Temperature and Relative Humidity Data in Bunker-Stored Rice

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ABSTRACT

A storage technique in which grain is piled on large, flat surfaces and covered with an airtight liner is described. A synopsis of the concept and development of this type of grain storage is given as are the design and construction details of systems currently being used in Arkansas. Temperature and relative humidity data collected while monitoring a field-scale unit equipped with an aeration system are presented. The results of a laboratory study addressing a method of removing moisture from the surface of these systems in order to prevent potential condensation are also presented.

INTRODUCTION

A grain storage technique new to the U.S. is being used to store rough rice in Arkansas. The technique consists of sealing dried rice at or below 12 to 13% moisture content* in large, covered piles. Airtight conditions in the grain mass are achieved by covering the rice with a liner that is practically impermeable to air diffusion. The dimensions of typical storage units currently being used in Arkansas are 30 m (100 ft) in width by 90 to 120 m (300 to 400 ft) in length, having a capacity of approximately 18,000 m^3 (500,000 bu). The storage units are often referred to as "controlled atmosphere storage units" but will be referred to as "bunker storage units" in this paper.

Since the introduction of the first bunker unit in Arkansas in the fall of 1985, 19 bunker storage units have been built in the state, representing a total capacity of approximately 340,000 m^3 (9.6 million bu). Thus, this storage technique has become popular in a relatively short time. Bunker storage of grain has been used commercially on this scale in other parts of the world, primarily in less humid, wheat-producing areas. However, problems associated with moisture migration, including spoilage at the grain surface due to condensation, have been cited. Research is needed to address these problems and the general feasibility of using this technique for rice storage in the U.S.

Two segments of an overall study addressing bunker storage of rice are presented in this paper. The first segment consisted of monitoring temperature and relative humidity at various locations in a field-scale bunker storage unit. The second was a laboratory experiment that investigated a method of removing surface moisture in bunker storage units. Another phase of the overall study that is not reported in this paper was the development of a mathematical model (Freer, 1988) that was used to simulate environmental conditions within these units as a means of assessing the ramifications of loading at various times throughout the year with grain at various moisture contents and temperatures.

LITERATURE REVIEW

Controlled atmosphere (CA) storage has been used as a grain preservation technique as early as the first century BC (Signaut, 1980). Various forms of this type of storage have been documented in many societies throughout history and are currently being used in both developed and underdeveloped countries. Although new for use as grain storage systems in the U.S., CA storage systems are being used successfully for storage of apples and pears. Dilley (1986) stated that approximately 50% of the apples stored in the U.S. are stored in controlled atmosphere storage systems.

Considerable research in CA grain storage and related aspects of this storage has been conducted worldwide. Shejbal, 1980, and Ripp et al., 1984, reported the proceedings of international symposiums on this topic. Research on CA storage of grains spans a wide variety of disciplines, including the entomological and microbiological aspects of these types of storages when both naturally and artificially produced atmospheres are used to prevent insect and microorganism growth. Equipment and techniques for producing artificial atmospheres to prevent insect and microbiological activity have also been reported for use in various storage systems.

Several structural designs and retrofits to conventional storage structures have been proposed and built to facilitate airtight storage, thus utilizing the CA concept. These designs include both above- and below-ground structures. Yates and Sticka (1984) and Navarro et al. (1984) reported the development of PVC (polyvinylchloride)-covered, above-ground bulk CA grain storage systems that were developed in Australia. They reported that systems similar to those depicted in Fig. 1 evolved from a previous concept of underground

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*All references to moisture content are on a wet basis.

storage that was attempted in New South Wales, Australia. This technique consisted of excavating a pit, lining the pit with plastic, filling the pit with wheat, and covering the wheat with a thin PVC liner and then with soil. Operational problems prompted a subsequent, above-ground approach in which the top liner covering the grain was covered with a 1 m-(3.3 ft) thick layer of soil. This approach also presented problems and significant labor costs that led to the present use of a heavy-duty, high-quality PVC material. This material provided a means of creating a nearly airtight seal without requiring soil covering. This technique has become very popular as a grain storage technique in Australia (Yates and Sticka, 1984).

Navarro et al. (1984) reported the use of a 50 by 150 m (164 by 492 ft) storage in Israel in which wheat at 11.4% moisture content (wet or dry basis was not indicated) was stored in an airtight structure similar to Fig. 1. The structure consisted of a polyethylene liner as a base, a PVC liner over the wheat surface, and a 2 m (6.6 ft)-high earth bank for sealing around the perimeter. No deterioration of the liner as to elasticity and resistance to tear was reported at 15 months of exposure. Oxygen concentration in the grain mass decreased to 6% while the carbon dioxide concentration increased to 9% within three months. A minimum oxygen concentration of 5% was reached with a corresponding carbon dioxide concentration of 9.8%. This composition resulted in adequate control of insects in the deeper layers of the bulk; however, at the surface layer where wheat moisture content was considerably higher some insects survived. Of particular note was the increase in moisture content at the surface of the grain bulk from 11.4% to greater than 13.5%. This increase was reportedly due primarily to temperature gradients measured within the surface layer. Mold was reported on the high moisture content wheat with associated reductions in germination percentage and baking quality. However, the total estimated damage for the 15-month storage duration was only 0.205% of the grain bulk mass.

Gough (1985) reported the findings of a study in which two 18 m (59 ft) diameter, semi-underground, concrete silos were used to store maize. The above-ground portion of the silos was oblate-spheroid shaped. Maize was loaded at 10 to 11% moisture content and stored for three years. Gough reported high moisture contents at the surface of the stored grain with water being present at unloading. There was also a layer of mold 15 cm (6 in.) thick at the surface. Moisture content rapidly decreased with distance away from the surface. Gough attributed moisture migration to "an air convection mechanism" that was produced by the temperature differential between the grain and outside air.

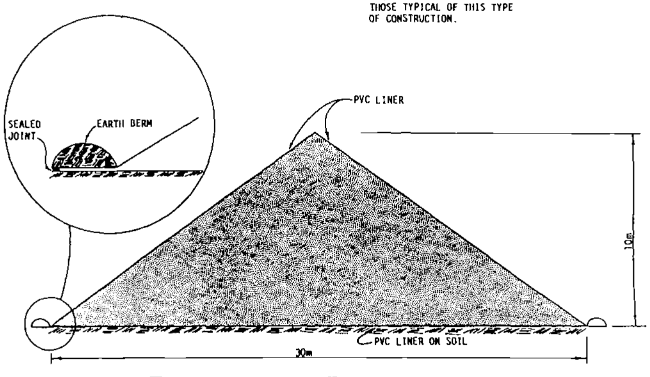


Fig. 1—Typical temporary-floor bunker storage unit.

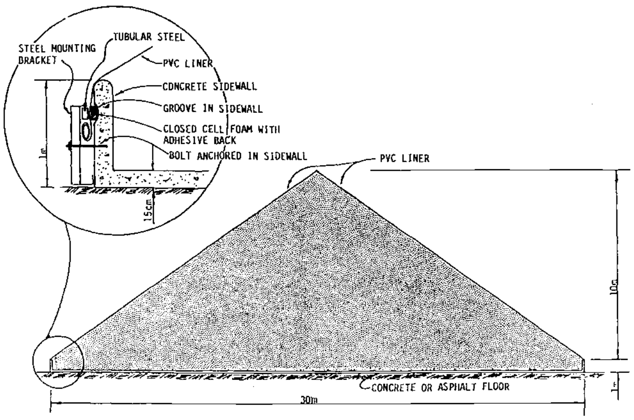


Fig. 2—Typical permanent-floor bunker storage unit.

BUNKER STORAGE SYSTEM DESIGNS

Several designs of CA storage units are being used in Arkansas. Two of the basic designs are depicted in Figs. 1 and 2. One common element in the design of the bunker units is the type of liner used to seal the grain mass. The material is a nylon fabric lined with PVC and usually has a reflective surface. The liner is typically 0.51 to 0.81 mm (20 to 32 mil) in thickness, depending on the manufacturer. One of the significant features of this material is its impermeability to gas flow, which is reported by one supplier to be 50 cc (3 in^3) of air per 645 cm^2 (100 in^2) per 24 h. The reported cost of this material is approximately \$4.84/m^2 (\$0.45/ft^2). Further information on the design and costs of these units is given in Siebenmorgen et al. (1986).

CURRENT RESEARCH EFFORTS

Operational experience with the first bunker storage unit built in Arkansas was gained in the spring of 1985. Condensation was observed at the surface of this unit during this time. Mold growth was subsequently observed on the surface of the rice, especially near the apex of the pile.

The following sections describe efforts that have been made to address some of the operational problems, particularly surface condensation, associated with bunker storage units. The first section details an aeration system installed in a field-scale storage unit along with

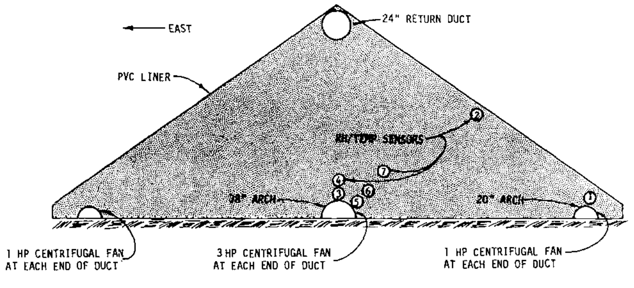


Fig. 3—Aeration system and RH/temperature sensor locations. Bunker was 30m (100 ft) wide. Probe 1 was placed 30cm (1 ft) above side duct. Probe 2 was placed 15cm (6 in.) under the surface. Probes 3 and 5 were placed 30 cm (1 ft), probes 4 and 6 91 cm (3 ft), and probe 7 2.7m (9 ft) from the surface of the center duct.

temperature and relative humidity data collected in this unit. The second section describes a laboratory experiment conducted to indicate the rate at which grain temperature and relative humidity can be lowered by circulating air between the grain surface and the PVC liner.

Bunker Unit Aeration System

It has been proposed to aerate the grain mass within bunker units during cool season months to alleviate problems associated with moisture migration. To test this proposal, a bunker equipped with the aeration system shown in Fig. 3 was monitored to determine the effects of the aeration system on conditions inside the grain mass. The design allowed air to be circulated through the grain mass by any or all of six centrifugal fans. A 2.24-kW (3-hp) fan was located at each end of the center duct, and a 0.746-kW (1-hp) fan was located at each end of the side ducts. The 61-cm (24-in.) duct located at the apex of the pile was included to allow air to either be exhausted to the atmosphere or returned to the fan inlets to create a closed system. A closed system was attractive from the standpoint of maintaining an oxygen-depleted and carbon dioxide-enriched environment.

The location of the side ducts was selected to permit aeration of the rice at the outside edges of the unit. The ducts were also placed to allow circulation of air between the PVC liner and the grain surface to enable moisture removal from the grain surface if condensation did occur.

Sensors measuring relative humidity and temperature of the intergranular air were placed at the seven locations depicted in Fig. 3 to monitor the conditions surrounding the ducts during aeration or recirculation. All probes were placed in one cross-sectional plane 55 m (180 ft) from the north end of the bunker. Because of the original intention of the bunker managers to operate the aeration system in the recirculation mode, probes were clustered near the center air inlet duct (probe nos. 3, 4, 5, and 6 in Fig. 3) to closely monitor conditions at this location. It was hypothesized that if problem situations occurred under such a management scheme, they would occur near the center air inlet duct. The sensors (PCRC-11 HPB, Phys-Chemical[†]) utilize a wafer of cross-linked polystyrene that produces a change in impedance proportional to relative humidity. The sensors were monitored with a "Humi-Temp" digital readout manufactured by Phys-Chemical. The reported accuracy of these probes is ± 0.5°C (0.9°F) in temperature measurement and ± 2.5 percentage points in relative humidity measurement. The sensors were calibrated using an environment created by a saturated salt solution prior to placing in the bunker. All sensors gave readings within the advertised ± 2.5% accuracy limits.

The bunker in which the sensors of Fig. 3 were located was filled during September 1986 with rice at approximately 12% moisture content. A management decision was made to cool the grain mass by introducing outside air instead of operating the aeration system in a recirculation mode. This prevented the development of an oxygen-depleted environment. The design airflow rate was 80 L(min-m^3) (0.1 cfm/bu).

Temperature and relative humidity data for approximately five months of system operation are shown in Figs. 4 and 5, respectively. As depicted in Figs. 4 and 5, the fans were not started until December 5. The data of Fig. 4 indicate that the average grain temperature at the lower sections of the bunker prior to starting the fans was approximately 28°C (82°F). Upon starting the fans, the grain cooled quickly. Probe #7, which was located 2.7 m (9 ft) from the surface of the center duct, indicated that the grain cooled from 33°C (91°F) to a minimum of 7.8°C (46°F) in five days. The grain temperature at probe #2, located 15 cm (6 in.) below the rice surface, increased from an initial temperature of 12°C (54°F) to a temperature of 32°C (90°F) in four to five days, reflecting the result of air movement through the higher temperature interior. The time required for the temperature at probe #2 to decrease from its 32°C (90°F) elevated temperature level to its previous temperature of 12°C (54°F) was approximately 10 days. Thus a significant time lag existed for cooling the surface of this type of unit when using this aeration system configuration.

Warm and cold temperature fronts passing through the bunker were observed from initial cooling through April. In general, however, grain temperature was maintained at approximately 10°C (50°F) after the fans were started. This is the temperature level recommended for conventional storage of rice in Arkansas (Benz, 1987).

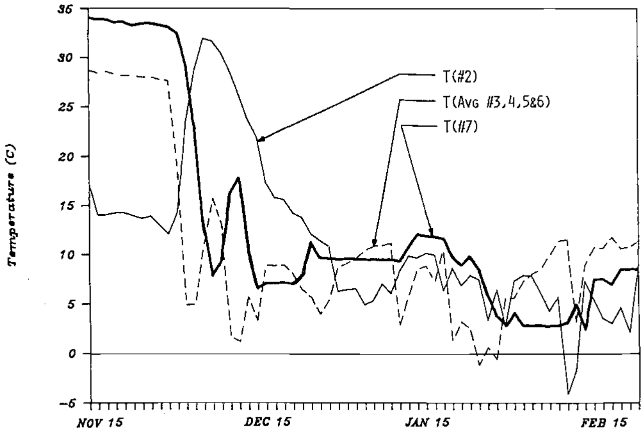


Fig. 4—Field-scale bunker temperatures.

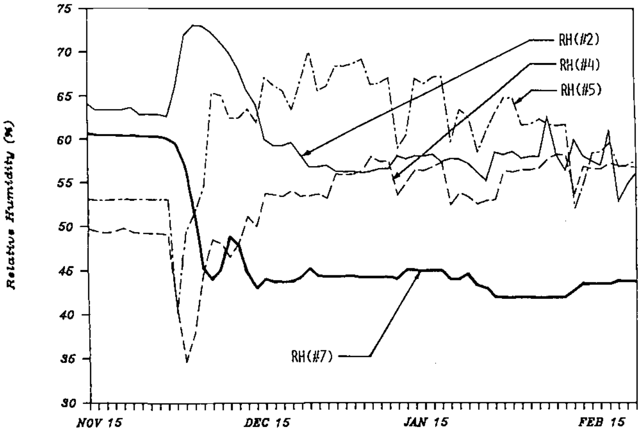


Fig. 5—Field-scale bunker relative humidities.

[†] Mention of a commercial name does not imply endorsement by the University of Arkansas.

Relative humidity readings both before and during fan operation are shown in Fig. 5. Readings at sensor locations 1, 3, 4 and 5, which were all located near the bottom of the bunker, were within a 5 percentage point relative humidity band. This should have been the case prior to any air movement due to fan operation if the ±2.5 percentage point accuracy criterion was maintained. Sensor #6, however, produced readings significantly lower than any of the sensors immediately adjacent to it. This trend remained consistent throughout the monitoring period. Thus, it is believed that sensor #6 was in error, and was therefore ommitted from consideration. Sensor #2, located near the bunker surface, and #7, located approximately 2.4 m (7.9 ft) above the bunker floor, gave significantly higher initial readings than those near the bottom (Fig. 5).

Figure 5 shows that the relative humidity within the grain mass at probe #2 increased when the fans were started, similar to the temperature increase shown in Fig. 4. Thus, the combined high temperature and high relative humidity conditions at the surface just after the fans started would promote condensation if low ambient air temperatures existed during this initial fan operating period. To illustrate, the dewpoint temperature corresponding to the conditions at the grain surface (sensor #2) of 30°C (86°F) and 70% RH is 24°C (75°F). The relative humidity at the surface leveled off to 57% after two weeks of fan operation and remained at approximately this level throughout the monitoring period. Figure 4 shows that the surface temperature remained under 10°C (50°F) after initial cooling. The dewpoint temperature corresponding to 10°C (50°F) and 57% RH is 1.5°C (35°F). Thus during cold weather, it would appear that some condensation could still occur at the surface. The equilibrium moisture content (EMC) of rice at these surface conditions was computed to be 12.6% (ASAE, 1987).

The data indicate that the relative humidity dropped from 60% to 43% at a location representing the bulk of the rice mass (sensor #7). Using an average temperature at sensor 7 of 8°C (46°F) (Fig. 4), the EMC was computed to be 11.3%. Thus, some drying of the grain mass resulting from moisture transfer to the surface occurred since the moisture content when the grain was loaded into the storage was at 12 to 12.5% MC.

The relative humidity of the sensors near the center duct (#4 and #5 in Fig. 5) increased initially after starting the fans but approached approximately 57% at the end of the moniotoring period, reflecting the average relative humidity of the ambient air during this time period. Sensor #1 (not shown in Fig. 5), located directly above one of the side ducts, closely tracked the relative humidity pattern indicated by sensors #4 and #5 and was very close in magnitude to that indicated by #7.

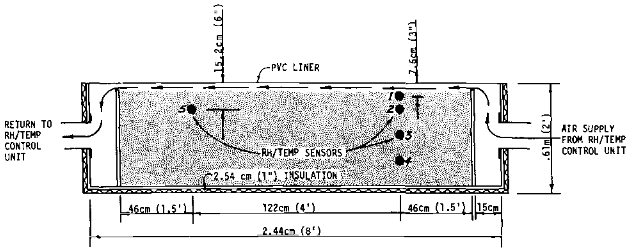


Fig. 6—Cross-section of apparatus used in surface moisture removal experiment.

The aeration system used in this bunker storage system precludes the formation of oxygen-depleted, carbon dioxide-enriched atmospheres. This should not be a problem at low temperatures. Aeration could be used during the fall and periodically during the winter to cool the grain mass to low temperatures. During the spring and summer, when surface condensation is not as severe a problem, a sealed atmosphere could be maintained by not operating fans. It is unknown, however, whether the rate of modified atmosphere development, after terminating fan operation, is sufficient to hinder insect growth and development during the spring and summer. Fumigation techniques have been fairly successful in prohibiting insect development in the bunkers described.

Surface Moisture Removal Experiment

A proposed method of removing surface moisture in cases of extreme moisture condensation or in reducing the moisture content of the upper layers of grain next to the PVC liner is to circulate outside air between the liner and the grain surface. In this situation, outside air would be introduced to remove the moisture in the upper layers of the grain, thus sacrificing the modified atmosphere within the grain mass.

As a means of investigating the potential of this method, a laboratory experiment was conducted to estimate the rate of temperature and relative humidity change within a mass of rice when air was passed between the rice surface and a PVC liner covering the rice. Convective air currents are not present throughout the grain mass in this type of drying as they are in typical grain drying systems where air is circulated throughout the grain mass.

The equipment is shown in Fig. 6. A 2.44 by 0.61 by 1.22 m (8 by 2 by 4 ft) plywood box, open on the top, was used as the rice container. The box was insulated on the sides, ends and bottom with 2.54 cm (1 in.) of fiberglass duct board insulation. After the box was filled with rough rice, a section of PVC liner was placed over the top of the box and secured with clamps to the sides of the box. A plenum was constructed at each end of the box such that air was forced to flow over the top surface of the grain.

Air was supplied to the upstream plenum by a relative humidity and temperature control unit (Parameter Generation and Control, Model 300 CFM Climate-Lab-AA). According to manufacturer's specifications, this unit is capable of maintaining the supply stream relative humidity within ± 0.5 percentage points of setpoint and the supply-stream temperature within ± 0.3°C (0.5°F) of the setpoint. Air was supplied to the upstream plenum, passed over the rice surface, into the downstream plenum, and back to the relative humidity and temperature control unit in a closed circulaton system. The airflow rate was measured with a hot wire anemometer and found to average 61.4 L/s (130 cfm). Air conditions were held constant at 15.6°C (60°F) and 55% RH. These temperature and relative humidity values represent ambient conditions that typically exist during times when such a moisture removal technique would be practiced. The moisture content of rice in equilibrium with air at these conditions is 12.0% as calculated using the Chung equation (ASAE, 1987). Twelve percent moisture content is considered safe for long-term storage of rough rice.

The ambient air surrounding the box was controlled via a wall thermostat and central air heater. The ambient air temperature occasionally rose above the thermostat setpoint of 20°C (68°F).

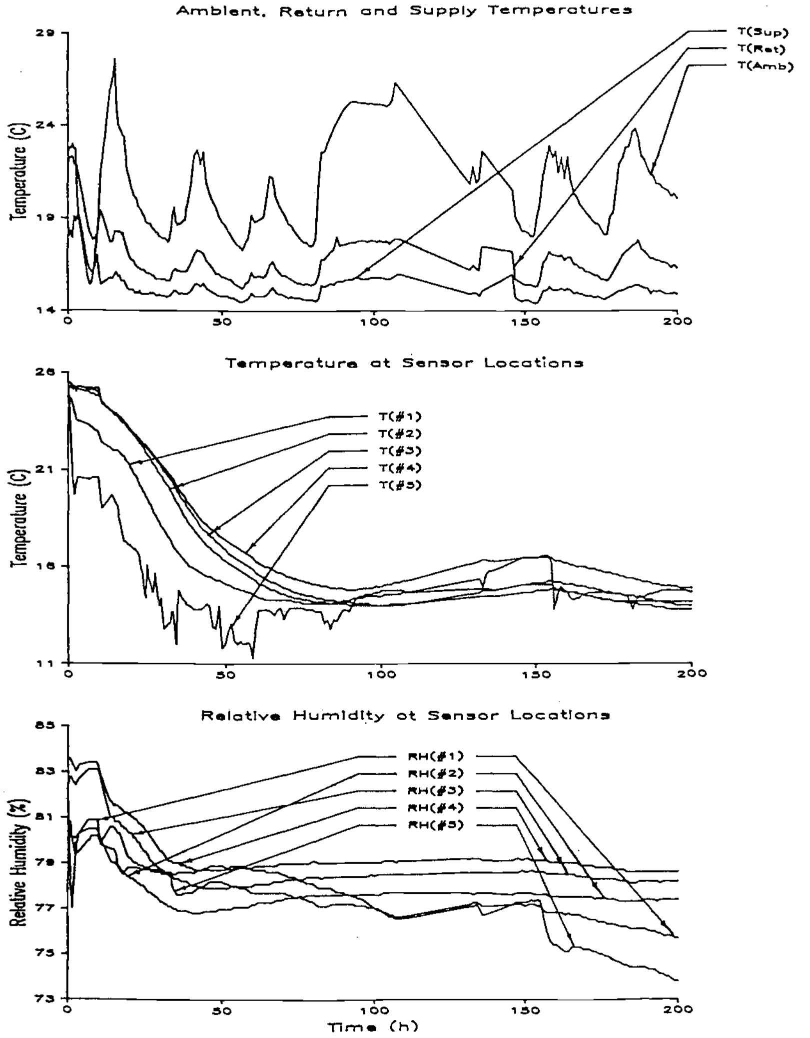
Rough rice that had been partially dried in an in-bin drying system was placed in the box. The average moisture content was 15.5%. Five relative humidity/temperature sensors, identical in design and manufacture to those used in the bunker storage unit, were placed in the locations shown in Fig. 6. The sensors were placed in a manner to allow measuring the temperature and relative humidity stratification from the rice surface. Thermocouples were used to monitor the ambient air temperature of the room and the airstream supply and return temperature. Data were recorded every hour for eight days.

Figure 7 shows the temperature and relative humidity of each sensor location for the test duration. The temperature of the rice at the various locations decreased rapidly from the initial average of 25°C (77°F) to an approximate steady-state value of 14°C (57°F). Steady-state temperature was reached in approximately 80 h. The slight but consistent rise in temperature at 150 h from the start of the test was caused by the room air temperature rising above 25°C (77°F) for an extended time.

Temperature of the upstream sensors decreased in similar patterns. The rate of temperature decline of the upstream sensors reflected the sensor proximity to the surface. For instance, the temperature of the grain at the top sensor (#1) decreased fastest with a noted offset below the rest of the upstream sensors immediately after the start of circulation. The rate of temperature decrease at sensor #2 increased after approximately one day of circulation, but the offset in temperature reduction from the other upstream sensors was much smaller than that of sensor #1, displaying a dampening effect with depth.

The data from the single sensor at the downstream end of the box indicated that cooling took place more rapidly at this location than at the upstream locations. It is postulated that some air at the downstream end of the box was penetrating the rice surface so as to produce some convective cooling. The cause of the peaked output is not known with certainty but is thought to have been caused by some turbulence and uneven airflow into the grain at this sensor location.

Initially, the relative humidity of the rice generally


Ambient, Return and Supply Temperatures

Temperature at Sensor Locations

Relative Humidity at Sensor Locations

Fig. 7—Temperature and relative humidity data of surface moisture removal experiment.

decreased. This initial decrease leveled off after approximately 48 h, after which the two sensors closest to the surface (#1 and #5) indicated the most reduction in relative humidity due to moisture transfer to the air stream. However, a definite stratification in relative humidity among the sensor locations did not appear until after approximately seven days of air circulation.

The overall conclusions of this experiment were that for the initial grain conditions and the drying air used, the grain temperature 46 cm (18 in.) from the surface was reduced to the drying air temperature in approximately three days. Although the overall rice relative humidity decreased within two days, a significant relative humidity stratification was not observed until approximately seven days from the start of the experiment.

CONCLUSIONS

The results of the monitoring study indicated that the bunker storage system with aeration system used could effectively cool the grain mass to a typically safe storage temperature of 10°C (50°F). The potential for condensation was reduced resulting from the cooling and lowering of relative humidity at the grain surface. The laboratory study indicated that a technique of passing air between the grain surface and the PVC liner reduced temperature to a steady-state value in approximately three days while a relative humidity stratification in the grain mass was not achieved until after seven days.

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