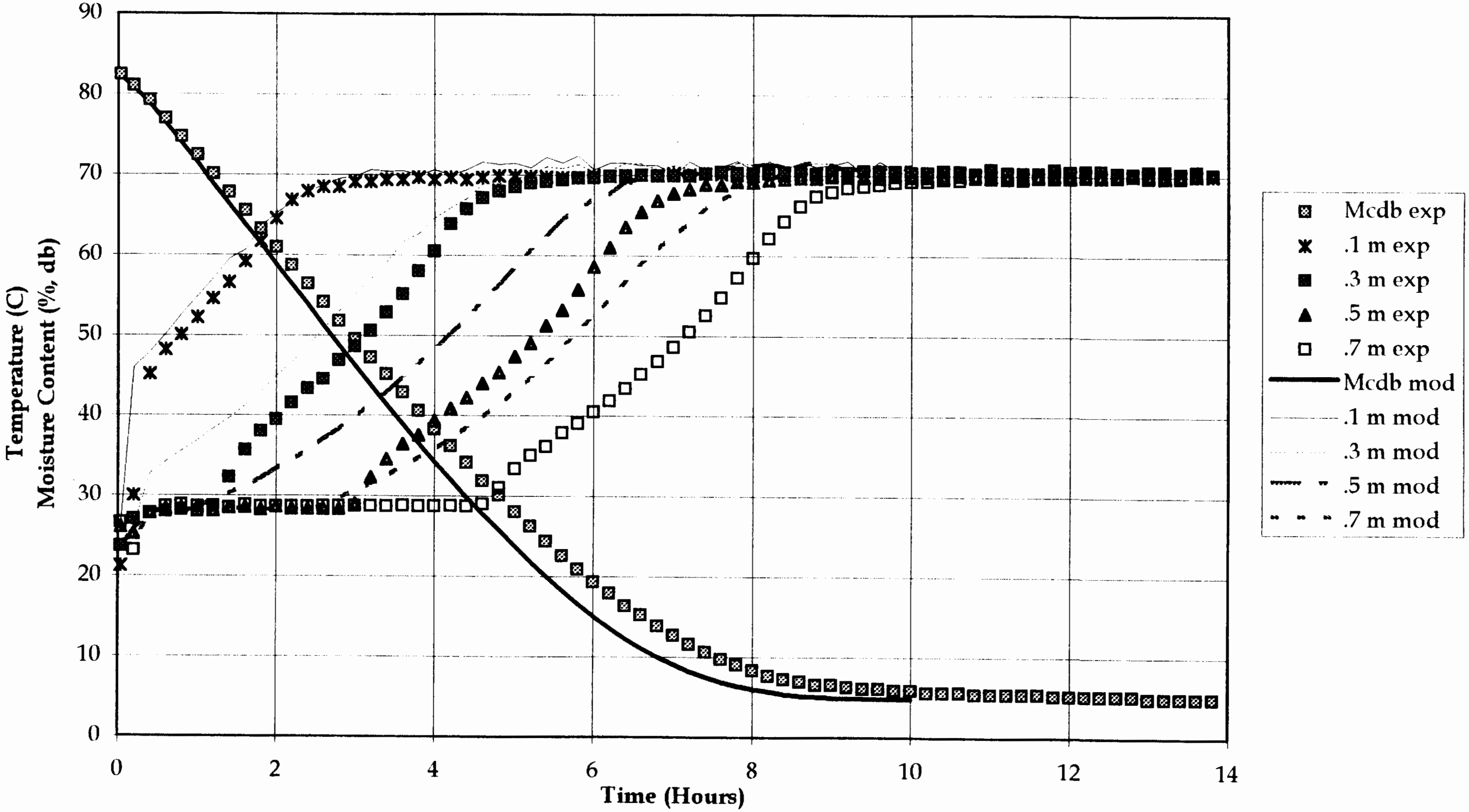


Figure 54. Batch 3 Model vs. Experimental Data.

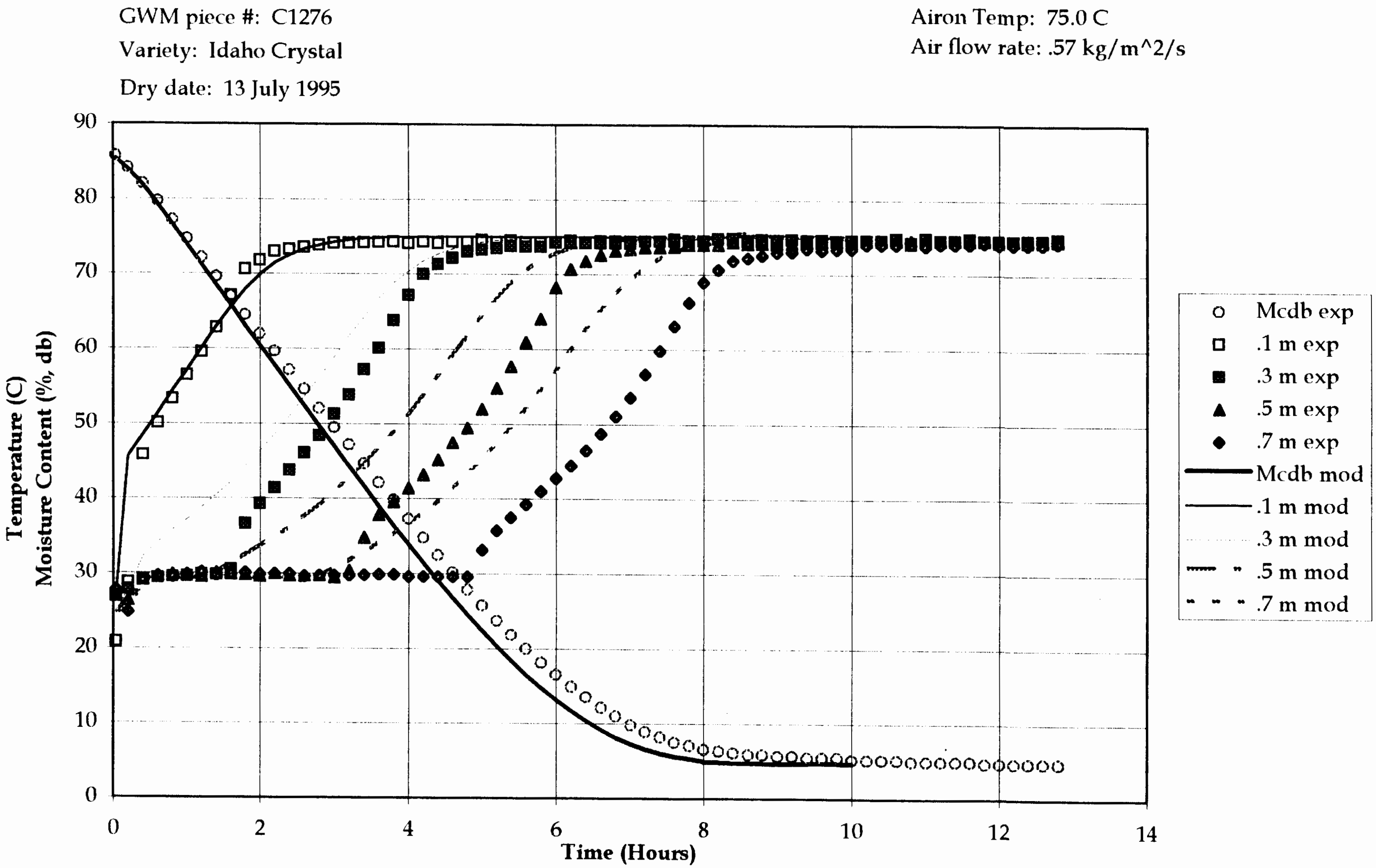
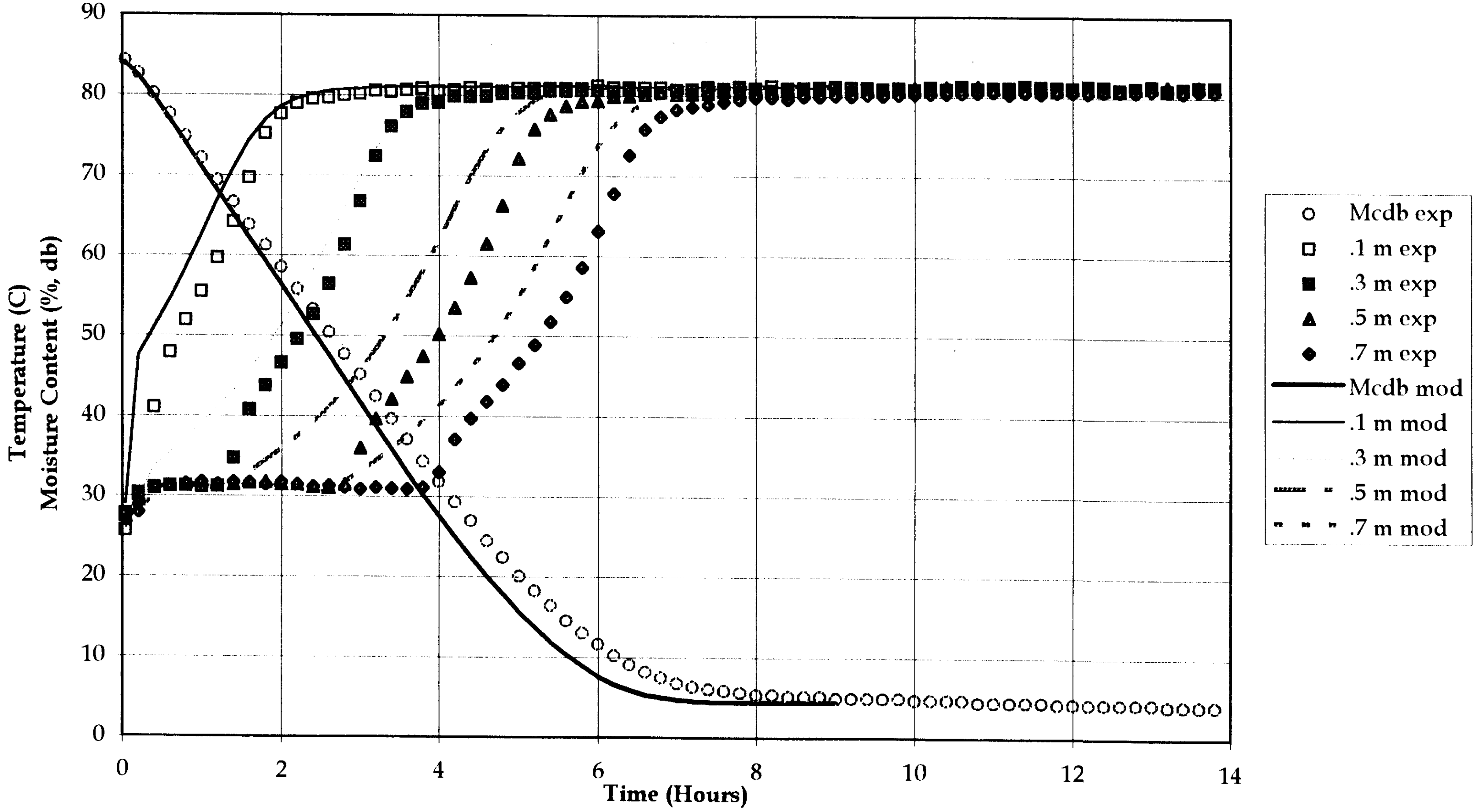


Figure 55. Batch 4 Model vs. Experimental Data.



GWM piece #: C1277
Variety: Idaho Crystal
Dry date: 14 July 1995

Airon Temp: 81.1 C
Air flow rate: .57 kg/m^2/s

Figure 56. Batch 5 Model vs. Experimental Data.

GWM piece #: C1278
Variety: Idaho Crystal
Dry date: 14 July 1995

Airon Temp: 86.7 C
Air flow rate: .57 kg/m^2/s

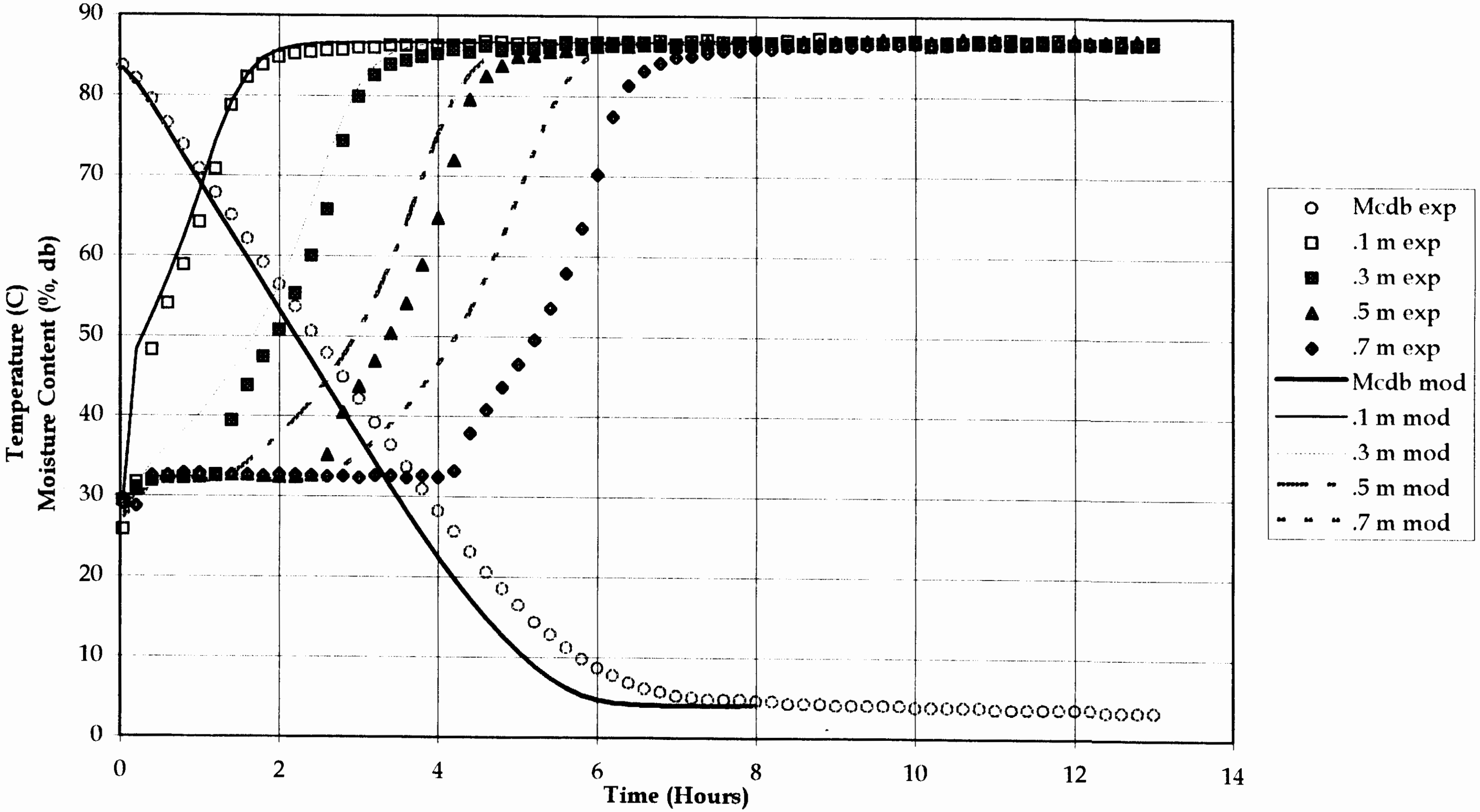


Figure 57. Batch 6 Model vs. Experimental Data.

GWM piece #: F2704
Variety: NW Harrington
Dry date: 22 July 1995

Airon Temp: 63.9 C
Air flow rate: .57 kg/m^2/s

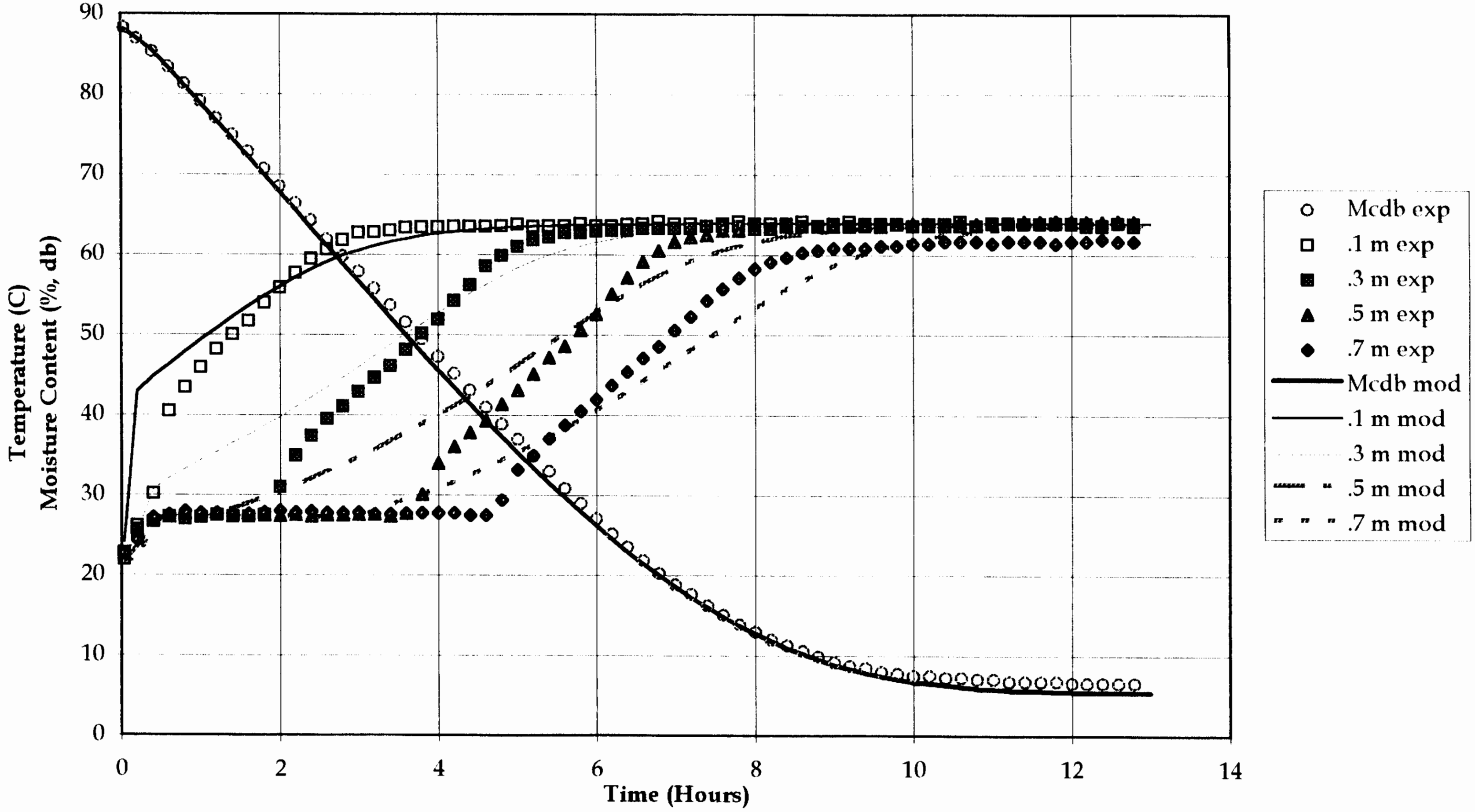


Figure 58. Batch 9 Model vs. Experimental Data.

GWM piece #: F2705
Variety: NW Harrington
Dry date: 22 July 1995

Airon Temp: 70.0 C
Air flow rate: .57 kg/m^2/s

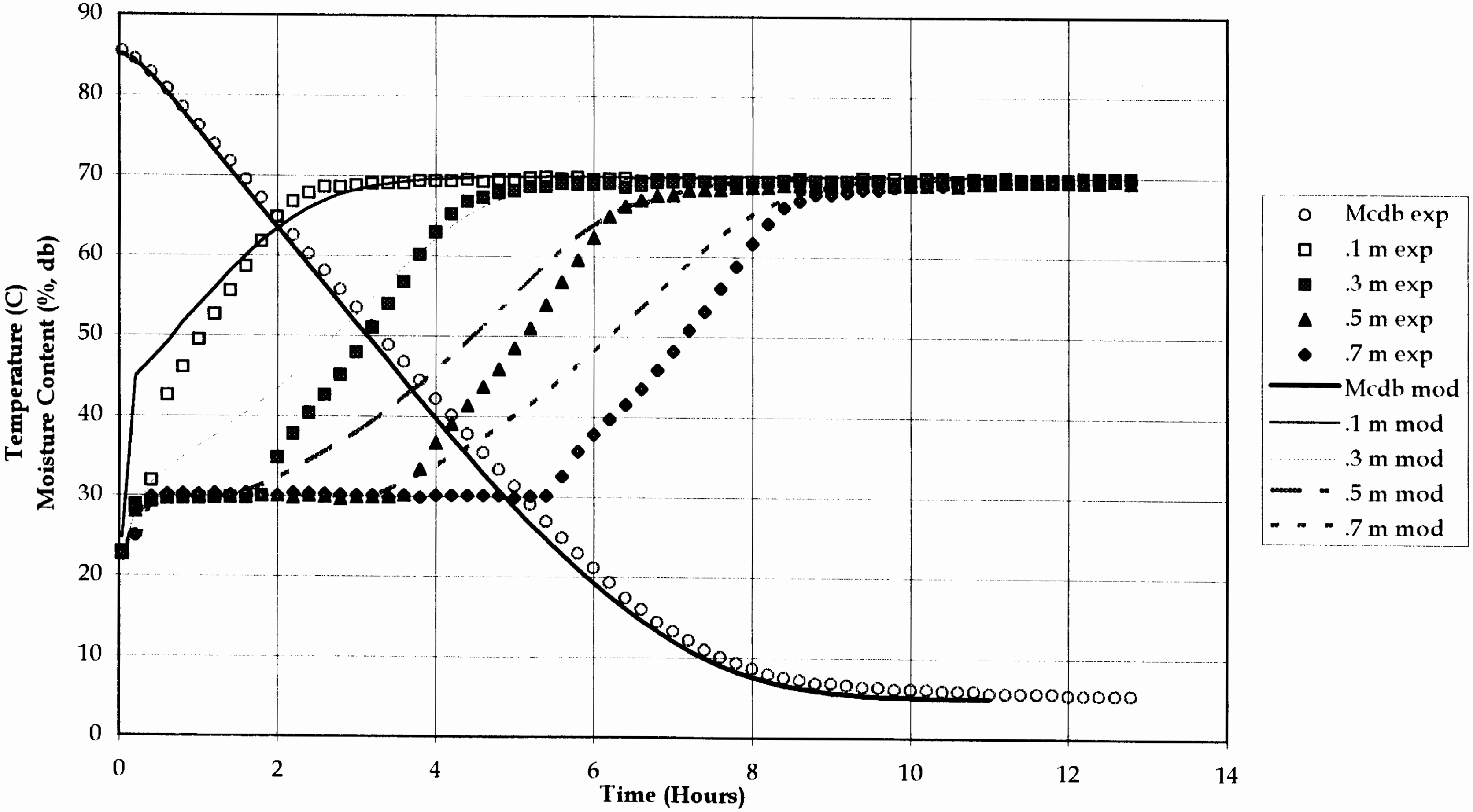
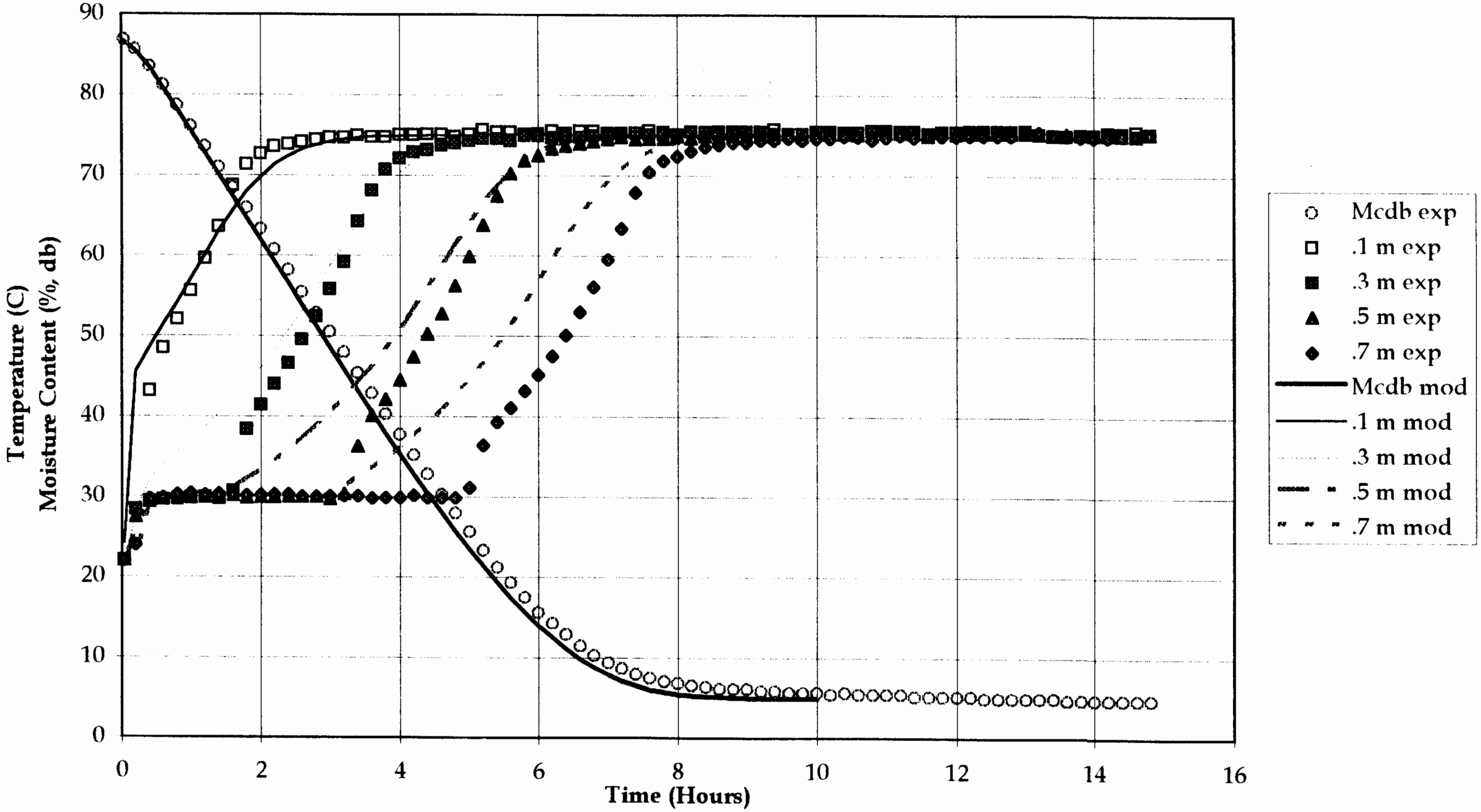


Figure 59. Batch 10 Model vs. Experimental Data.



GWM piece #: F2706

Variety: CN Harrington

Dry date: 23 July 1995

Airon Temp: 75.0 C

Air flow rate: .57 kg/m^2/s

Figure 60. Batch 11 Model vs. Experimental Data.

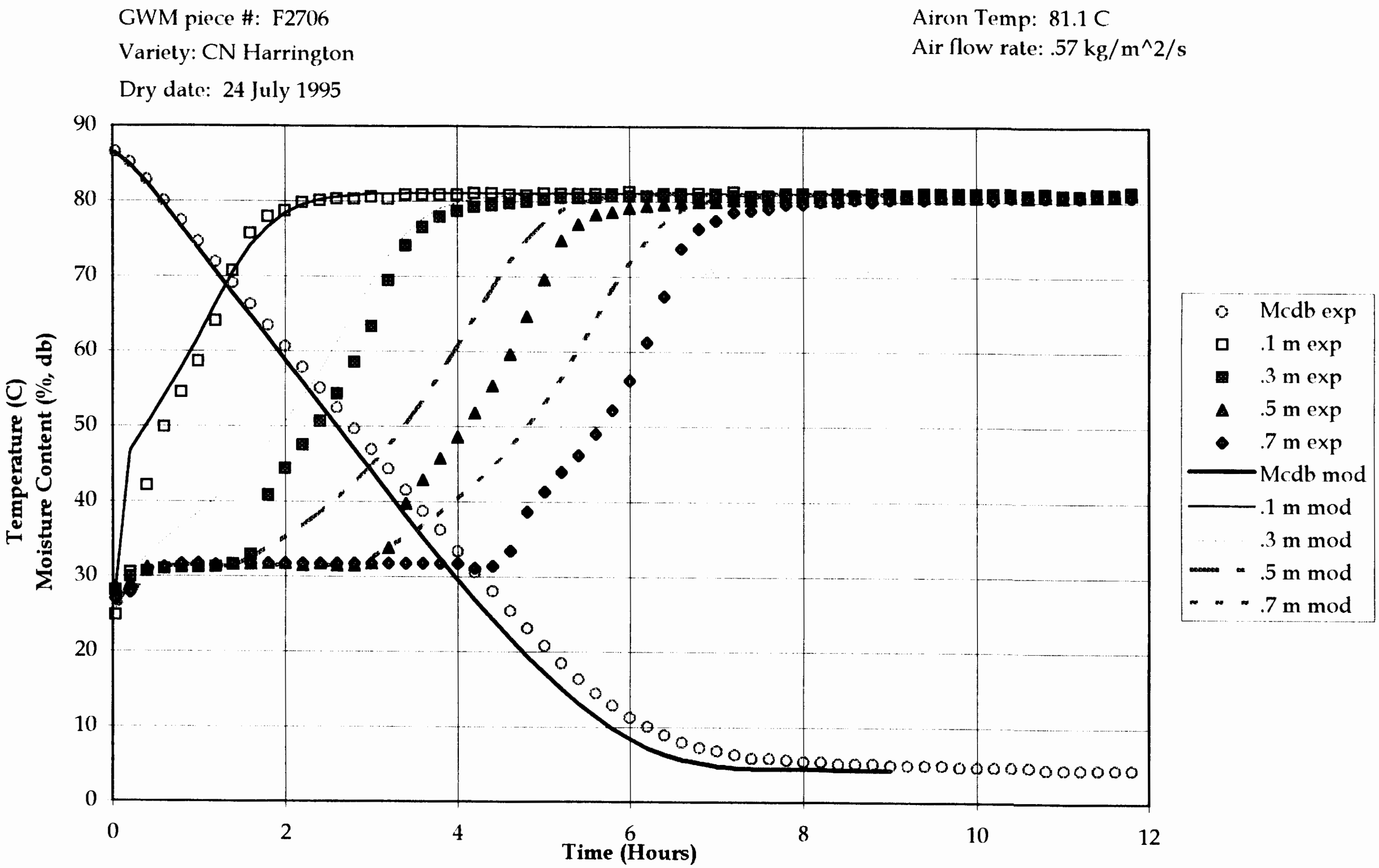


Figure 61. Batch 12 Model vs. Experimental Data.

GWM piece #: C1317
Variety: Idaho Crystal
Dry date: 9 August 1995

Airon Temp: 65.6 C
Air flow rate: .57 kg/m^2/s

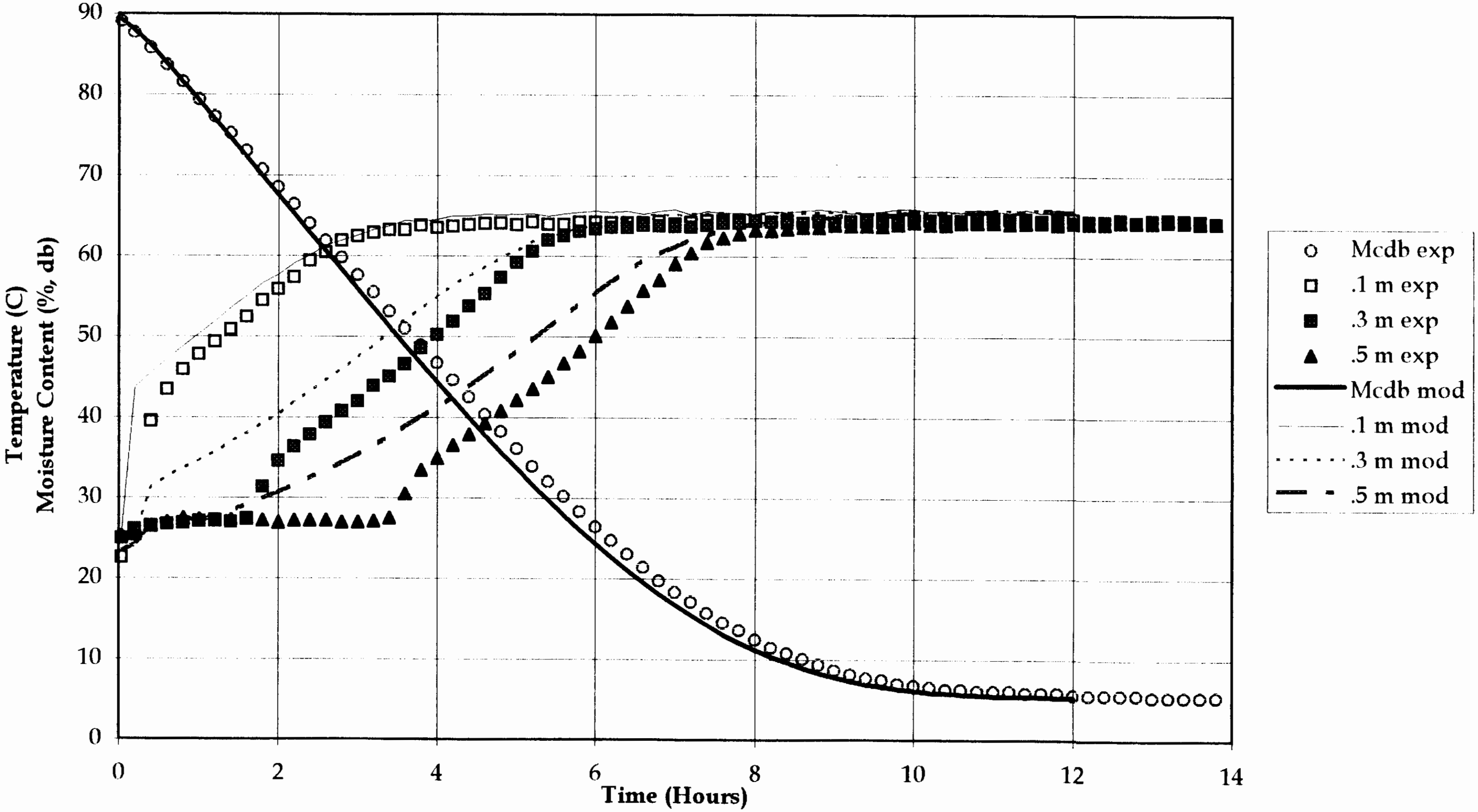


Figure 62. Batch 13 Model vs. Experimental Data.

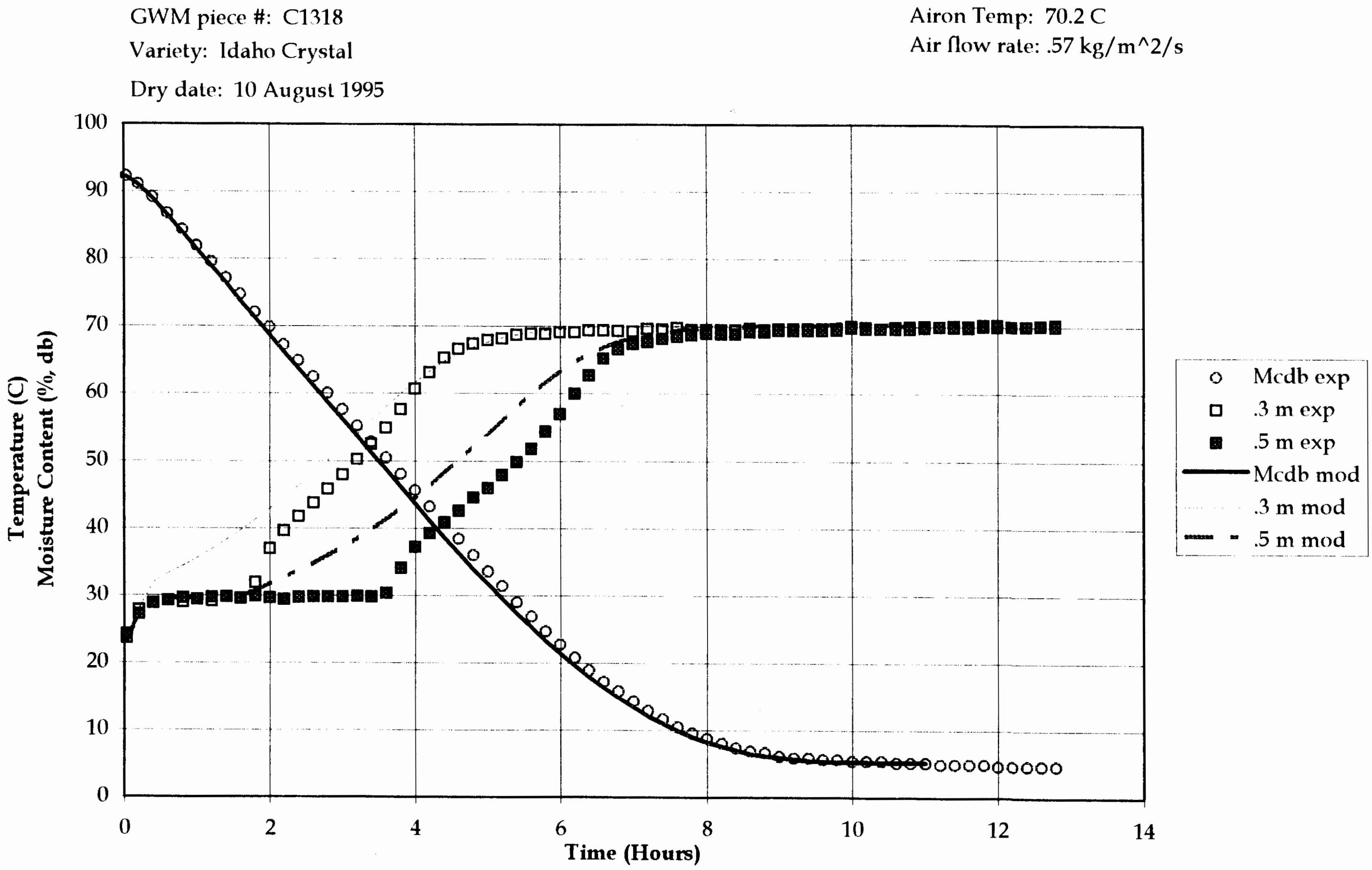
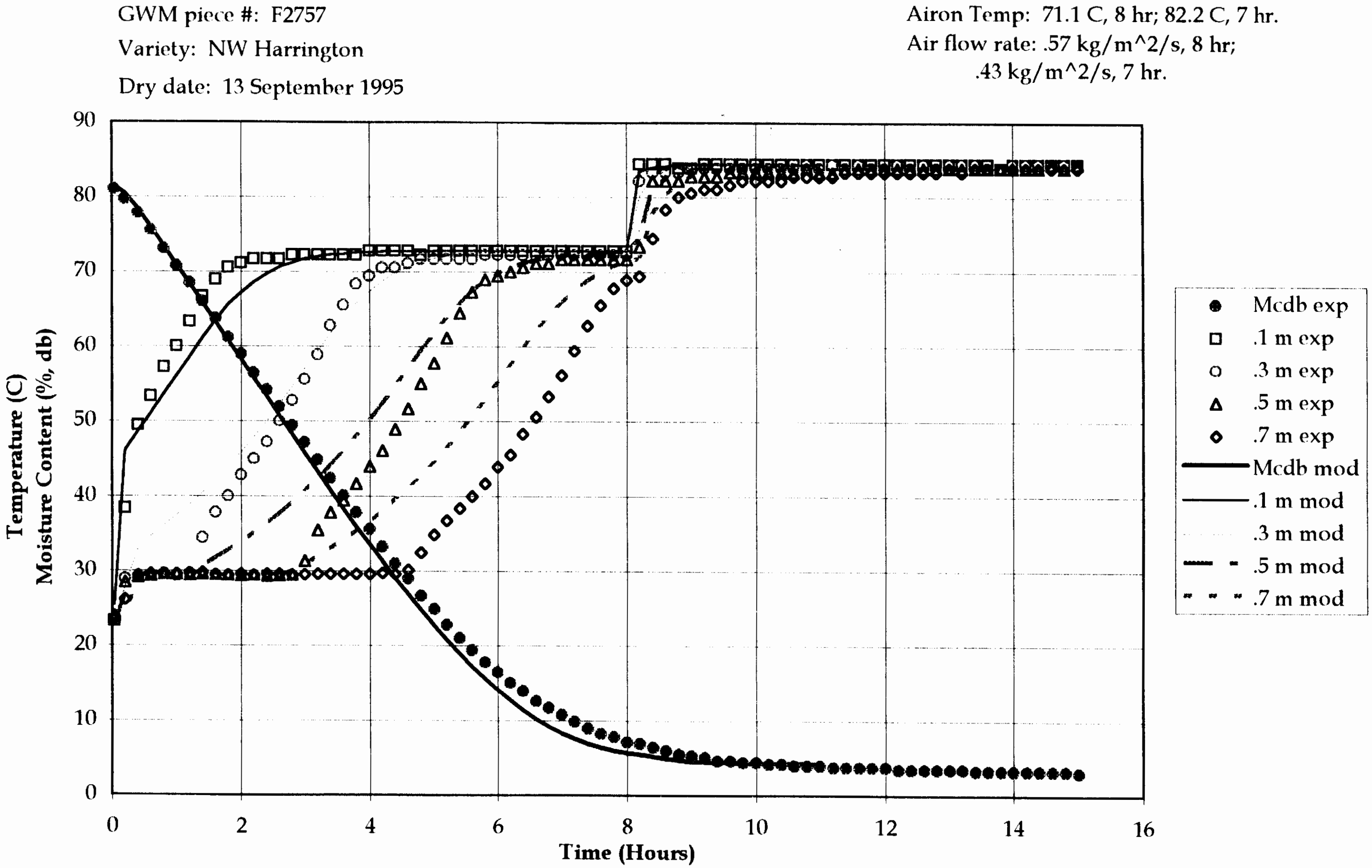


Figure 63. Batch 14 Model vs. Experimental Data.



GWM piece #: F2757

Variety: NW Harrington

Dry date: 13 September 1995

Airon Temp: 71.1 C, 8 hr; 82.2 C, 7 hr.

Air flow rate: .57 kg/m^2/s, 8 hr;
.43 kg/m^2/s, 7 hr.

Figure 64. Batch 20 Model vs. Experimental Data.

GWM piece #: F2758
Variety: NW Harrington
Dry date: 14 September 1995

Airon Temp: 73.3 C, 10 hr; 83.3 C, 6 hr
Air flow rate: .57 kg/m^2/s, 6 hr;
.57->.24 kg/m^2/s, 4 hr
.24 kg/m^2/s, 6 hr.

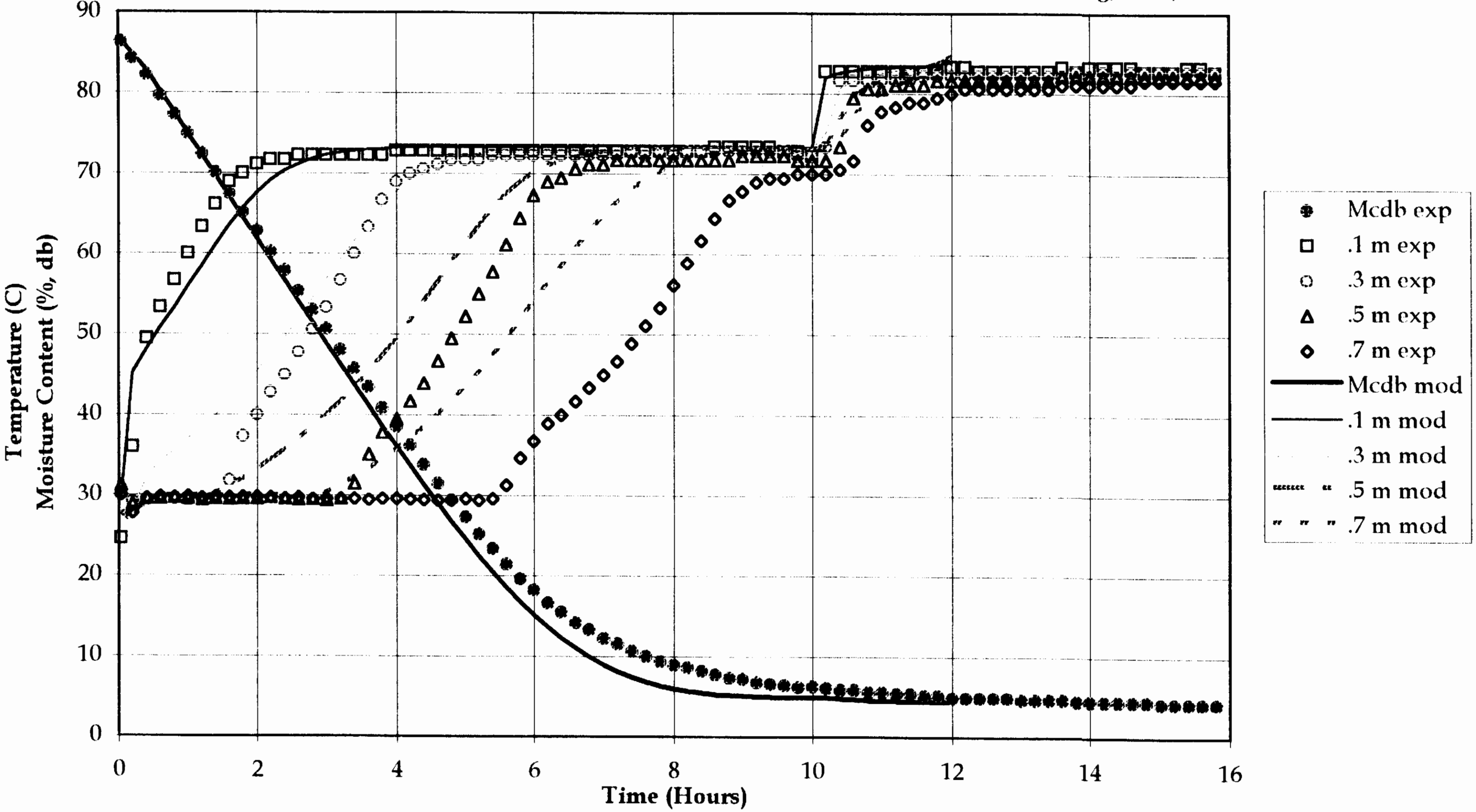


Figure 65. Batch 21 Model vs. Experimental Data.

GWM piece #: F2759
Variety: CN Harrington
Dry date: 15 September 1995

Airon Temp: 72.2 C, 10 hr; 83.3 C, 6 hr
Air flow rate: .57 kg/m^2/s, 6 hr;
.57->.24 kg/m^2/s, 1 hr
.24 kg/m^2/s, 7 hr.

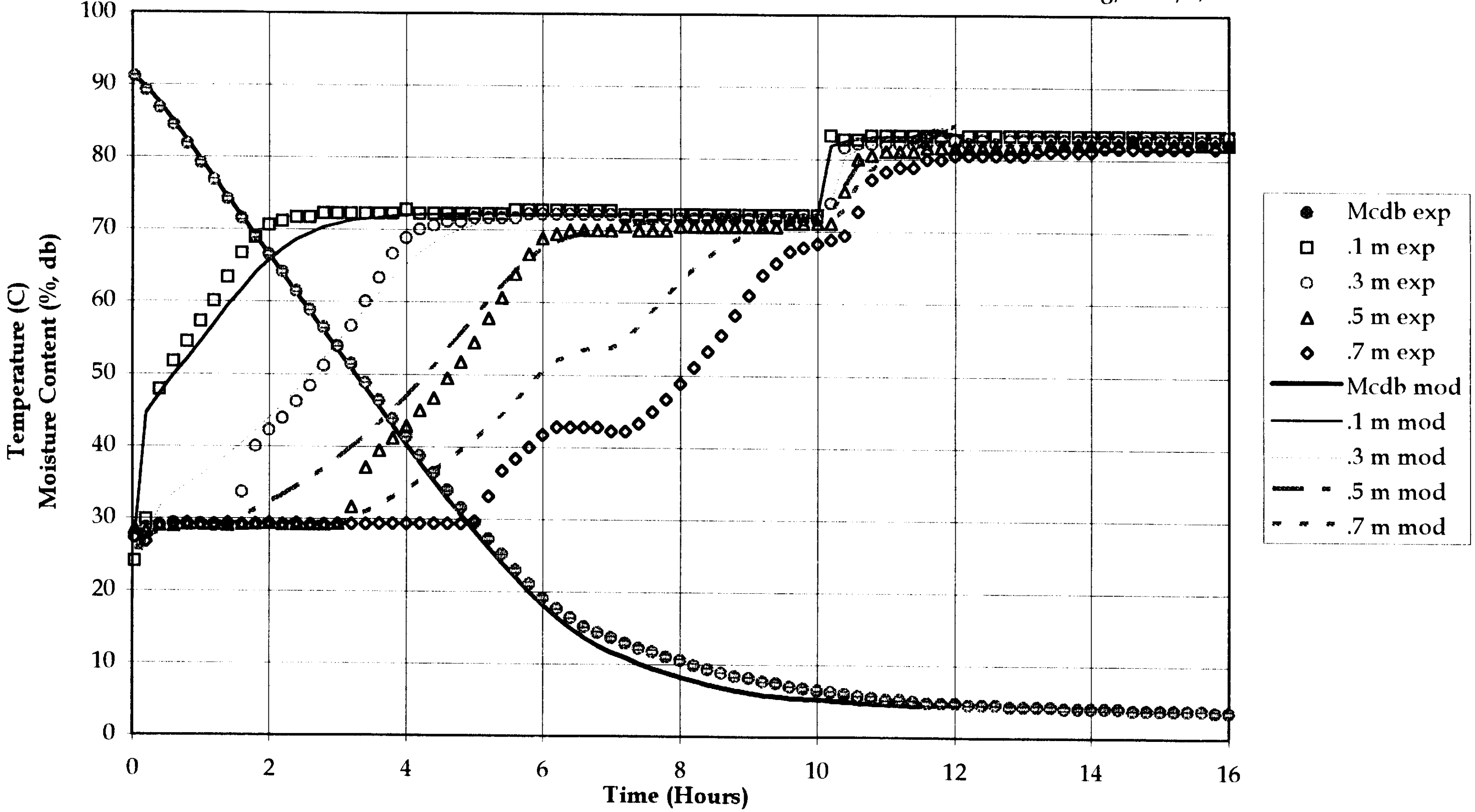
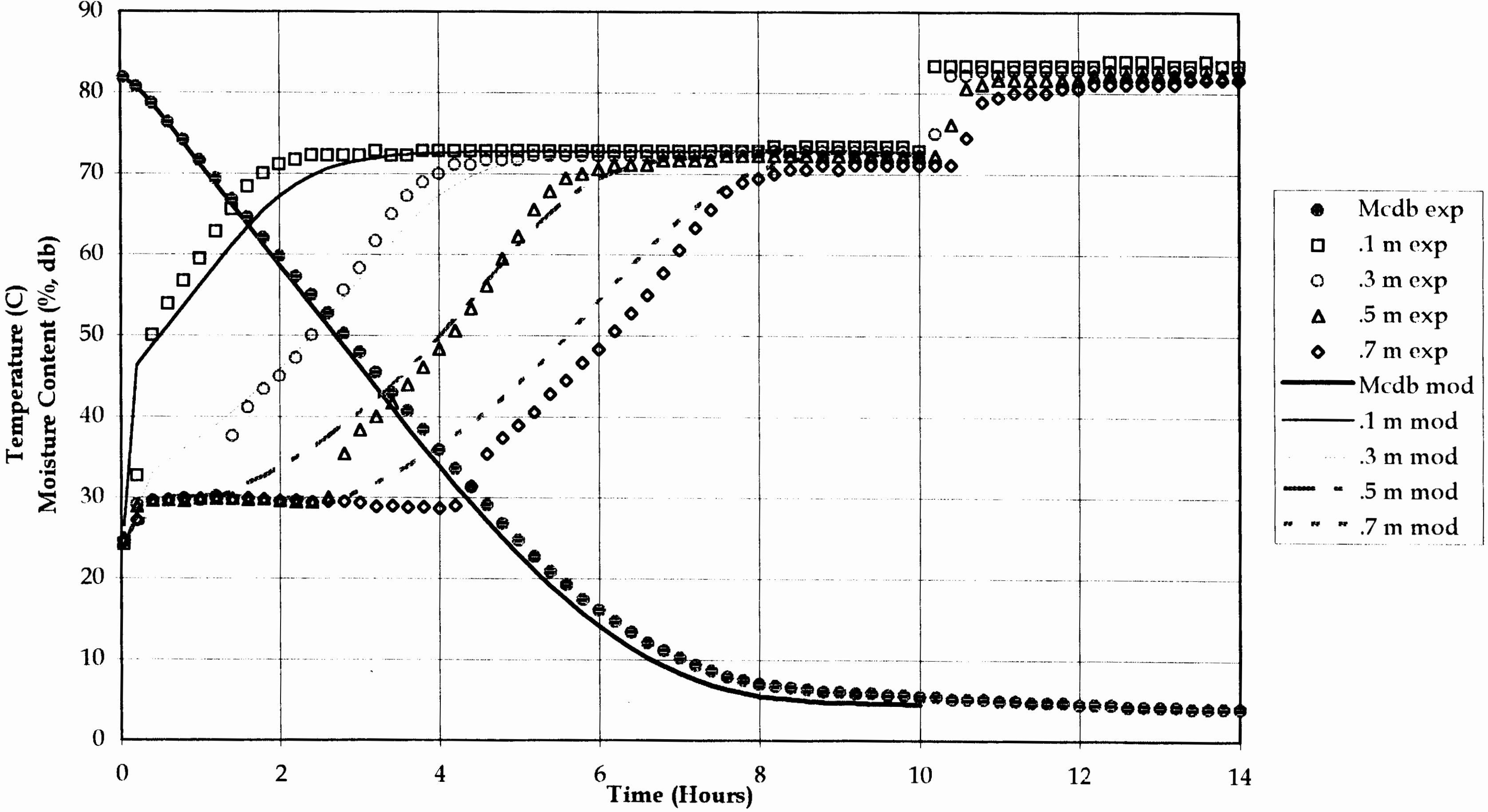


Figure 66. Batch 22 Model vs. Experimental Data.



GWM piece #: F2774
Variety: MT Harrington
Dry date: 30 September 1995

Airon Temp: 72.8 C, 10 hr; 83.3 C, 4 hr.
Air flow rate: .57 kg/m^2/s, 6 hr;
.57->.24 kg/m^2/s, 4 hr;
.24 kg/m^2/s, 4 hr.

Figure 67. Batch 24 Model vs. Experimental Data.

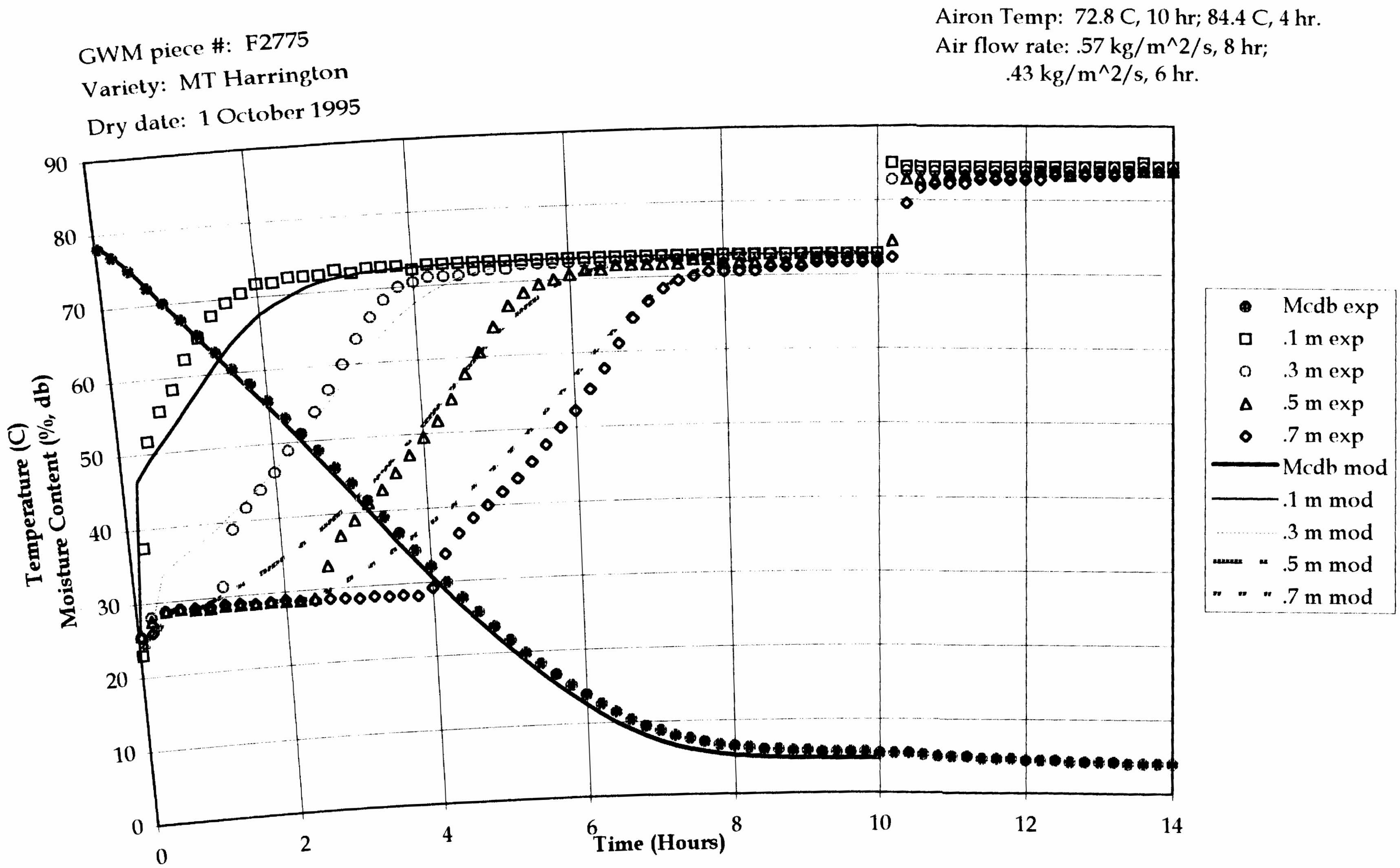


Figure 68. Batch 25 Model vs. Experimental Data.