AERATING OVER-DRY GRAIN IN THE NORTHWEST

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ABSTRACT. *Grain in the U.S. Northwest is typically both over-dry and too warm for safe storage after harvest. Laboratory and computer studies were used to examine aeration with cool and high humidity air to alleviate both deficiencies, while maintaining grain quality with safe storage conditions. A wide range of high humidity aeration conditions was produced in the laboratory to study the effect of moisture condensation on the grain and moisture adsorption during and after cooling the grain. Computer simulations were used to evaluate long-term temperature and moisture changes from aeration. Results demonstrated the possibility of maintaining optimum grain temperature and moisture content when these processes are correctly managed. The tests showed that moisture accumulation (by adsorption), but not moisture condensation, needs to be monitored for safe aeration management. Unsafe storage conditions can occur when aerating for long, or even short, periods with high relative humidity air.*

Keywords. *Grain, Aeration, Moisture content, Drying, Storage, Wheat*

INTRODUCTION

The Northwest states of Idaho, Montana, Oregon, Utah, and Washington annually produce approximately 25% of the wheat and 40% of the barley in the U.S. (USDA, 1997). Approximately half of this annual production goes directly into on-farm storage bins (Halderson, 1985; Sallukhe et al., 1985). Cereal grains, like many agricultural products, are typically at their highest quality level in most regards immediately after harvest and cleaning. During subsequent processing, storage, and transportation the products may lose significant marketable value due to quality and other losses. Typical of the Northwest is Idaho where stored wheat and barley lose almost 10 percent of their value during storage (Halderson, 1985). About half of this loss is due to quality loss in the grain and half due to selling the grain at lower than standard moisture contents.

Grain in the Northwest experiences these losses in spite of favorable naturally occurring weather conditions during the usual storage periods. The safe storage moisture content for starchy cereal seeds is below 13% (Christensen and Kaufmann, 1968), a moisture limit that varies with grain type. This moisture limit corresponds to an equilibrium relative humidity of about 65%, corresponding to the lower moisture content limit of survival for the most persistent microorganisms in grain storage (Christenson and Meronuck, 1986). Banks and Fields (1995) indicated that reducing the temperature of stored grain from field temperature to 14°C would slow the growth of most insects and pests. Lower temperatures are helpful to minimize moisture migration (Foster and Tuite, 1992). A storage temperature near 5°C and grain moisture content of

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about 12%, wet basis, give excellent control of insects and molds while maintaining maximum marketable weight.

In the Northwest (and other locations) cereal grains are generally over-dry at harvest. The average grain moisture content is significantly less than the standard allowable moisture contents, and a high percentage of the grain is harvested, stored, and finally marketed in this over-dry condition. The low moisture contents cause an economic loss since the producer's gross income is directly reduced by selling less total weight with over-dry grain. Common aeration techniques compound this problem by not limiting moisture loss during aeration. However, favorable cool aeration temperatures in the Northwest are usually concurrent with high relative humidity levels (at night) that can prevent extra moisture loss during aeration.

Aerating with high humidity air has potentially negative consequences if it causes condensation of moisture on cool grain or results in excessive moisture adsorption during aeration. However, aerating during times of optimum relative humidity may reduce or eliminate the producer's weight loss penalty. The aeration process is normally used to cool grain and stop moisture migration inside the bins by distributing the temperature inside the bin uniformly. It is preferable to start aeration in late summer in the Northwest because the usual overnight low temperatures are favorable for cooling. During fall and winter aeration, overnight low temperatures of 0°C and below are common. During the fall aeration process in warmer climates, the weather sometimes becomes warm and humid. Some moisture from this ambient air is adsorbed by the grain during aeration, but most of the moisture would be expected to condense on the grain surface according to Foster and Stahl, (1959). In the Northwest, high humidity ambient conditions tend to occur at low temperatures.

Foster and Stahl (1959) reported that grain moisture content increased in the layers within 0.3 to 1.5 m of the grain surface during downward airflow aeration in the fall and winter in both Indiana and Iowa. In Iowa, with an upward aeration process, they observed a moisture increase in the grain around the duct that resulted in grain caking. Aldis and Foster (1980) concluded that condensation on the bottom layer of grain during upward airflow is affected by basic psychrometric considerations: the difference between the inlet air dew point temperature and the grain temperature. They also stated that four additional factors significantly affect moisture transfer between the grain and air: 1) the length of the time that the grain is exposed to the air, 2) the amount of air to which the grain is exposed, 3) the humidity of the air, and 4) the difference between the temperature of the air and the grain.

Literature reviews here and by Halderson (1985) indicated that researchers with the United States Department of Agriculture (USDA) have studied stored grain aeration systems in the Hard Winter Wheat Area, the Corn Belt, the Southeast U.S., and Southwest U.S. but no research of this type has been done for grain aeration in the Northwest. However, recommendations for reducing or preventing loss has been adapted and applied from the other areas (Halderson, 1985).

OBJECTIVES

After reviewing the literature on aeration outside of the Northwest and evaluating the climatic conditions here, the objectives established for this study were to:

1. Define and evaluate the adverse (high humidity) ambient conditions that cause moisture adsorption and condensation problems when aerating over-dry grain, using laboratory tests.

2. Modify the Thompson NATAIR model for use with soft white wheat and validate the modified version with laboratory aeration tests.
3. Determine the temperature and moisture effects of long-term aeration with both moderate and high humidity ambient conditions on over-dry grain in the Northwest, using computer simulations.
4. Evaluate the potential, based on laboratory test and computer simulations, for maintaining optimum temperature and moisture content in stored grain in the Northwest by managing aeration with moderate or high humidity air.

METHODS

Adsorption and condensation experiments

Laboratory experiments were conducted to study the extent of grain wetting from moisture accumulation (by adsorption) and condensation under constant inlet air conditions during the aeration of wheat. Approximately 0.36 t of soft wheat (class SWS) was harvested in the fall of 1993 at about 9%, wet basis, moisture content and stored for about four months. Test wheat was placed in a column simulating a grain storage bin and aerated by forcing air upward through the grain mass. To monitor changes in the grain condition with respect to time and position, the moisture content of the grain and air temperature and relative humidity were measured at regular intervals and fixed heights through the grain.

A relatively high airflow rate of 0.64 m^3/min-t was used to promote greater moisture accumulation to evaluate severe moisture adsorption conditions. A lower airflow rate of 0.38 m^3/min-t was used to evaluate moisture condensation. This lower rate is at the upper end of the range in common use in the Northwest. This rate was also selected to be high to accelerate the moisture and temperature effects in the experiments. The moisture content sampling interval was limited to avoid disturbing or changing grain position in the grain bed. The sampling intervals for the adsorption tests were generally 2, 6, 12 and sometimes 60 hours. More frequent samples were taken during a few tests. A time interval of 20 minutes was selected during preliminary tests to evaluate the condensation process.

The simulated grain storage bin consisted of a wooden column open at the top, with a perforated duct and an attached humidity and temperature environmental control cabinet. All components of the system are shown in figure 1. The environmental control cabinet was an air wash system supplying conditioned air with constant dry bulb and dew point temperatures. The simulated bin was plywood with a height of 2.4 m, an inside area of 0.28 x 0.28 m, and a wall thickness of 2.5 cm. Five holes of 5 cm diameter were made at the center of two opposite sides of the simulated bin at heights of 0.05, 0.3, 0.8, 1.5, and 2.1 m.

On one side of the simulated bin, the holes were used for insertion of the temperature and humidity sensors, which were monitored with a data acquisition system. On the other side, the holes were used to take grain moisture samples. A 0.15 m diameter perforated duct with 1.33 mm diameter holes (40% open), was at the bottom of the simulated bin. A length of 1.8 m of 0.15 m diameter flexible insulated air duct connected the environmental control cabinet with the simulated bin. Air was supplied to the simulated bin using a variable speed fan to deliver the design airflow rate of 0.38-0.64 m^3/min-t. The airflow rate was monitored inside the connecting duct just before the perforated duct in the simulated bin, using a hot-wire anemometer.

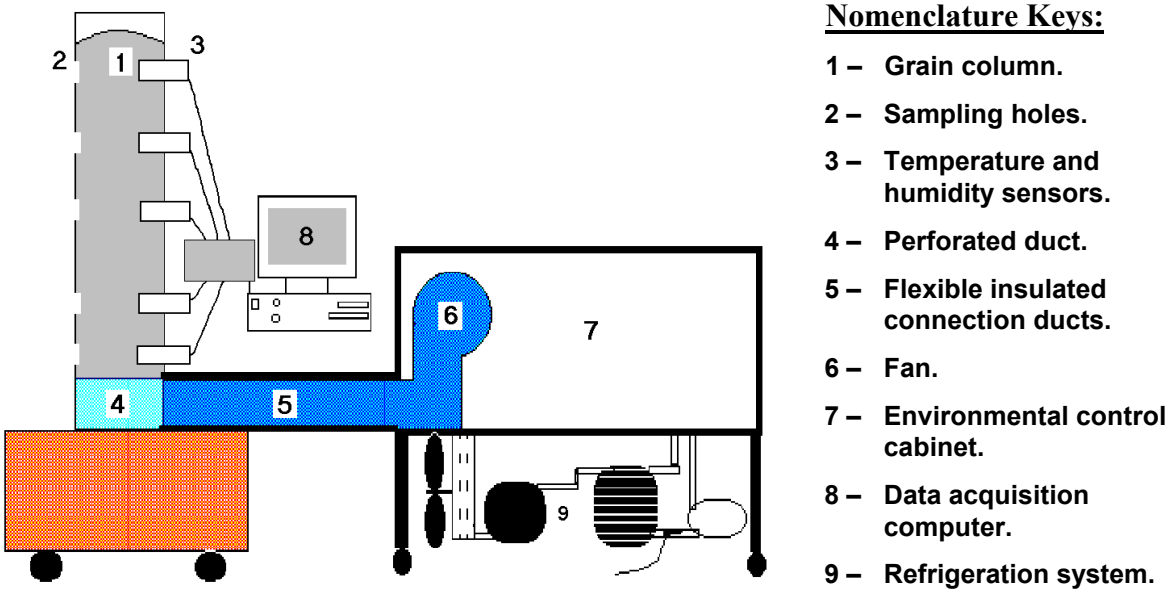

Figure 1. Laboratory apparatus used during aeration tests.

Thin-film capacitance sensors were calibrated and used for humidity measurement in the simulated bin as described in Yearsley et al. (1986), Plummer et al. (1989), and Casada et al. (1992). These sensors included integrated-circuit temperature sensors at each location. Temperatures were also monitored with thermocouples inserted at the measuring positions. The data acquisition system displayed the humidity and temperature readings continuously and recorded them at 30-second intervals.

All sample moisture contents were determined by the standard whole grain oven method (ASAE, 1994a). The relative humidity (RH) of the air produced by the environmental control cabinet was measured before entering the grain using a commercial thin-film capacitance instrument with a calibrated accuracy of ±1% RH below 90% RH and ±2% RH above 90% RH (100% NIST traceable calibration by the manufacturer—Vaisala, Inc., Woburn, MA 01801). This instrument was installed near the air inlet to the simulated bin.

Test wheat was aspirated and cleaned in two passes through a fanning mill. Random moisture content samples indicated a range of 8.5 to 8.9 percent moisture content, wet basis, before testing began. The wheat was then placed in plastic bags and stored for 2 to 3 days in a refrigerator until it was cooled to the desired temperature for the test. After each test, the small amount of grain with surface moisture was allowed to dry (most grain in the simulated bin did not adsorb significant amounts of moisture during the tests). The wheat was then poured into plastic containers and left for two days and mixed frequently by hand stirring and by pouring the grain from one container to another to insure uniformity before reuse. The grain was placed in the simulated bin by pouring it through the top opening.

Before starting each test, moisture samples were drawn from the five sampling holes. At the same time, temperatures and humidity from the same sampling positions were recorded from the thermocouples and humidity sensors. The environmental control cabinet was then configured

Table 1. Conditions for experimental tests.

Test	Test Objective	Grain Initial Moisture Content, % wb	Grain Temp. (°C)	Air Temp. (°C)	Air Dew point (°C)	Air Relative Humidity,%	Grain ERH, %	$P_g - P_a$ kPa
1	Accumulation	9.6	0.0	20.0	15.1	74	22.6	–1.59
2	Accumulation	8.5	0.0	20.0	10.0	53	17.1	–1.13
3	Accumulation	8.7	0.0	15.0	10.5	75	18.1	–1.17
4	Accumulation	9.1	5.0	20.0	15.3	75	21.4	–1.57
5	Accumulation	9.6	5.0	15.0	11.8	82	24.1	–1.19
6	Accumulation	9.1	0.0	15.0	7.2	60	20.0	–0.90
7	Accumulation	9.5	0.0	15.5	9.9	72	22.3	–1.14
8	Accumulation	9.1	0.0	20.0	15.1	74	20.1	–1.61
9	Accumulation	9.3	0.0	10.5	7.0	72	21.1	–0.79
10	Accumulation	10.0	0.0	11.0	6.6	80	24.5	–0.91
11	Accumulation	9.8	0.0	18.0	16.7	97	23.8	–1.90
12	Accumulation	10.1	2.5	13.0	11.7	97	26.3	–1.29
13	Condensation	10.0	0.0	15.0	16.7	97	24.6	–1.50
14	Condensation	9.6	0.0	10.0	8.8	97	22.7	–1.05
15	Accumulation	10.8	10.0	10.0	8.8	97	33.0	–0.79

to generate the selected dry-bulb and dew point test temperatures. The test was started by setting the fan to deliver the specified airflow rate.

Fifteen tests were selected to study the aeration of wheat. Test conditions are described by five variables as presented in table 1: initial grain temperature, initial grain moisture content, aeration air temperature, aeration air relative humidity, and vapor pressure difference. Two of the tests addressed moisture condensation conditions and the remainder studied moisture accumulation from adsorption under a variety of conditions.

Vapor pressure considerations

Moisture is transferred between the grain and surrounding air by a vapor diffusion process. The difference between the partial pressure of the vapor inside the kernel and the surrounding air is the driving force (Brooker et al., 1992). Aeration air with a lower vapor pressure (P_a) than the product vapor pressure (P_g) will tend to remove moisture from the grain. When the vapor pressure of the circulating air is higher, moisture will be added to the grain. Kanujoso (1987) developed a FORTRAN program to calculate the vapor pressure difference ($P_g - P_a$), using psychrometric equations presented by Brooker (1967), for calculation of the saturation vapor pressure of pure water.

The vapor pressure of water inside the grain kernel (table 1) was calculated using the equilibrium moisture relationship:

$$P_g = ERH * P_{sg} \tag{1}$$

ERH was originally calculated by Kanujoso (1987) using the modified-Henderson equation for soft wheat, ASAE (1994b). The FORTRAN program was modified in this study to use the

Chung-Pfost equation (ASAE, 1994b). This program was never used with the NATAIR model discussed below that used the modified-Henderson equation for ERH calculations.

Computer simulations

Mathematical simulation is a useful and important tool for studying almost every biological process. Simulation of grain aeration processes is imperative for the appropriate engineering design and improvement of such systems (Bakker-Arkema, 1985). To supplement experimental results, a mathematical model was also used to simulate the aeration process using historical weather data. The Thompson (1972) NATAIR model was modified for soft white wheat and used for simulations. The equations used in the model are listed here (definitions are listed in the Nomenclature section following the Summary and Conclusions):

The saturation vapor pressure of pure water (ASAE, 1994c).

$$P_S = R \cdot \exp\left(\frac{A + BT + C_2T^2 + DT^3 + ET^4}{FT - G_2T^2} \right) \tag{2}$$

The air relative humidity.

$$RH = \frac{P_a}{P_s} \tag{3}$$

The heat balance between the air and the grain (Thompson, 1972).

$$\begin{aligned} &0.24T_o + H_o(1060.8 + 0.45T_o) + C_pG_o + (H_f - H_o)\cdot(G_o - 32) = \\ &0.24T_o + H_f(1060.8 + 0.45T_f) + C_pT_f \end{aligned} \tag{4}$$

The moisture balance between the air and the grain (Thompson, 1972).

$$H_f - H_o = \frac{(M_o - M_f)\cdot R^*}{100} \tag{5}$$

Equilibrium relative humidity (modified-Henderson) for soft wheat (ASAE, 1994b).

$$ERH = 1 - \exp\left[-1.2299 \times 10^{-5} \cdot (T_G + 64.346) \cdot M^{2.5558}\right] \tag{6}$$

Specific heat of soft wheat (Brooker et al., 1992).

$$C_p = 1.394 + 0.0409 \cdot M_W \tag{7}$$

Dry matter-to-air ratio (see Thompson, 1972)

$$R^* = \frac{(\rho_{dm} \cdot x)}{(\rho_a \cdot V \cdot t)} \tag{8}$$

The procedure of the aeration simulation model is described by Thompson (1972). The model uses equation 8 to calculate the dry matter-to-air ratio. This ratio is a function of layer thickness, time step, and the airflow. Jindal and Siebenmorgen (1994) have discussed the importance of this ratio and the factors affecting it. For the experimental tests shown in table 1,

the R^* used for wheat with an airflow of 0.64 m^3/min-t, a 0.5 hr time step, and a layer thickness of 0.01 m was 0.4395.

Simulation of aeration using actual weather data

A bin height of 4.8 m and airflow of 0.11 m^3/min-t was simulated using the modified Thompson's NATAIR model. Weather data for Spokane, Washington was used (NOAA, 1993). The weather data was collected by the National Oceanic and Atmospheric Administration every 3 hours for the year 1993. Using an initial grain moisture content of 8.5% w.b. with the weather data, two situations were simulated (table 2). The first case was a moderate scheme designed to cool and raise the moisture of over-dry grain to normal (12–13% w.b.). The second case studied the extreme situation of cooling and raising the moisture content with no upper limit on moisture.

Table 2. Simulated conditions for aeration of over-dry grain.

Aeration fan operates when all three conditions are met:		Humidity	Temperature	Moisture
Case IA –	normal cooling (w/o drying)	$40\% < rh_{air} < 80\%$	$-2^0C < T_{air} < (T_{grain} - 2^0C)$	(assumed to be low)
IB –	normal rewetting	$40\% < rh_{air} < 80\%$	$-2^0C < T_{air} < 10^0C$	$mc_{grain} \leq 12\%wb$
Case II –	extreme rewetting (and cooling)	$40\% < rh_{air}$	$-1^0C < T_{air} < 10^0C$	any mc_{grain}
	Initial condition: T_{grain} 27°C, mc_{grain}=8.5% wb			

RESULTS AND DISCUSSION

Moisture adsorption.

The temperature difference between air and grain, the air temperature, and the air relative humidity all affected moisture adsorption largely through their impact on vapor pressure. Tests comparisons that varied only temperature difference (Tests 11, 12, and 15), only air temperatures (Tests 7 and 9), and only air relative humidities (Tests 3 and 6) are given in Alghannam (1995). Larger temperature differences, warmer air, and more moist air produced larger vapor pressure differences between the air and grain (table 1), which resulted in greater moisture adsorption. Although the vapor pressure differences tend to dissipate over time as the grain equilibrates, the larger initial vapor pressure differences always produced greater moisture adsorption. Time of aeration had a similar effect on increasing moisture adsorption. All tests conducted in this study showed greater adsorption with longer duration of aeration (see Test 15, fig. 5, for example).

Moisture condensation

Moisture condensation on stored grain is a fundamental psychrometric process, dependent on the difference between the air dew point temperature and the grain temperature. In Tests 13 and 14 (fig. 2), the 20-minute aeration period was followed by about 10 hours of monitoring

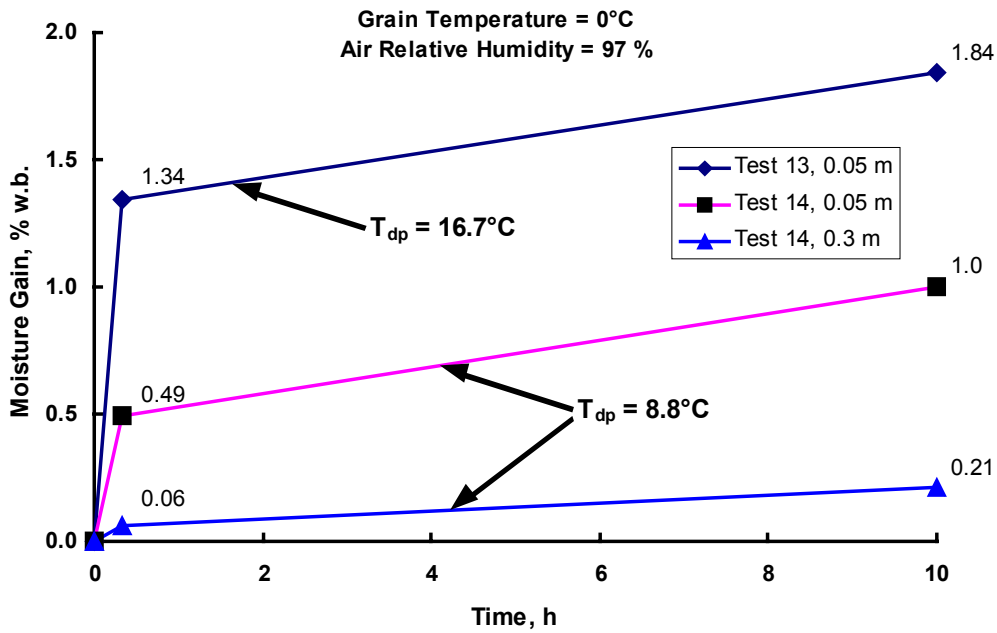

Figure 2. Moisture condensation affected by air dew-point temperature and grain depth.

conditions with the fan off. The length of aeration is seen as the peak of the reading given by the humidity sensor at a height of 0.05 m in figure 3. The test with the higher air dew point temperature in figure 2 produced a greater increase in the grain moisture from condensation as expected. The grain moisture near the entrance increased by 0.49% in 20 minutes during aeration

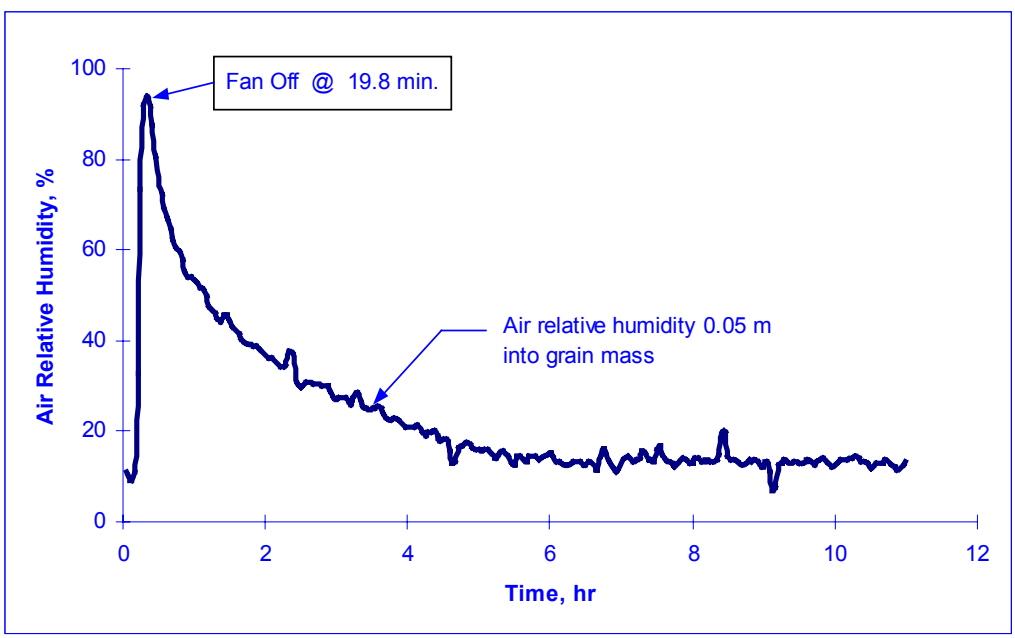

Figure 3. Moisture condensation effect as indicated by air relative humidity in Test 13.

with an air dew point temperature of 8.8°C and 1.34% in 20 minutes with air at 16.7°C dew point temperature. The grain influenced by moisture condensation was limited to the lowest 0.3 m

above the perforated duct with only a slight effect at 0.3 m during the first 20 minutes. Longer periods of condensation conditions were evaluated in preliminary tests, but the humidity still reached a peak at about 20 minutes then decreased as the grain both warmed and adsorbed moisture.

The moisture content increased both during and after the 20-minute aeration period in these condensation tests. During the initial 20 minutes there was direct moisture condensation on the grain with some of this condensate being adsorbed. During the next ten hours, some of the remaining condensate was also adsorbed, as shown by the second moisture content increase at 0.05 m. In addition, some condensate must have diffused further up into the simulated bin (shown by the second moisture content increase at 0.3 m) because of the vapor pressure gradient that existed. The humidity measurements in figure 3 also reflect this movement of condensed moisture after 20 min. The measured humidity in the interstitial air decreased from the peak, as the condensate was adsorbed, until it was again in equilibrium with grain at a low moisture content after about 6 hours. This equilibration of the humidity indicates that all of the condensed moisture had been adsorbed before the measurement at 10 hours.

There was a limited time that condensation occurred on the grain before the grain warmed to above the dew point temperature (stopping condensation) and moisture was redistributed. This indicates that aeration management could be based on the equilibrium moisture content of the air without a need to stop aeration during short periods of condensation conditions. This does not mean aeration with air at 97% relative humidity is acceptable (such a humidity results in an equilibrium moisture content well above safe levels). It does indicate that a humidity level with an acceptable equilibrium moisture content (say 12 to 13% wet basis) would not cause a serious problem solely because there is a short period of condensation on the grain.

Aeration during adverse (high humidity) weather conditions.

Foster and Stahl (1959) stated that aeration fans can be operated continuously from late summer until mid fall, except during the adverse conditions of rain and fog. This was also mentioned by Davis (1959), Halderson (1985), and others. To study the impact of operating the aeration process for periods with such adverse climatological conditions, a relatively long test, shown in figure 5, was conducted. Foggy or rainy weather conditions were simulated by an aeration process in the simulated bin with 97% air relative humidity and grain and air temperatures of 10°C. The aeration period for this test was a total of 41 hours with aeration and non-aeration alternating approximately every eleven hours except for the last aeration period of 8 hours, shown by the humidity sensor readings in figure 4.

An increase in the grain moisture content was observed during the three periods of aeration. Increases of 4.5, 6.91, 7.31, and 8.09% w.b. moisture content, respectively, were observed for the four consecutive aeration periods at the 0.05 m level. After this long period of aeration the grain was approaching an equilibrium state with the aeration air. Figure 5 also shows a decrease of moisture adsorption rate as the grain approaches the equilibrium point, which is typical of thin-layer adsorption phenomena. By the end of the experiment, grain caking was observed around the duct to the point that it was difficult to insert the sampling probe to draw the sample. As a result of the high moisture content, sprouting also appeared in the grain at the bottom of the simulated bin after the conclusion of the test.

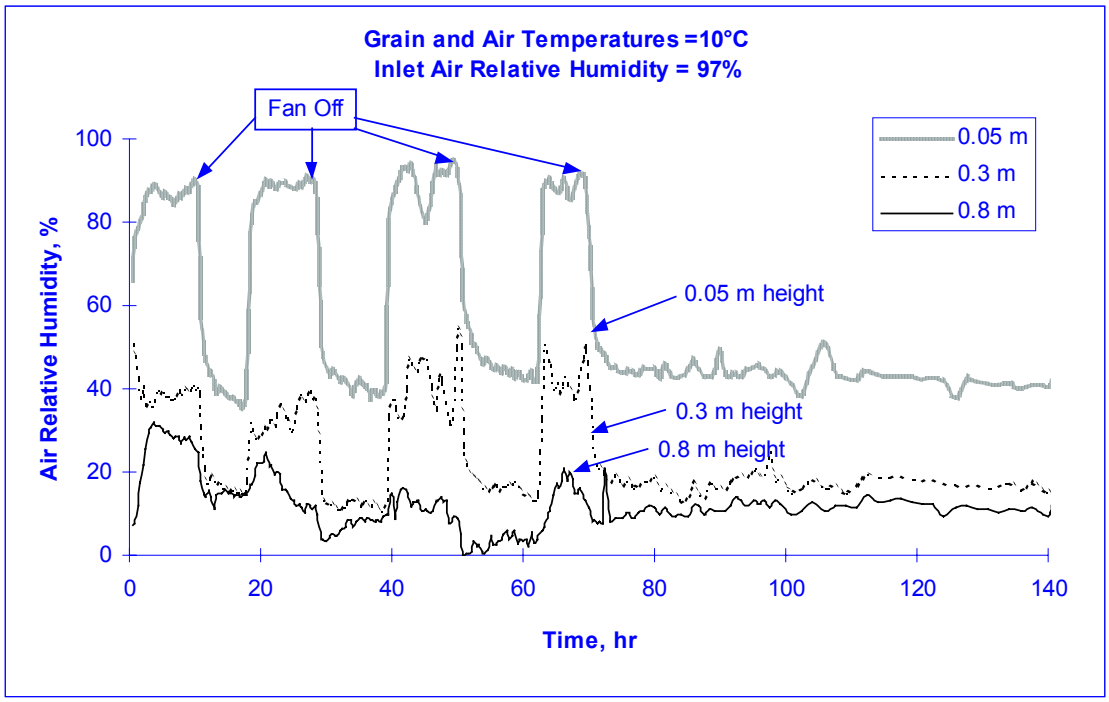

Figure 4. Moisture changes and model simulations for adverse laboratory moisture conditions.

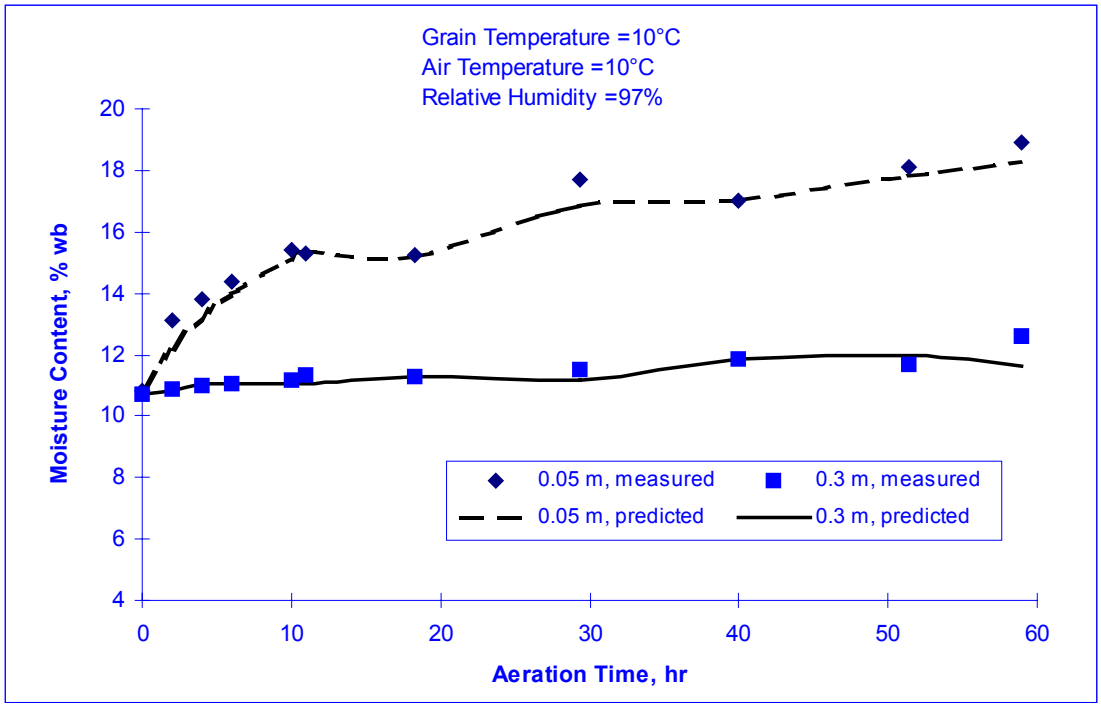

Figure 5. Interstitial air relative humidity during aeration with adverse weather conditions.

Validation of computer model

The predictions of the modified NATAIR model were compared to all of the experimental tests. Table 3 shows the average error of difference between the measured and predicted results. Results of the model simulation in figure 5 demonstrate the close agreement with the experimental results in a typical case. (This test was considered typical because it had an average difference of 0.32% moisture content, which was close to the overall average of 0.30%.) In this test, the maximum difference between the experimental results and the model prediction was 0.89% moisture content in the period of 60 hours (with 41 hours of aeration). The maximum difference for any sample for all tests was 1.66% moisture content, but the majority of test maximums (column 3, table 3) showed much less than 1% difference between the measured and predicted moisture contents. The errors can be attributed to the following factors: (1) using the same grain repeatedly may have created scattered wet spots from inadequate mixing; (2) the initial temperature of the grain between the sampling holes may have differed from the known temperatures at the holes, and which could not be included in the model prediction; and (3) the effect of the assumptions mentioned above for the model.

Table 3. Comparison of experimental moisture contents and model simulations.

Test	Average Difference* (% moisture)	Maximum Difference (% moisture)	Test Length (hr)	Number of Moisture Samples
1	0.10	0.18	2	2
2	0.46	0.85	6	4
3	0.19	0.35	6	4
4	0.26	0.41	6	4
5	0.40	0.53	6	4
6	0.32	0.56	13	6
7	0.40	0.91	13	6
8	0.35	0.59	12	6
9	0.25	0.36	6	4
10	0.47	0.97	14	6
11	0.62	1.66	6	8
12	0.41	1.34	12	14
13	0.01	0.01	0.25	1
14	0.03	0.03	0.25	1
15	0.32	0.98	60	20
Avg.	**0.30**	**0.65**		

*Average magnitude of the difference.

Simulation predictions.

The modified NATAIR model was used with weather data for the eastern Washington and northern Idaho area to simulate the aeration process. The cooling of the grain (fig. 6) was rather slow because of the simultaneous rewetting taking place. Faster cooling could be achieved if the aeration control was modified early in the season to emphasize more cooling and less rewetting while the grain is warmest. As always with aeration, the grain furthest from the entrance cooled last, so that layer of grain is a critical location for temperature monitoring with a feedback control system. The time in figure 6 is storage time, not aeration time—the fan operated only when Case IB conditions (table 2) were valid. However, longer aeration time is a characteristic of rewetting over-dry grain. This is economically viable because the benefit of the added moisture nearly always offsets the additional cost of fan operation. (Also, a feedback control system could stop the fans in those rare cases where it is not economically beneficial.)

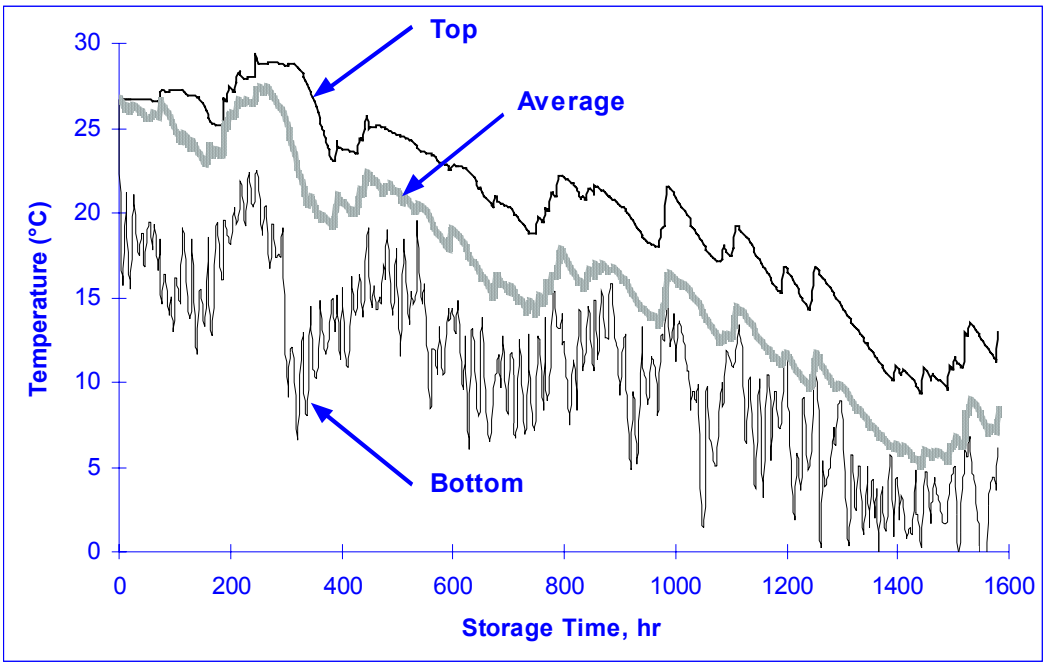

Figure 6. Temperature simulation for cooling and rewetting test.

Figure 7 shows that moisture was effectively added to reduce the amount of over-dry grain in the bin. For most of the aeration period, this control scheme effectively managed grain moisture content—raising the moisture of over-dry grain without causing excessively high (unsafe) moisture contents anywhere in the bin. However, toward the end of the aeration period, the grain at the bottom of the bin reached moisture levels that were too high for safe long-term

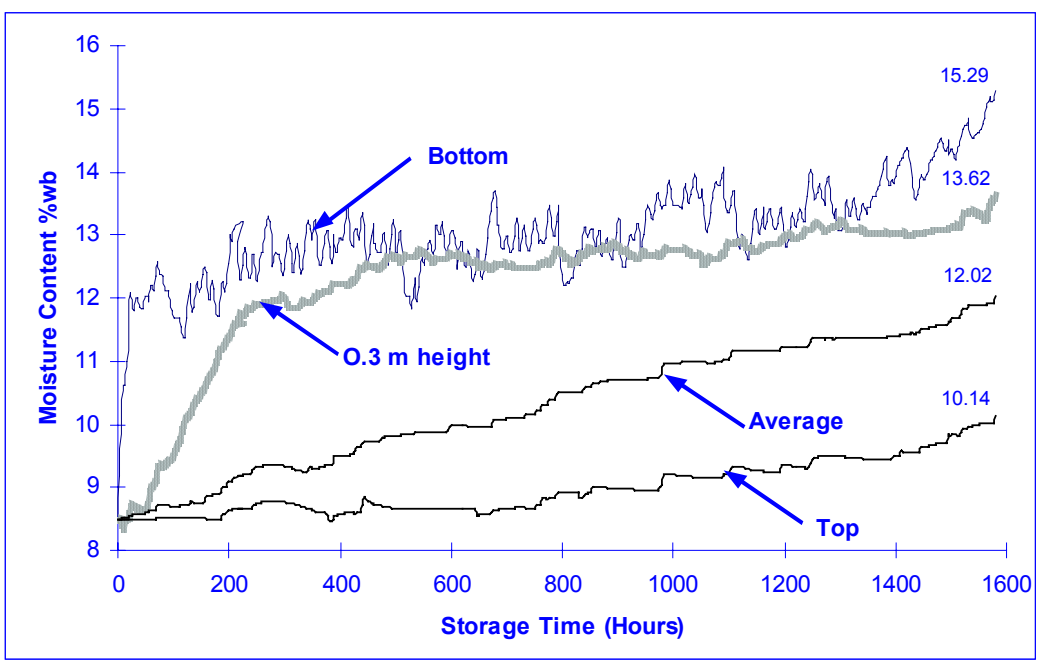

Figure 7. Moisture content simulation for cooling and rewetting test.

storage. This suggests that a more complex control scheme is needed to manage aeration for long periods. The simple scheme shown in table 2 (Case IB) does not guard sufficiently against over-wetting the first layers of grain after an extended period. The maximum relative humidity allowed by the scheme (80%) can yield an equilibrium moisture content above safe storage levels.

A feedback aeration control system could be programmed to change the aeration conditions when the wettest grain reaches the maximum permissible moisture level—12 to 13% w.b. Thus, a critical location for monitoring moisture with a feedback control system would be near the entrance where the highest moisture levels occur. This indicates a useful capability of a feedback control system. It can maximize moisture addition to dry grain and then change the aeration scheme when needed as the stored grain moisture content increases. It makes a feedback control system slightly more effective at adding moisture than existing (non-feedback) commercial technologies as reported by Casada et al. (1992). This superior performance from a feedback control system would be expected since it selects appropriate conditions for aeration based on the actual grain conditions, rather than just choosing conditions that are generally appropriate based on (reasonable) assumptions.

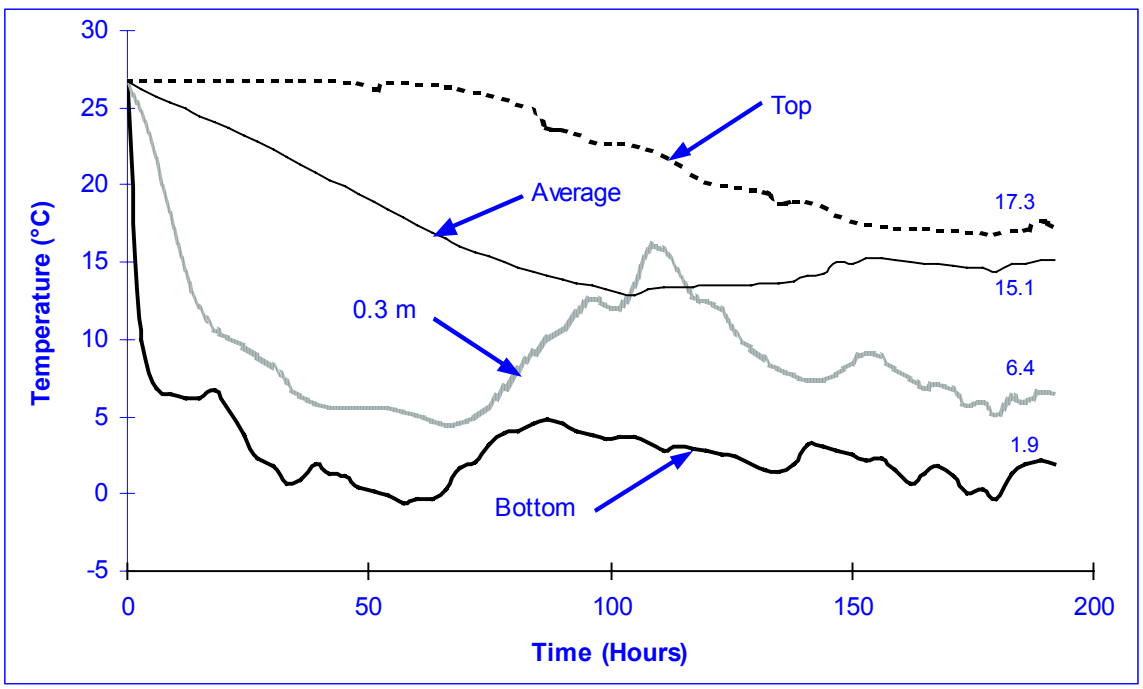

Figure 8 – Temperature simulation for aeration during adverse weather conditions.

The effect of long-term aeration during adverse weather conditions was also studied with the model. The aeration process was simulated using weather data from Spokane, WA beginning in January and starting with warm grain. These winter months typically have the combination of the highest relative humidity at the lowest temperature in the Northwest. Running the aeration fan for 195 hours (Figs. 8 and 9) caused an increase in the grain moisture content of the bottom layer from 8.5% to 17.3% and a decrease in temperature from 27°C to 2°C in the same layer. However, the cooling front was not moved completely through the grain during this time. Figure

8 demonstrates that it is quite possible to over wet part of the bin quickly (i.e., before cooling is complete) during extremely wet weather without sufficient aeration criteria and feedback control.

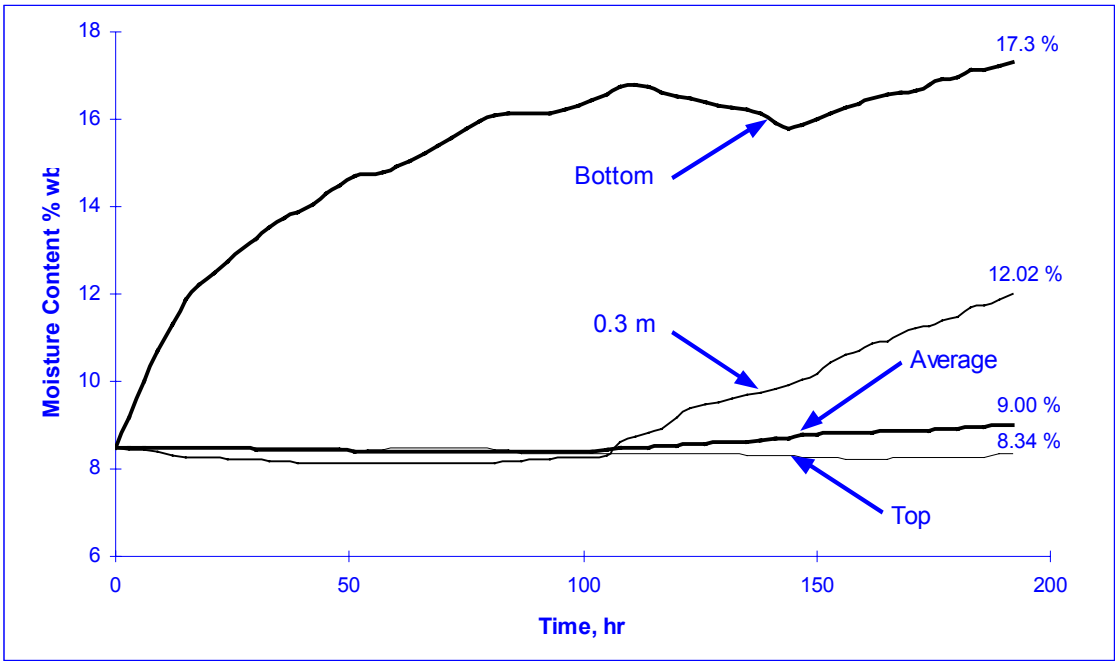

Figure 9. Moisture content simulation for aeration during adverse weather conditions.

SUMMARY AND CONCLUSIONS

Aeration of stored grain in the Northwest to maintain optimum temperature and moisture content was simulated in the laboratory and with a computer model. The feasibility of aeration with high humidity air during storage was evaluated by studying potential problems that could occur and management techniques that will limit these problems. The following conclusions were developed:

1. Larger temperature differences, warmer air, and more moist air all produced greater grain moisture adsorption during aeration because of larger vapor pressure differences between the air and grain.
2. Moisture condensation on cool grain under high humidity conditions occurred only briefly in these tests and was soon distributed through a large mass of grain at safe storage moisture contents, suggesting that aeration with high humidity air may be managed based on the equilibrium moisture content of the air.
3. The modified NATAIR Model was effective for predicting temperature and moisture changes during aeration of soft white wheat.
4. Large moisture accumulations may create unsafe storage conditions, sometimes quickly (less than 100 hours), when aerating with high humidity air, which necessitates careful control of the aeration process.
5. Aeration with air at moderate relative humidity (40% to 80%) can effectively cool the grain and maintain normal and safe moisture contents when the highest bin moisture contents are monitored to manage the aeration.

REFERENCES

Aldis, D.F. and G.H. Foster. Moisture changes in grain from exposure to ambient air. *Transactions of the ASAE.* 23(5):753-760.

Alghannam, A. 1995. *Aeration to safe rewet stored grain in the Pacific Northwest.* M.S. Thesis. University of Idaho, Moscow 83844.

ASAE Standards. 41st ed. 1994a. S352.2 DEC92. Moisture measurement—unground grain and seeds. 469. St. Joseph, MI: ASAE.

ASAE Standards. 41st ed. 1994b. D245.4 DEC93. Moisture relationships of grains. 432–436. St. Joseph, MI: ASAE.

ASAE Standards. 41st ed. 1994c. D271.2 DEC93. Psychrometric data. 44–51. St. Joseph, MI: ASAE.

Bakker-Arkema, F.W. 1985. Modeling of forced convection in in-store grain drying: the state of art. Paper presented at the International Seminar of Preserving Grain Quality by Aeration and In-store Drying, Kuala Lumpur, Oct. 9-11.

Banks, J. and P. Fields. 1995. Physical methods for insect control. In: *Stored-Grain Ecosystems.* D.S. Jayas, N.D. White, and W.E. Muir (eds.). New York: Marcel Dekker Inc.

Brooker, D.B. 1967. Mathematical model of the psychrometric chart. *Transactions of the ASAE.* 10(4): 558-560, 563.

Brooker, D.B., F.W. Bakker-Arkema, and C.W. Hall. 1992. *Drying and Storage of Grains and Oilseeds.* New York: Van Nostrand Reinhold.

Casada, M.E., D. Pietersma, A. Al-Ghannam, J.L. Halderson, J.B. Johnson, 1992. Performance of an In-Bin Moisture sensor. ASAE Paper No. 92-6506. St. Joseph, MI: ASAE.

Christensen, C.M., H.H. Kaufmann. 1968. Maintenance of Quality in Stored Grains and Seeds. Agricultural Extension Service, University of Minnesota.

Christensen, C.M. and R.A. Meronuck. 1986. *Quality Maintenance in Stored Grains and Seeds*. Minneapolis: University of Minnesota Press.

Davis, E.H. 1959. A study of climatological data to determine the feasibility of drying Idaho grain corn with natural unheated air. M. S. Thesis, University of Idaho, Moscow 83844.

Foster, G.H. and B.M. Stahl. 1959. Operating grain aeration systems in the corn belt. Mkt. Res Rep. 337. Washington: U.S.D.A.

Foster, G.H., and Tuite. 1992. Aeration and stored grain management. In: *Storage of Cereal Grains and Their Products.* D.B. Sauer (ed.) St. Paul, Minnesota: AACC.

Halderson, J.L. 1985. Results of a grain storage study in Idaho. *Transactions of the ASAE.* 28(1):246-250.

Jindal, V.K., and T.J. Siebenmorgen. 1994. Simulation of low temperature rough rice drying and rewetting in shallow beds. *Transactions of the ASAE.* 37(3):863-871.

Kanujoso, B.W. 1987. Analysis of rough rice aeration under tropical conditions. Ph.D. Dissertation. Kansas State University, Manhattan.

NOAA. 1993. Local Climatological Data, Spokane, WA. National Oceanic and Atmospheric Administration.

Plummer, D.J., C. Grinstead, J.E. Dixon, and J.L. Halderson.1989. Temperature and relative humidity data acquisition system for aerated grain storage. ASAE Paper No. 89-408. St. Joseph, MI: ASAE.

Sallukhe, D.K., J.K. Chavan, and S.S. Kadam. 1985. *Postharvest Biotechnology of Cereals.* Boca Raton, FL: CRC, Inc.

Thompson, T.L. 1972. Temporary storage of high-moisture shelled corn using continuous aeration. *Transactions of the ASAE*. 15(2):333-337.

USDA. 1997. *Agricultural Statistics 1997.* U.S.D.A. Washington: U.S. Government printing Office.

Yearsley, G., M.R. Johnson, H. Kuhr, and J.L. Halderson. 1986. Electronic design of aeration controls with feedback. ASAE Paper No. 86-305. St. Joseph, MI: ASAE.

NOMENCLATURE

Constants for equation 2:

$A = -27405.526$	$D = 0.12558E\text{-}3$	$G_2 = 0.039381$
$B = 97.5413$	$E = -0.48502E\text{-}7$	$R = 22{,}105{,}649.25$
$C_2 = -0.146244$	$F = 4.34903$	

C = constant for modified-Henderson equation

ERH = equilibrium relative humidity, decimal or percent

G = grain temperature, °F for equation 4

H = absolute humidity of air, kg water per kg dry air

K = constant of modified-Henderson equation

M = moisture content, percent dry basis

M_w = moisture content , decimal wet basis

N = constant of modified-Henderson equation

P_a = partial pressure of water vapor in the air, Pa

P_g = partial pressure of water vapor in the grain, Pa

P_s = saturation vapor pressure of pure water at T, Pa

P_{sg} = saturation vapor pressure of pure water at grain temperature, Pa

R^* = dry matter-to-air ratio, kg dry matter per kg air

RH = relative humidity, %

T = air temperature, °C (°F in equation 4)

T_g = grain temperature, °C

C_p = specific heat of soft wheat kJ/kg-C (Btu/lb-°F in equation 4)

Subscripts: o = initial value
f = final value