MODELING TEMPERATURE AND MOISTURE CONTENT CHANGES IN BUNKER-STORED RICE

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ABSTRACT

A two-dimensional model that describes the temperature and moisture content changes for a bunker storage unit was developed. Various combinations of initial grain temperatures, initial grain moisture contents, and loading dates were used to determine any advantages or disadvantages of each. Temperature and moisture content contour plots, dry matter loss, and condensation data were analyzed.

The effects of only the loading dates on dry matter loss appeared to be minimal for all combinations tested. Relatively high dry matter loss values were experienced at the extreme temperature/moisture content combination of 30° C and 15% (w.b.). The combined effect of high initial temperatures and moisture contents resulted in an appreciable amount of moisture migration to the peak of the bunker cross-section making this area more susceptible to spoilage and microbial activity.

INTRODUCTION

Conventional storage involving the use of concrete and/or metal bins is the most commonly used storage technique in the United States and, until recently, was the only means of storage and preservation used. With the onslaught of surplus grain, a storage and preservation technique new to the U.S. has been introduced from Australia. This technique is called 'controlled atmosphere storage' and is also referred to as 'bunker storage'. In this article, controlled atmosphere (CA) storage implies that tht interstitial atmosphere of a product consists of lower than normal concentrations of oxygen (O_2) and higher than normal concentrations of carbon dioxide (CO_2) resulting from respiration in an air-tight environment. A more detailed description of bunker storage systems can be found in Siebenmorgen et al. (1989).

LITERATURE REVIEW

Haugh and Isaacs (1967) report that movement of gases in any porous media such as grain is caused by pressure, temperature, and gas concentration gradients. They also report that pressure gradients in a sealed storage are caused by atmospheric pressure and temperature changes. Finally, they state that the effects of diurnal and shorter-time temperature changes are more pronounced than those due to atmospheric pressure change especially in sealed storages.

The heat and mass transfer processes within a bunker storage are driven by temperature and moisture content differences. Processes which create temperature changes include respiration of the grain and of any insects and/or mold that are present. Because the respiration rate of grain increases with temperature, and because the respiration process produces energy, locations with elevated respiration rates can have significanatly higher temperature and moisture content levels than the rest of the grain in the bunker. Person et al. (1966) state that grain temperature is of primary concern during storage, as quality can be maintained over a wide range of moisture contents if the grain temperature is in the 10 to 15° C range. This is not interpreted to mean that the moisture content of the grain can be ignored but that the grain temperature plays the more significant role.

Another significant thermal process is the solar input at the bunker surface. This is an ever-changing process that is difficult to predict because of the many factors involved, including bunker orientation, geographical location, the solar absorptance/reflectance properties of the cover material, windspeed, and cloudiness factors. However, Babbit (1945) concluded that with a diurnal temperature change of 11° C, temperature variations in a large mass of wheat were present only to a depth of 15.24 cm (6 in.) from the grain surface. He also stated that these temperature changes cause convection currents within the grain mass and are the major driving force behind the movement of gas within a grain mass.

Respiration of grain, insects, and/or molds, in addition to producing thermal energy, can also produce water vapor and, thus, affect moisture content. Moisture content can further be affected by the process of moisture migration. This process, driven by vapor pressure gradients, has the effect of removing small amounts of water vapor from the total grain mass and depositing them in a relatively small area (Stewart, 1975).

Another process affecting moisture content is condensation underneath the bunker cover along the surface of the grain. This generally occurs in the fall when the outside air temperature decreases while the grain mass is still warm.

Grain spoilage, insect growth, and mold growth are accelerated by heat and moisture accumulation. Temperature gradients caused by outside air temperatures can cause vapor pressure gradients resulting in moisture migration to a given area, making

Article has been reviewed and approved for publication by the Food and Process Engineering Div. of ASAE. Presented as ASAE Paper No. 88-6050.

Published with the approval of the Director, Arkansas Agricultural Experiment Station.

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this area highly susceptible to spoilage. Modeling the heat and mass transfer processes within a grain mass in a bunker could be used to evaluate various options concerning the management of bunker storage units.

Objectives

The objectives of this research were to:

1. Adapt an existing computer model to simulate heat and mass transfer within rough rice in bunker storage under Arkansas climatic conditions.
2. Use the model to predict the effect of various storage parameters as a means of providing management information for a bunker storage system. To achieve this objective, the following sub-objectives were formulated.
   a. Develop a procedure to estimate dry matter loss to be used as a grain quality indicator.
   b. Analyze the effects of loading date, initial grain temperature, and initial grain moisture content on dry matter loss.
   c. Investigate areas within the bunker where the probability of grain spoilage, molding, and insect activity would be the greatest.
   d. Evaluate the potential for moisture condensation on the grain surface underneath the bunker cover.

Model Description and Assumptions

The original model used in this research was obtained from Dr. T. V. Nguyen, a research scientist with the Commonwealth Scientific and Industrial Research Organization (CSIRO) of Australia. This Fortran-based model simulated the two-dimensional temperature and moisture changes in a bunker-type storage unit (Nguyen, 1986a). His original model was applicable to the storage of wheat and is listed in Freer (1988). The model was revised and expanded to simulate the two-dimensional temperature and moisture changes in rough rice under Arkansas climatic conditions.

Model Theory

The governing momentum, mass, and energy differential equations that describe the heat and mass processes occurring within the bunker unit were solved numerically. The detailed equations and the method of solution can be found in Nguyen (1986a).

Time Step

The original model allowed the simulation time step to be varied. In the process of modifying the originial model, a time step of 24 h was chosen. A consideration for choosing this value was that a reasonably accurate average daily temperature distribution could be determined from available weather data, and a daily basis provided a convenient format.

Because grain is a good insulator, it has a dampening effect on diurnal ambient air temperature variations at depths greater than six inches (Babbit, 1945). Therefore, the effects of neglecting the solar input during the day and the heat loss during the night were considered minimal in relation to the long-term effects caused by seasonal daily temperature variations. As such, a 24-h time step was used and the solar heat input during the day as well as the heat loss during the night were neglected.

Boundary Conditions

It is necessary to know the air temperature surrounding the bunker to accurately predict temperature differences between the grain within the bunker and the atmosphere surrounding it. A temperature distribution equation was developed to predict the average daily outdoor air temperature throughout the entire year. The general form of the equation is

$$T = A + B\cdot\cos[2 (J - C)/D] \qquad (1)$$

where

T	=	average daily temperature,
A, B and C	=	constants for a given geographical area,
D	=	period of the wave (365.25 days),
J	=	day of the year (Julian).

The 30-year monthly temperature normals from a weather station in Newport, Arkansas (NOAA, 1983) were used to determine the values of the three constants using a least-squares regression analysis. Data from Newport were chosen so that the model would be applicable to the surrounding areas in which a number of bunker storage units are presently located. In order to perform the regression, an assumption was made that the 30-year monthly normal occurred in the middle of each month. These values, the 30-year monthly normals, and other data from the regression analysis are shown in Table 1.

The values predicted by the outdoor air temperature equation were assigned to be the temperatures at the boundary between the atmospheric air and the grain surface. At the end of each 24-h time step, the average daily outdoor air temperature and, thus, the boundary condition, was updated. Since the bottom of the grain mass is exposed to the ground, this boundary temperature was considered to be a constant 18° C (68° F) based on eastern Arkansas soil temperatures.

TABLE 1. Weather data and regression analysis results for determining the average daily temperature distribution

Mid-Month Julian Day	30-Year Monthly Aug. Temperature (° C)	Predicted Monthly Avg. Temperature* (° C)	Temperature Difference Squared
15	3.2	4.1	0.81
45	5.6	5.6	0.00
74	10.4	9.7	0.49
105	16.6	15.7	0.81
135	21.2	21.5	0.09
166	25.4	26.0	0.36
196	27.3	27.7	0.16
227	26.2	26.2	0.00
258	22.5	21.8	0.49
288	16.5	16.0	0.25
319	10.1	10.0	0.01
349	5.2	5.7	0.25
		Sum =	3.72

*Using equation (1) with A = 15.9, B = 11.8 and C = 197.4

Changes Within the Original Model

The original model used the properties of wheat rather than rough rice; therefore, two primary changes had to be made to make the model applicable to rough rice. The first change involved the ratio of the latent heat of vaporization of water in the grain to that of free water. Nguyen (1986b) states this ratio for rough rice as

$$h_s / h_v = 1 + 2.566\exp(-20.176M) \quad (2)$$

where

h_s = latent heat of vaporization of water in grain,
h_v = latent heat of vaporization of free water,
M = grain moisture content, decimal dry basis.

The second change made in the original model involved the calculation of the equilibrium relative humidity (ERH) of rough rice. Chung's equilibrium relative humidity equation with associated coefficients for rough rice (ASAE, 1986) was employed:

$$ERH = \exp\{[-A/(T+C)]\exp(-BM)\} \quad (3)$$

where

A = 594.61 (constant for rough rice),
B = 21.732 (constant for rough rice),
C = 35.703 (constant for rough rice),
M = grain moisture, decimal dry basis,
T = grain temperature, ° C.

Contour Plots

The original model had the capability to construct approximate contour maps. These maps were difficult for the user to understand. A contouring software package was used to construct a more detailed contour plot of the significant variable arrays within the program.

Input Variables

The values of 35 variables were input to the program. These variables included grain thermal properties, bunker dimensions, initial grain temperature, and initial moisture content. The model is intended to apply to bunkers of the scale described by Siebenmorgen et al. (1989). Typical dimensions of these units are 30m in width by 90 to 120m in length, having a capacity of approximately 18 000 m^3. Restrictions as to dimensional limits of the model were not investigated. All required air, water, and rough rice properties, except the bulk thermal conductivity of long-grain rough rice, were found in the literature. The conductivity values for short-grain and medium-grain rough rice at 13% wet basis (w.b.) MC are reported as 0.114 W/m·K and 0.104 W/m·K, respectively (ASAE, 1986). As a result of a sensitivity analysis described in Freer (1988), the bulk thermal conductivity was found to have little effect on model results. Thus, the thermal conductivity value for medium-grain rough rice was used in the model.

Dry Matter Loss

The generally accepted definition of rough rice dry matter is all material, including hulls, that remains after all water has been removed. Therefore, if the moisture content of a sample is known, the amount of dry matter within that sample can be readily determined. Respiration is the process of oxidizing (combusting) carbohydrates and yielding carbon dioxide, water vapor and energy. Therefore, respiration consumes dry matter.

Seib et al. (1980) state that the amount of dry matter loss (DML) from respiration is an indication of grain quality. They also state that rough rice stored at 15% and 18% w.b. MC fell below U.S. Grade Nos. 1 and 2 if DML exceeded 0.75%. Furthermore, they developed the following expression to determine the DML of rough rice as a function of grain temperature, grain moisture content, and storage time:

$$DML = 1 - \exp\{-At^C\exp[D(T-60)]\exp[E(M-0.14)]\} \quad (4)$$

where

DML = dry matter loss, decimal form,
t = storage time, h/1000,
T = grain temperature, ° F,
M = grain moisture content, decimal wet basis,
A,C,D & E = constants.

Equation 4 was developed for long-grain rough rice with a constant airflow being forced through the grain sample. However, bunker storage units described by this model are governed by static, non-aerated conditions. Only natural convection air currents would be present. Storage of rice in air-tight units is a relatively new process, and no applicable research could be found regarding DML under these static conditions. Since the respiration process consumes O_2 and since bunker storage units are theoretically airtight, a shortage of O_2 would decrease the respiration rate as well as decrease the rate of DML. Therefore, for bunker conditions, equation 4 would be expected to over-estimate the actual DML since it was based on the premise of having adequate O_2 to be used by the respiration process. In the program, equation 4 was used as the basis for calculating the relative DML values for all simulation runs tested. Therefore, conclusions based on absolute DML values cannot be drawn.

Seib et al. (1980) determined the constants of equation 4 for both medium-grain and long-grain rough rice using a non-linear, least-squares regression analysis. The values of the constants for long-grain rough rice used in this model were found to be

A = 0.001889,
C = 0.7101,
D = 0.02740,
E = 31.63.

Another critical assumption of equation 4 is that grain under consideration starts with 100% dry matter. Also, the particular grain moisture content and temperature that are used within the equation are assumed to be constant over the storage time interval used. These assumptions must be considered when determining the value of the input variables of the equation in order to utilize it in the most appropriate manner within the rice bunker model.

One possible way to determine the values of the input variables T and M of equation 4 is to use the average grain temperature and the average grain moisture content over the storage time in question. This approach could lead to inaccurate results because of the inherent assumption that the rate of change of DML is constant (linear) with respect to time, when in fact it is exponential. A second way of determining the most appropriate values of the input variables to equation 4 is to use a DML rate that involves determining the derivative of the DML equation with respect to time. The resulting derivative would be the rate of DML and is computed from equation 4 as

$$d(DML)/dt = ACt^{(C-1)}c^{y}c^{z}c^{-xc^{y}c^{z}} \tag{5}$$

where

$x = At^{c}$,
$y = D(T-60)$,
$z = E(M-0.14)$.

The procedure for utilizing this approach was to use the current grain temperature and the current grain moisture content in equation 5 to determine the rate of DML at a particular point of time in the simulation. The rate of DML was then multiplied by the current time step to determine the DML over that time step interval. The cumulative DML for a simulated period was determined by summing these individual DMLs from the beginning of the simulation period. The use of rates should be more accurate than the use of averages because the grain temperature and moisture content are not assumed constant for the entire storage time used. Therefore, the method of rates was used to calculate DML.

Experimental Design

Thirty-five input variables are utilized by the program and are listed in Freer, 1988. Of these 35, the following were chosen for evaluation:

1. initial grain temperature,
2. initial grain moisture content,
3. loading date.

These three were selected because the bunker operator has a certain amount of control over the values of each.

Initial Grain Temperature

Grain temperatures of 10, 20, and 30° C were chosen as representative at the time of loading. This wide range of temperatures allowed for testing the advantages and disadvantages of high and low initial grain temperatures. It should be noted that even though the initial grain temperature was treated separately from the loading time, the grain temperature at the time of loading is highly dependent on the seasonal time of loading.

Initial Grain Moisture Content

Insofar as conventional storage is concerned, 13% w.b. MC is generally accepted as being a safe storage moisture content level for rice. Therefore, is was decided to model the bunker unit at 13%, at a moisture content level slightly above 13% (15%), and at a moisture content slightly below 13% (11%). Unless otherwise noted, all grain moisture contents are on a wet basis.

Loading Date

A major purpose of using bunker storage units is to provide storage for the new rice crop that is harvested from August to October. Therefore, 1 August (Julian day = 213) was chosen as a practical day for a loading date. Also, in years in which a large crop would be harvested, additional storage volume would be necessary during or soon after the harvest season. Therefore, 15 October (Julian day = 288) was chosen as another loading date. Finally, 1 April (Julian day = 91) was chosen so that representative results of loading the bunker in the spring could be ascertained. This alternative is not as practical as the other two, but it could be used if enough advantages could be gained.

Storage Duration

A simulation period length of 12 months was chosen for all runs. This value was chosen so that the bunker would be exposed to the full range of outside air temperatures. Also, 12 months was a convenient and practical storage length.

In summary, the storage duration chosen was 12 months. The three values chosen for loading dates were 1 April, 1 August, and 15 October. The three values chosen for initial grain temperature were 10, 20, and 30° C. The three values chosen for initial grain moisture content were 11, 13, and 15%. The three sets of three variables represent 27 possible combinations of initial conditions.

Results and Discussion

Dry Matter Loss Analysis

The original model utilized a 41 by 21 array or grid to designate inidividual locations within the bunker. There were 41 grid points in the x-direction and 21 grid points in the y-direction. DML values for four grid points representing both critical and representative areas within the bunker were compared in each initial condition (IC) combination. Figure 1 illustrates the location of these grid points (labeled as points 424, 438, 518, and 598) within the 41 by 21 array used in the model. Of the four grid point locations chosen, one was in the peak of the bunker where the biggest problem area was observed to occur. The other three grid point locations chosen were in the lower center of the bunker, the midpoint of the right side and on the surface approximately halfway between the bottom corner and

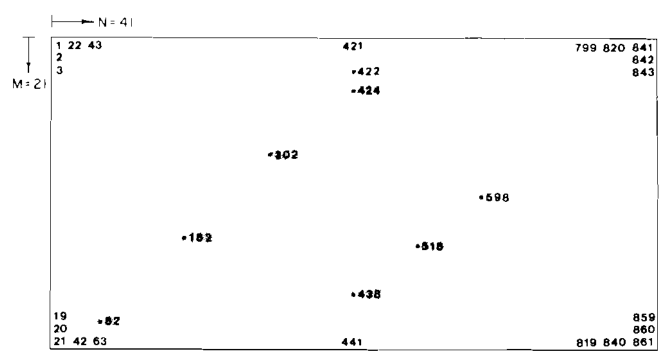

Figure 1-Cross-section of a bunker storage unit with grid orientation. Grid consisted of 41 points (N) in the x-direction and 21 points (M) in the y-direction.

the top. These three were chosen so as to yield realistic and logical comparisons between the conditions in various locations of the bunker. The cumulative DML values resulting from the ICs used in the simulation were normalized to facilitate comparison. The normalization procedure involved expressing each DML value as a percentage of the maximum DML attained from all sets of ICs in the experimental design. The maximum DML value of 2.554% resulted from an initial grain temperature of 30° C, an initial grain MC of 15% and a loading date of 15 October. Tables 2, 3, and 4 display the normalized DML values for various initial temperature and MC conditions and loading dates of 1 April, 1 August, and 15 October, respectively. The normalized DML values were used in the following sections to evaluate the effects of initial grain temperature, initial grain MC, and loading date.

LOADING DATE — DML EFFECTS

To determine the effects of loading date, the DML results from each combination of initial grain temperature and MC were combined for each of the three loading dates. For the IC combination of 10° C and 11% MC, the widest range of normalized DML values for any one of the four grid point values over all three loading dates was 10.6 to 12.3%, occurring at grid point 424. Therefore, varying the loading date produced a difference of less than two percentage points of DML for this temperature and MC combination. Likewise, for 20° C and 13% MC, the largest difference was 26.2 to 29.5% (at grid point 598), which was less than four percentage points of normalized DML for any one of the grid point values over all three loading times. After further examination in this manner, the largest difference in the normalized DML values for any one of

TABLE 2. Normalized cumulative dry matter loss (DML)

Initial Grain MC	Initial Grain Temperature (°C)											
	10				20				30			
	Bunker Grid Points											
(% wb)	424	438	518	598	424	438	518	598	424	438	518	598
11	12.3	11.0	10.2	13.0	16.8	16.1	16.4	15.7	26.3	23.3	26.4	19.0
13	23.1	20.5	19.1	24.4	31.6	30.2	30.9	29.5	50.0	43.8	49.6	35.9
15	43.4	38.4	35.8	45.6	59.2	56.8	57.9	55.4	94.6	82.5	93.0	67.7

*Values for 1 April loading date.
†These DML values are a percentage of the maximum DML value attained for all initial conditions tested. (The maximum DML value of 2.554% resulted from an initial grain temperature of 30° C, an initial grain MC of 15%, and a loading date of 15 October).

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13	20.6	20.5	19.0	22.5	30.2	30.1	30.7	27.4	52.0	43.2	49.3	33.6
15	38.5	38.4	35.7	42.1	56.9	56.5	57.6	51.4	98.7	81.4	92.4	63.4

*Values for August 1 Loading Date.
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13	19.9	20.6	19.0	21.8	29.8	30.1	30.6	26.2	52.5	42.9	49.1	31.7
15	37.3	38.4	35.6	50.8	56.3	56.5	57.5	49.1	100.0	80.8	92.1	59.7

*Values for 15 October loading date.
†These DML values that are a percentage of the maximum DML value of 2.554% resulted from an initial grain temperature of 30°C, an initial grain MC of 15%, and a loading date of 15 October).

the four grid point values over all three loading dates was eight percentage points (59.7 to 67.7%), which corresponded to the ICs of 30° C and 15% MC at grid point 598.

None of the three loading dates tested yielded consistently higher DML values over the other two. No correlation was detected that would indicate that any one of the three loading dates was significantly better or worse than the other two. Therefore, the effects of loading time appear to be minimal. This being the case, the DML values resulting from one loading date were thoroughly examined, and any conclusions drawn from this examination were considered applicable to the DML data resulting from all three loading dates.

Initial Grain Temperature and Moisture Content — DML Effects

Table 3 displays the normalized DML values for a 1 August loading date. Figure 2 is a graphical representation of the normalized cumulative DML values for grid points 424, 438, 518, and 598 from Table 3. The additional DML that resulted from increasing the initial temperature from 20° C to 30° C was significantly more than the additional DML that resulted from increasing the initial temperature from 10° C to 20° C. Likewise, increasing the initial MC from 13% to 15% resulted in a larger increase in DML than increasing the initial MC from 11% to 13% at a given temperature, as would be expected given the exponential form of equation 4.

The initial grain temperature and MC combination of 10° C and 11% MC resulted in the lowest DML of the combination tested. The combination of 30° C and 15% MC resulted in the highest DML values for all grid locations considered incurring 6-10 times as much loss as the combinations of 10° C and 11% MC. Within these two extremes, the other seven temperature and MC combinations had DML values that were located in the middle and lower portion of the range outlined by these two extremes. In other words, the combination of 30° C and 15% MC that resulted in the highest DML values was isolated on the upper extreme of the outlined DML range; no other combinations tested produced DML values that were in the upper third of the outlined DML range. The combination of 20° C and 15% MC had DML values of only slightly more than half the magnitude of those at the upper extreme of the DML range, while the combination of 30° C and 13% MC incurred about half as much DML as the combination of 30° C and 15% MC. All other combinations resulted in DML values that were no more than about 40% of those at the upper extreme.

It would be difficult to conclude that any one temperature and MC combination is optimum regardless of other factors. From an economical standpoint, the combination that yields the least amount of DML would be best. However, all combinations of temperature and MC are not probable for any given time of the year. For example, an initial grain temperature of 10° C on 1 August is not a viable possibility, since the bunker operator probably could not produce this condition. Recall from equations 4 and 5 that the DML rate is directly related to grain temperature and grain MC. Therefore, to minimize DML the grain must be cooled and/or dried. The expense involved in this process may or may not be worth the advantage in suffering less DML, depending on how much reduction in DML could be attained from aerating the grain. In any situation, the temperature and MC combination utilized by the bunker operator would depend on the amount of DML that he was willing to accept within the physical constraints of producing certain conditions.

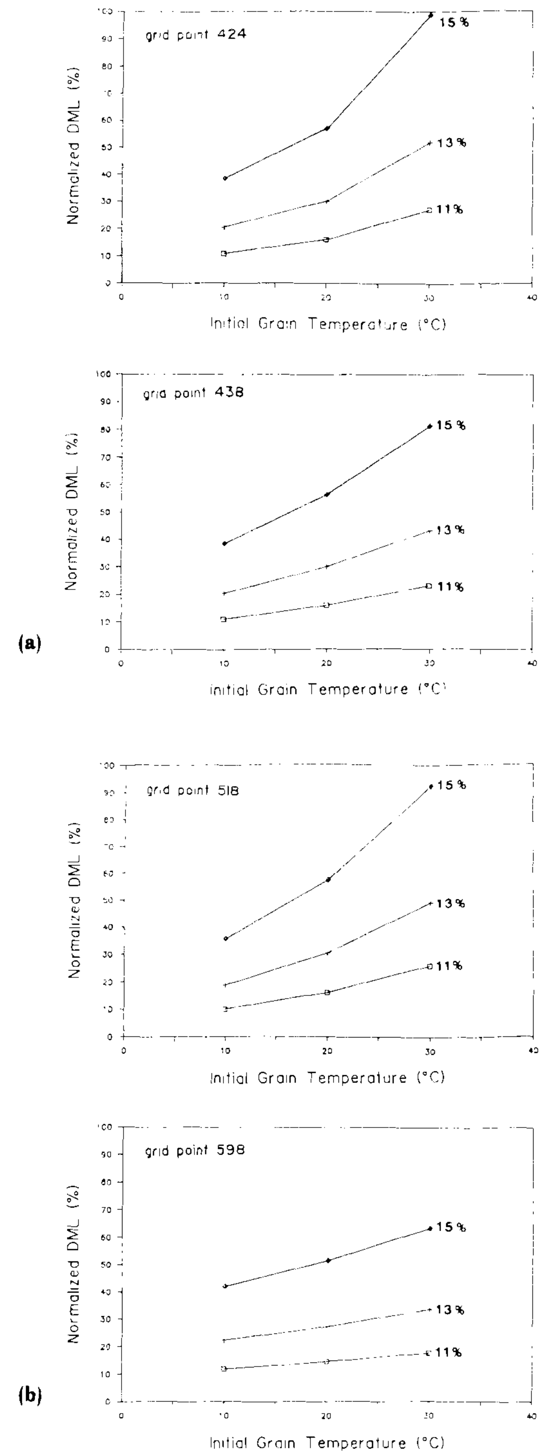

Figure 2-Normalized cumulative dry matter loss values after one year of simulating for a loading date of 1 August at grid points 424, 438, 518, and 598 of Table 3.

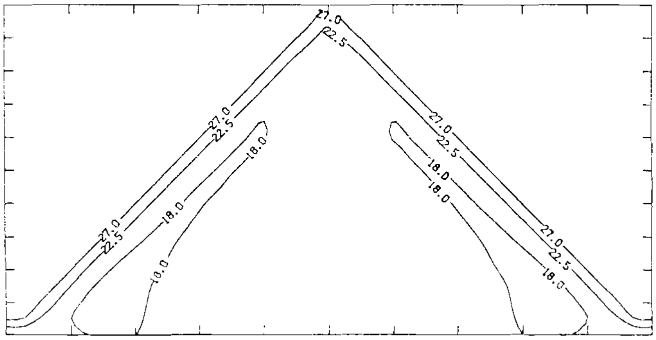

Figure 3-Temperature contour plot after one year of simulation consulting from an initial grain temperature of 20° C, an initial grain moisture content of 13% and a loading date of 1 August.

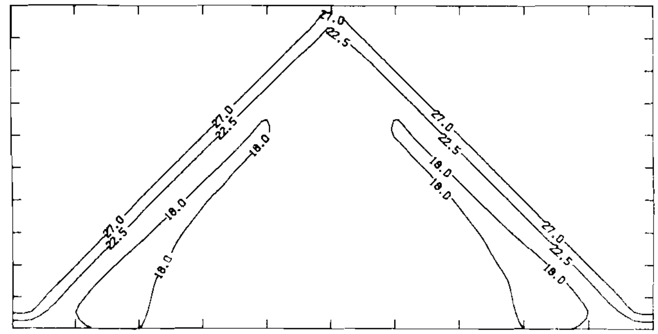

Figure 5-Temperature contour plot after one year of simulation resulting from an initial grain temperature of 20° C, an initial grain moisture content of 15% and a loading date of 1 August.

Contour Plots

A qualitative method of evaluating the effects of grain temperature and MC is through the use of contour plots. These plots were used to show the temperature and MC distribution within the bunker at the end of a simulated time period.

Temperature Contour Plots

A typical temperature contour plot is displayed in Fig. 3. For this plot, the initial grain temperature was 20° C, the initial grain MC was 13%, and the loading date was 1 August (Julian day = 213). After a one-year simulation, the bulk of the grain mass was still very near the initial grain temperature of 20° C. Therefore, for this set of ICs, the temperature of the bulk of the grain mass had changed very little except near the surface where the warmer outside air temperatures that were present at the end of the simulation run were the controlling factor. Figure 4 depicts the contour plot resulting from the ICs of 20° C, 13% MC, and a loading date of 15 October (Julian day = 288). As in Fig. 3, the bulk temperature of the grain mass was still about the same as the initial grain temperature (20° C) except near the surface, as before. The temperature contour plot corresponding to the ICs of 20° C, 15% MC, and 1 August is displayed in Fig. 5. This graph is very similar to Fig. 3 in regards to the temperature distribution.

Figure 6 depicts the temperature contour plot that resulted from using the ICs of 30° C, 15% MC, and 1 August loading date. This set of ICs should be the most adverse that the grain would be subjected to under any reasonable storage practice. Notice that the warmest

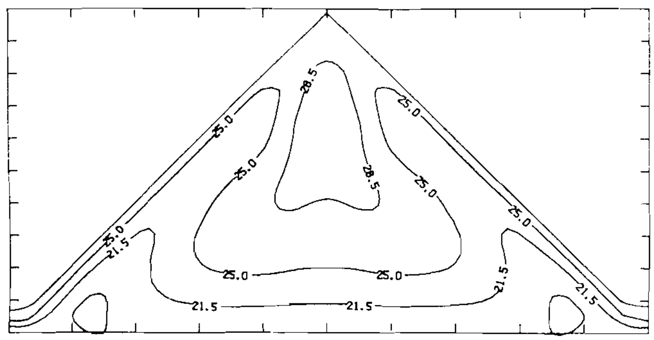

Figure 6-Temperature contour plot after one year of simulation resulting from an initial grain temperature of 30° C, an initial grain moisture content of 15% and a loading date of August 1.

area of the grain mass was in the top-center of the bunker. Because grain spoilage and the DML rate increase with increasing temperature, the upper-middle section of the grain was most likely to incur the highest amount of DML and grain spoilage because of the elevated temperature. The simulation results (Freer, 1988) indicate that changing the MC from 13% to 15% while holding all other parameters equal did not appear to greatly affect the resulting temperature distribution within the bunker.

Moisture Content Contour Plots

A typical MC contour plot of the bunker resulting from a one-year simulation period is presented in Fig. 7. The ICs for this plot were 20° C, 13%, and 1 August.

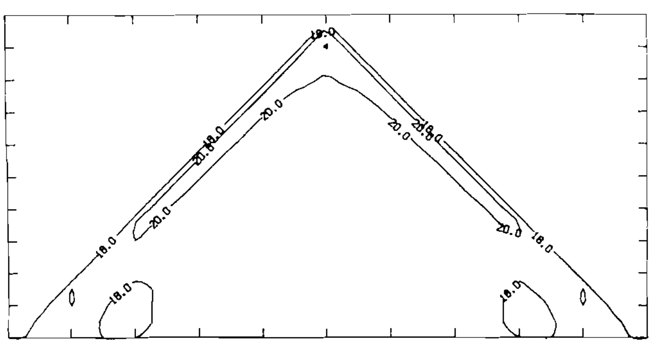

Figure 4-Temperature contour plot after one year of simulation resulting from an initial grain temperature of 20° C, an initial grain moisture content of 13% and a loading date of 15 October.

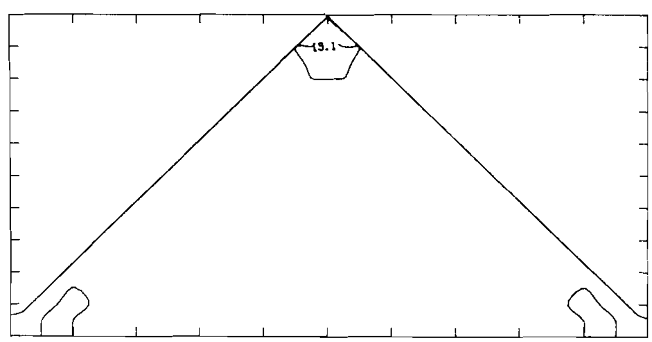

Figure 7-Moisture content contour plot after one year of simulation resulting from an initial grain temperature of 20° C, an initial grain moisture content of 13% and a loading date of 1 August.

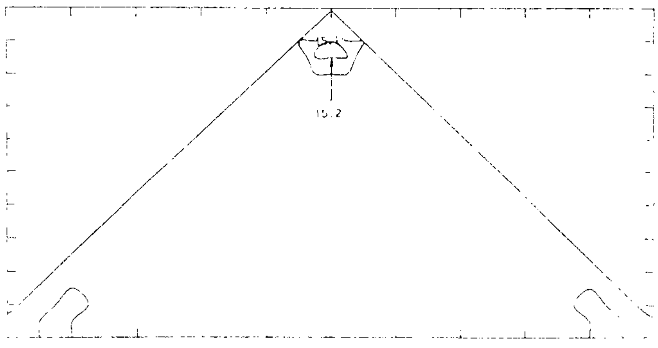

Figure 8-Moisture content contour plot after one year of simulation resulting from an initial grain temperature of 20° C, an initial grain moisture content of 15% and a loading date of 1 August.

For this set of ICs, the bulk of the grain was still at the initial MC of 13%. The MC for a small area at the peak of the bunker cross-section increased from 13% to 13.1%. Therefore, very little net moisture migration had taken place after the one-year simulation length. Figure 8 depicts the MC profile resulting from the ICs of 20° C, 15%, and 1 August. Again, very little moisture migration appears to have occurred since the bulk of the grain was still at the initial MC of 15%. For this set of ICs, a maximum MC of 15.2% occurred at the peak of the bunker cross-section. As in the earlier case, the moisture migrated to the upper center of the grain bulk.

From these results it was shown that both initial grain temperature and MC had an effect on moisture migration. The combined effect of high initial temperature and MC resulted in an appreciable amount of moisture migrating to the peak of the bunker cross-section. Therefore, the peak of the bunker had the highest potential for grain spoilage, insect activity, and mold growth.

Condensation Potential

Condensation on the grain surface just below the bunker liner is a concern of bunker operators. The probability of grain spoilage, insect activity, and mold activity is increased if condensation occurs. Figure 9 with ICs of 10° C, 13%, and 15 October loading date, Fig. 10

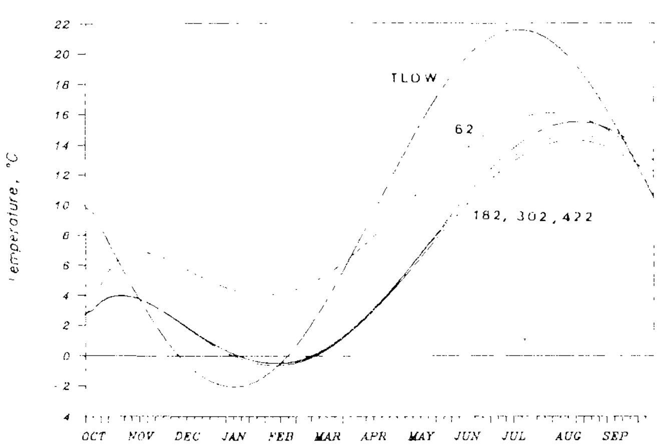

Figure 9-Predicted daily low temperature (TLOW) and simulated daily dewpoint temperature during one year of simulation for surface grid points 62, 182, 302, and 422 for an initial grain temperature of 10° C, initial grain moisture content of 13% and a loading date of 15 October.

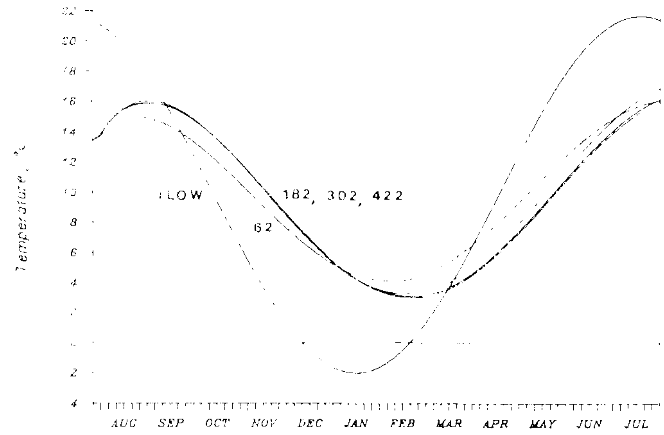

Figure 10-Predicted daily low temperature (TLOW) and simulated daily dewpoint temperature during one year of simulation for surface grid points 62, 182, 302, and 422 for an initial grain temperature of 20° C, an initial grain moisture content of 13% and a loading date of 1 August.

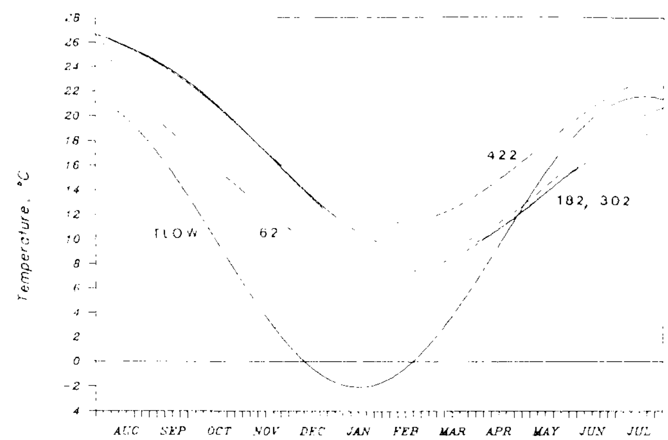

Figure 11-Predicted daily low temperature (TLOW) and simulated daily dewpoint temperature during one year of simulation for surface grid points 62, 182, 302, and 422 for an initial grain temperature of 30° C, an initial grain moisture content of 15% and a loading date of 1 August.

with ICs of 20° C, 13%, and 1 August and Fig. 11 with ICs of 30° C, 15%, and 1 August depict the predicted daily low temperature vs. the simulated daily dewpoint temperatures of the intergranular air at four grid point locations (Fig. 1) along the surface of the bunker. Anytime the value of the predicted low temperatures (TLOW) drops below any of the grid point dewpoint temperatures, the potential for condensation greatly increases. From these three figures, the potential for condensation was shown to be generally in the fall and early winter. Also in Fig. 11, TLOW was initially lower than the four grid point temperatures. It remained lower until late spring. Therefore, the potential for condensation lasted for a longer period of time for this set of ICs (30° C, 15%, 1 August 1) than for the other two sets (10° C, 13%, 15 October, and 20° C, 13%, 1 August), as would be expected because of the higher initial MC.

Stream Function

The stream function (vorticity) is an indicator of the magnitude and direction of the convective air currents

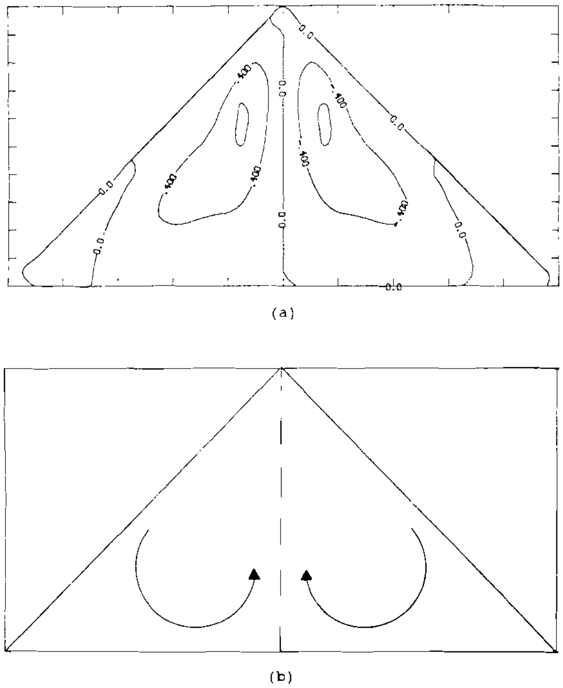

Figure 12-Stream function (vorticity) contour plot after one year of simulation resulting from an initial grain temperature 30° C, an initial grain moisture content of 15% and a loading date of 1 August - (a) stream function contour values, (b) corresponding convective air current directions. Units are L/s.

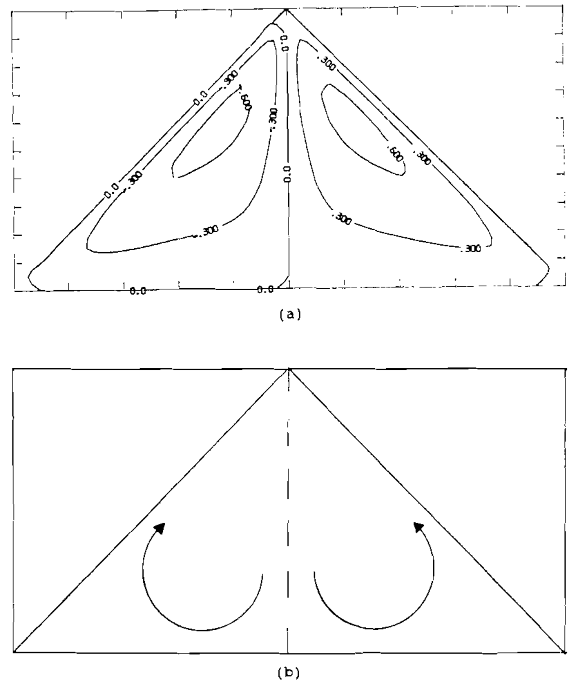

Figure 13-Stream function (vorticity) contour plot after one year of simulation resulting from an initial grain temperature of 10° C, an initial grain moisture content of 15% and a loading date of 1 August -(a) stream function contour values, (b) corresponding convective air current directions. Units are L/s.

within the bunker. Figure 12(a) depicts the values of the vorticity array that resulted from using the ICs of 30° C, 15%, and 1 August. Figure 12(b) describes the direction of the convective currents that corresponds to Fig. 12(a). For this set of ICs, the convective currents within the bunker move up through the center and then descend along the outer surface of the grain. For this pattern of air currents to occur, the grain would have to be warmer than the surrounding outside air.

Figures 13(a) and (b) are the resulting vorticity plots from using ICs of 10° C, 15%, and 1 August. The convective air currents resulting from this set of ICs are moving in the opposite direction to those discussed above. The reason for this is that the bulk of the grain is cooler than the outside air. Therefore, the cooler air in the center of the grain would descend and then rise along the grain surface as it is warmed by the outside air. The air currents and moisture migration patterns are similar to those observed in conventional storage systems.

Conclusions

The conclusions of this research were as follows:

1. No correlation was detected that would indicate any one of the three loading dates tested was significantly better or worse than the other two. Therefore, the effects on DML of only the loading date appeared to be minimal for all ICs tested.
2. Initial temperature and moisture content were shown to affect the predicted DML. However, of the initial temperature and moisture content combinations tested, relatively large DML values were experienced only at the extreme temperature/MC combination of 30° C and 15%. Relative to the DML experienced for this combination, most other initial temperature and moisture content combinations yielded DML values that were less than 50% of this maximum value.
3. It was shown that both initial grain temperature and moisture content had an effect on moisture migration. The combined effect of high initial temperatures and moisture contents resulted in an appreciable amount of moisture migrating to the peak of the bunker cross-section. Therefore, the peak of the bunker had the highest potential for grain spoilage, insect activity and mold growth.
4. The most likely time for condensation on the grain surface was shown to be in the fall. The potential for condensation increased with the initial grain temperature and/or the initial grain MC.

Acknowledgment: The authors wish to thank Commodity Storage, Ltd./Arkansas of Grubbs, Arkansas for the financial support of this project.

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