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I am submitting herewith a thesis written by John Richard Lehman entitled "The Effect of Forced Ventilation with High Moisture Air on Bulk Loads of Snap Beans." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Agricultural Engineering.

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THE EFFECT OF FORCED VENTILATION WITH HIGH MOISTURE AIR ON BULK LOADS OF SNAP BEANS

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

John Richard Lehman

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My very special thanks goes to my wife, Melissa, for all she has done.

ABSTRACT

Snap beans (Phaseolus Vulgaris) often experience loss of quality during transport to market. An apparatus designed to simulate conditions encountered by snap beans during transport was used in this study. Efforts were made to establish the effectiveness of forced ventilation with high moisture air in reducing this loss of quality.

The study consisted of six tests. Each test was conducted as follows. Freshly harvested beans were used to fill two containers. One received forced air ventilation; the other did not. After 24 hours, the beans were removed and evaluated in terms of texture, color, and moisture content. The weight lost during the 24 hour period was also determined. During the tests, the psychrometric properties of the ventilating and surrounding air were determined. The temperature of the beans in each container was also measured.

Forced ventilation with high moisture air was found to be highly effective in cooling beans, without excessive dehydration. The parameters used as indicators of quality were not shown to be significantly improved by the use of forced ventilation under the conditions experienced during this study.

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CHAPTER I

INTRODUCTION

Snap beans (Phaseolus Vulgaris) are a major vegetable crop in the United States, with Tennessee being a leading producer of snap beans for processing. Several processing plants are also located in the state. To utilize these growing and processing facilities efficiently, it is necessary for processors to transport beans from a large geographic area. This allows the processors to extend the processing seasons for more economic operation. However, this technique requires that the beans be hauled substantial distances after harvest, resulting in several hours delay before processing. If nothing has been done to halt biological activity in the pod, the quality of the beans may deteriorate severely during this period.

Temperature is of great importance in quality preservation. The rate of respiration increases as temperature increases. This leads to greater heat production and, thus, higher temperatures. To halt this cycle, some method of cooling must be used. Ideally, the beans should be cooled, and the temperatures maintained at an optimum level. This would slow the metabolic rate and prevent growth of microorganisms, but would still be above the threshold of physiological cold damage. This method is frequently used for high value fruit and vegetable crops, but the high cooling capacity required of this method cannot be economically justified for snap beans. Although refrigeration is not feasible,

more economical low capacity cooling methods can often be effective. One such method is the use of forced air cooling. A truck equipped to utilize forced air cooling is depicted in Figure A1, in the Appendix. The velocity head of the truck causes air to flow into the duct then along the floor of the truck and up through the beans. The flowing air removes heat from the beans as it moves out the open top of the truck into the atmosphere.

A laboratory apparatus for studying the effects of forced convection cooling on bulk loads of snap beans was developed by Wilhelm et al. (1973). Preliminary tests indicated that forced convection was an effective method of cooling, but that ambient air tended to remove too much moisture from the beans. Consequently, an evaporative cooling chamber, yielding high moisture air at a temperature slightly below ambient, was designed for use with the system.

The objective of this study was to evaluate the effectiveness of high moisture air in cooling bulk loads of snap beans.

CHAPTER II

REVIEW OF LITERATURE

I. GENERAL CONSIDERATIONS

The term "snap bean" is used to describe the immature green pod of the kidney bean (Phaseolus Vulgaris). Its origin can be traced to the American Indians (Ware and McCollum, 1968). Snap beans were adopted by the Europeans and have since been a major vegetable crop. Human population increases have lead to corresponding increases in snap bean acreages. The constraints imposed by hand harvesting were removed by the development of an efficient mechanical harvester. The mechanical harvester allowed the snap beans to be grown in large acreages and harvested rapidly. A major consequence of mechanical harvesting was the increased tendency toward bulk handling as opposed to small unit loads, such as bushel baskets. This technique improved efficiency but often increased damage experienced during transportation of the snap beans to market.

Loss of quality during transport has long been a problem with fresh fruits and vegetables. In 1915 approximately five million dollars was lost due to deterioration of perishable freight transported by rail (Nelson, 1926). Nelson also stated that much of this loss could have been avoided by providing better environmental conditions during shipment. In 1929, Hawkins listed the best shipping temperatures and

humidities for several vegetable commodities. More recently, the United States Department of Agriculture has published this information, as well as refrigeration requirements to maintain ideal conditions (Ashby, 1970; Lutz and Hardenburg, 1968, Wright et al., 1954). The current recommendation for storage of snap beans is that they be maintained between seven and ten degrees Celsius with a relative humidity range from 90 to 95 percent. Under these conditions storage can extend up to ten days (Ashby, 1970).

However, it is not always feasible to maintain ideal conditions for vegetables. For snap beans, economic conditions do not allow for the refrigeration of loads unless the holding or storage period is extremely long. Therefore, economical methods of minimizing deterioration are needed. An understanding of the processes of deterioration is necessary before these methods can be developed.

II. RESPIRATION

The fact that snap bean pods are living organisms and as such are respiring is fundamental in the process of deterioration (Mitchell et al., 1972). Platenius (1942) cited respiration as the most important factor in the deterioration of harvested vegetables.

Snap beans have a high rate of respiration. Benoy (1929) measured the initial rate of respiration as 0.7 gm CO_2/hour/100 gm of dry weight. On a fresh weight basis, Platenius (1942) found that a kilogram of snap beans produced 321 mg CO_2 per hour. Both Benoy and Platenius found a considerable drop in the respiration rate during the first day

of storage. After 26 hours, Benoy measured the respiration rate as 0.3 gm CO_2/hour per 100 gm dry weight.

The respiration rate of any vegetable is highly sensitive to temperature. This is particularly true for snap beans. Tewfik and Scott (1954) indicated that the rate of respiration of snap beans increased 62 percent when the temperature of storage was increased from 0°C to 7°C. Another indication of the effect of temperature on respiration is Van'thoff's rule. It states that for each ten degree Celsius temperature rise the rate of respiration should double. This is referred to as the Q10 value. For snap beans, according to measurements made by Platenius (1942), an increase in temperature from 0.5°C to 10.0°C resulted in a Q10 of 5.1. For an increase in temperature from 10.0°C to 24.0°C, the Q10 factor was 2.5; again greater than the expected value of 2.0.

Respiration also produces heat. Wilhelm et al. (1975) have developed an equation to predict the heat produced by respiring snap beans as a function of storage temperature. The data used to develop this equation were compiled by Lutz and Hardenburg (1968).

$$\log_{10} (Q) = 0.4363\ T + 0.904, \qquad (1)$$

where T is in degrees C, and

Q is in kJ/(kg·day).

From this equation and the specific heat of snap beans, it can be determined that beans initially at 70°C would produce enough heat to raise the storage temperature 0.5°C in one hour. Unless this heat is removed it would cause an increase in the rate of respiration and

increased deterioration of the snap beans. Thus removal of excess heat could effectively aid in maintaining the quality of stored snap beans.

Other factors also influence the rate of respiration of snap beans. One is oxygen concentration. Platenius (1943) found the effect of oxygen on respiration in snap beans to be minimal for concentrations slightly below normal atmospheric levels. However, he did indicate that lowered oxygen levels could serve as a limiting factor in some cases, and that at concentrations below 1 percent oxygen, the effect was drastic. At this concentration anaerobic respiration occurs. In a study on sweet corn, Smittle et al. (1972) found chemical changes normally associated with anaerobic respiration occurring at oxygen concentrations only slightly below normal levels when temperatures were high. A similar process might occur in snap beans. Broken snap bean pods have higher respiration rates. The increased respiration at the point where the pod was detached from the stem or at points of breakage is referred to as oxidation. Extensive oxidation results in extreme discoloration and is a major problem encountered by snap bean processors.

At lower temperatures, Singh et al. (1973) found snap beans coated with wax, which limited available oxygen, to be of higher quality than uncoated beans after 14 days storage.

Techniques of limiting respiration are developed because the continued respiration of the pod results in changes in its chemical composition and physical characteristics. These changes ultimately make the pod unacceptable as a food and merit close study.

III. CHEMICAL CHANGES DURING STORAGE

Chatfield and Adams (1931) have established the following average values for the composition of snap beans: water 88.9 percent, protein 2.4 percent, fat 0.2 percent, ash 0.77 percent, fiber 1.4 percent, sugars 0.37 percent, starch 2.2 percent, and total carbohydrates 7.7 percent. Great variation in the relative percentages of all constituents could occur without greatly altering palatability. The above values are not necessarily the most desirable in all cases, but do provide guidelines of acceptability.

Scientists have previously determined that snap beans held for a time after harvest experienced changes primarily in carbohydrate composition. Changes in fats and ash were relatively insignificant. There were some changes in protein composition. Platenius (1942) indicated that protein decomposition is possible even with sugars available for respiration. Parker and Stuart (1935) found protein synthesis to occur in beans with nitrogen being translocated from the pods. However, neither study showed any major change in protein.

Fiber content is related to maturity. Thus the continued maturation of the pods after harvest would result in an increase in fiber content. Sistrunk (1965) found an increase in both fiber content and maturity of beans held one day after harvest at 12°C and 29°C. Another study showed similar results with storage temperatures of 2°C, 10°C, and 21°C, where a slight difference in fiber content was measured after one day. The temperature of storage was also found to have some effect, but neither was significant (Guyer, Kramer and Ide, 1950).

In general, storage of snap beans would be expected to decrease non-structural carbohydrates, since sugars and starches would be metabolized during respiration. Several studies have verified this fact (Parker ans Stuart, 1935; Williams et al., 1958; Sistrunk, 1965). However, varying storage conditions can cause differences in composition that might be significant. In fact, some studies indicated a short term increase in total sugars could occur. However, there was usually a significant decrease in sugars by the fifth day of storage. The study by Sistrunk (1965) illustrated this. He found an initial increase in total sugar and then a significant decrease by the fifth day. This was explained by the sugar-starch metabolism of the organism.

Starch-to-sugar and sugar-to-starch conversions take place constantly in snap beans. While the snap beans are attached to the plant, photosynthetic activity in the leaves supplies additional carbohydrates as they are needed. When the snap beans are detached there is no longer a replenishing source of carbohydrates. Therefore, the sugars and starches stored in the snap bean must be utilized. Thus the total carbohydrates must decrease (Platenius, 1942).

The principal factor influencing the utilization of sugar or starch was temperature. Sistrunk (1965) found that sugars were converted to starch in snap beans held at 2°C. While at 13°C the balance shifted toward a higher percentage of total sugars. Williams et al. (1948) found a fairly constant level of sucrose for snap beans stored 24 hours at room temperature. Parker and Stuart (1935) determined that if snap beans were mature enough to contain seeds, the seeds tended to increase in percentage starch and decrease in percentage sugar, while

the pods gained sugar at the expense of starch. Maturity was thus established as an important factor in the sugar and starch composition of snap beans. Sistrunk (1965) stated that the starch-to-sugar conversion can be effective in improving the quality of snap beans, and that it was common practice to hold snap beans for from 12 to 36 hours between harvest and processing to realize these benefits.

Another important chemical constituent of snap beans is ascorbic acid. In a study by Guyer et al. (1950), the ascorbic acid content dropped 12 percent in the first day of storage. The study was conducted at temperatures of 2°C, 10°C, and 21°C; but no significant differences could be attributed to storage temperature. However, the lowest temperature was found to be somewhat detrimental to ascorbic acid; a result also obtained by Ezell and Wilcox (1959).

The overall effect of short term, one day, storage of snap beans cannot be readily stated. For some parameters, such as ascorbic acid levels, the effect was detrimental. For sugar and starch, the effect was possibly favorable. Finally, the loss of quality due to increased fiber content was dependent upon the maturity of the pods at harvest.

Although the effect of these chemical changes upon quality has not been completely established, an understanding of the processes involved indicates that a decrease in chemical activity, particularly the activity caused by respiration, would maintain higher quality.

IV. CHANGES IN PHYSICAL CHARACTERISTICS

The changes in the physical characteristics of snap beans are, for the most part, manifestations of internal chemical changes. As such they give an indication of the actual quality of the beans.

The important physical parameters in snap beans are color, texture, and moisture content. A parameter related to moisture content, and of importance in storage studies, is weight loss. Maintaining acceptable levels for all these parameters is necessary for a quality product.

Of the listed characteristics, moisture content is probably the least sensitive to chemical changes in the pod. The major factor in changing moisture content during storage is the relative humidity of the storage environment. In studies where no control of relative humidity was exercised and air movement was minimal, the moisture content of the snap beans remained fairly stable (Parker and Stuart, 1935; Guyer and Kramer, 1952). This does not mean that no moisture was lost, but that the moisture loss was proportional to the loss in dry weight. Other studies have indicated that air movement can result in moisture loss (Wilhelm et al., 1973; Comin and Junnila, 1946).

Weight loss is closely associated with moisture loss, because the pods of snap beans are almost 90 percent water, but dry matter losses can also occur, even during short term of storage. In a study conducted at 30°C in an almost saturated environment, Benoy (1929) calculated a 6 percent loss in dry weight after 24 hours. Other studies have shown weight loss to be dependent on temperature (Sistrunk, 1965; Guyer and

Kramer, 1952). They also found an average weight loss of approximately 4 percent (fresh weight) for beans held 24 hours at room temperature.

Texture evaluations of snap beans refer primarily to maturity and fiber content. These have been discussed previously.

Color changes also depend on chemical changes and can be very significant in terms of overall quality. In fact, consumer preference can be closely related to color. The effect of storage on color was generally undesirable. Snap beans graded organoleptically by color were of significantly lower quality after one day of storage. The temperature of storage also significantly influenced color of snap beans. Snap beans stored at 2°C graded significantly higher than snap beans stored at 10°C (Guyer et al., 1950). Sistrunk (1965) obtained similar results with a Hunter color difference meter. He established a significant effect for length of time stored and temperature of storage. The effect of temperature was dependent upon variety and not significant for all varieties tested.

For several reasons, changes in the above physical parameters are important in determining the effectiveness of various methods for maintaining quality in harvested beans. First, they are objective measures and are usually easy to obtain (Mohsenin, 1968). Additionally, some correlation has been shown between physical parameters and quality by sensory evaluation (Guyer et al., 1950).

Epidermal sloughing, a problem encountered during processing of beans, might be classified as a physical characteristic. Sistrunk and Cain (1960) found short term storage to be effective in reducing sloughing. But in another study, Sistrunk (1965) found the effect of storage on sloughing to be unpredictable.

V. POST-HARVEST DISEASES

Another important factor in the deterioration of snap beans after harvest is disease. The possible diseases of snap beans are too numerous to list; but they may be caused by fungi, bacteria, and viruses, or they may be physiological diseases. Control of diseases is accomplished in many ways. Some, such as anthracnose, are prevented by not introducing the causal agent. Others are controlled by using resistant varieties. Russeting can be avoided by eliminating chilling injury. However, there are always bacteria and fungi present on the surface of beans ready to attack at points of injury (Smith et al., 1966). Thus chemical treatments have been tried in some cases and have met with limited success (Wells and Cooley, 1973). The main means of controlling disease in the transportation and storage situation remains the control of temperature and elimination of diseased pods (Duckworth, 1966).

VI. TEMPERATURE AND QUALITY

If there is a factor common to all of the preceding it is the relationship between temperature and almost every factor responsible for deterioration of snap beans. Guillou (1958) reached a similar conclusion and stated that the deterioration experienced in one day at 10°C would occur within the first hour at 32°C. Although an ideal temperature has been stated, any process that will cause a reduction in temperature toward this ideal will be effective. Watada and Morris (1966) obtained a 21 percent increase in shelf life of snap beans by

lowering the storage temperature from 25°C to 20°C. Thus, even a small amount of cooling can be effective in preservation of quality. When the effect of the heat of respiration on bean temperatures is considered, it becomes obvious that a method of cooling that will remove the heat of respiration and lower bean temperatures slightly will maintain higher quality beans. One such method is forced air cooling.

Forced air has been found to be effective in removing heat from blanched vegetables (Coffelt and Winter, 1972). Henry and Bennett (1972) compared a forced air-water spray device to a hydrocooler and found them to be equally efficient. Wilhelm et al. (1975) used forced air to cool summer squash in Tennessee with favorable results. Forced ventilation of snap beans by Wilhelm et al. (1973) was less successful due to excessive moisture loss by the beans in certain circumstances. Their findings support statements by Guillou and Richardson (1965) on the importance of high humidities in preventing deterioration of vegetables.

From this it might be concluded that forced ventilation of snap beans with high moisture air could slow the deterioration in quality experienced during transport to market.

CHAPTER III

PROCEDURE

I. DESCRIPTION OF EQUIPMENT

A treatment chamber designed by Wilhelm et al. (1973) was used to simulate conditions encountered by snap beans during transport in an air scoop equipped truck. The chamber was 1.22 m x 1.22 m x 1.22 m with a removable partition which divided it into two equal sections such that one could receive forced ventilation and the other would not. The air supply was provided by an electrically driven centrifugal fan with a variable speed drive. A schematic representation of the entire system is depicted in Figure 1. The air travelled from the fan through 2 m of 15.2 cm diameter duct. A pitot tube was used to measure the air velocity in the duct.

The air was cooled and humidified prior to flowing through the beans by the humidifier chamber shown in Figure 2. The air flowed through burlap panels saturated with water. The bottom of the chamber was a reservoir, and a spray system kept the burlap saturated. After passing through the cooler, the air flowed into the box and through the beans.

The temperature and relative humidity of the flowing air were determined from wet and dry bulb determinations at selected points as shown in Figure 1. These included the air intake of the fan, output of the evaporative cooler and the output after flow through the beans.

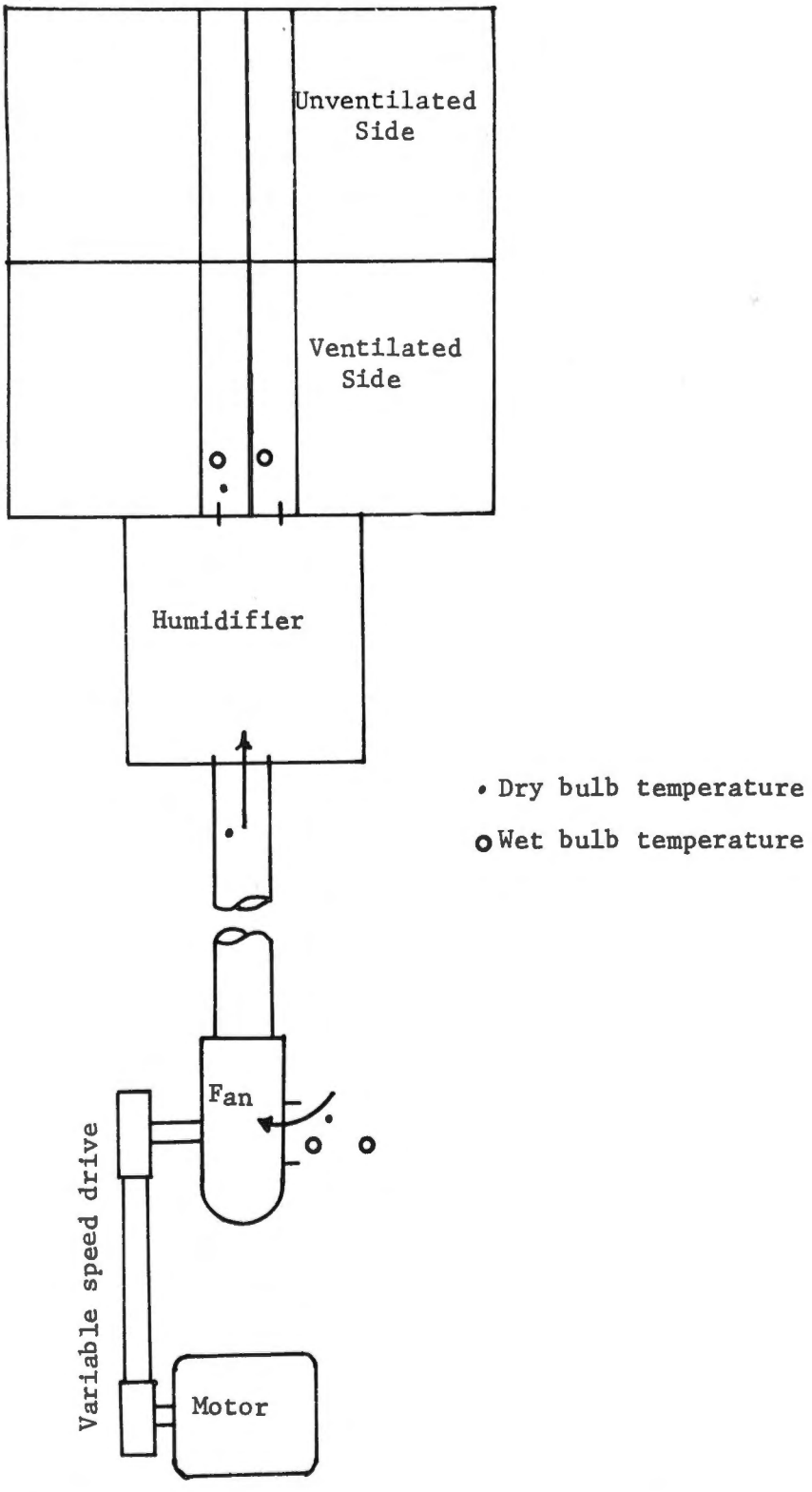


FIGURE 1. Schematic of apparatus used in this study. The fan forces outside air through the humidifier and up through the beans. Temperatures were measured at indicated points.

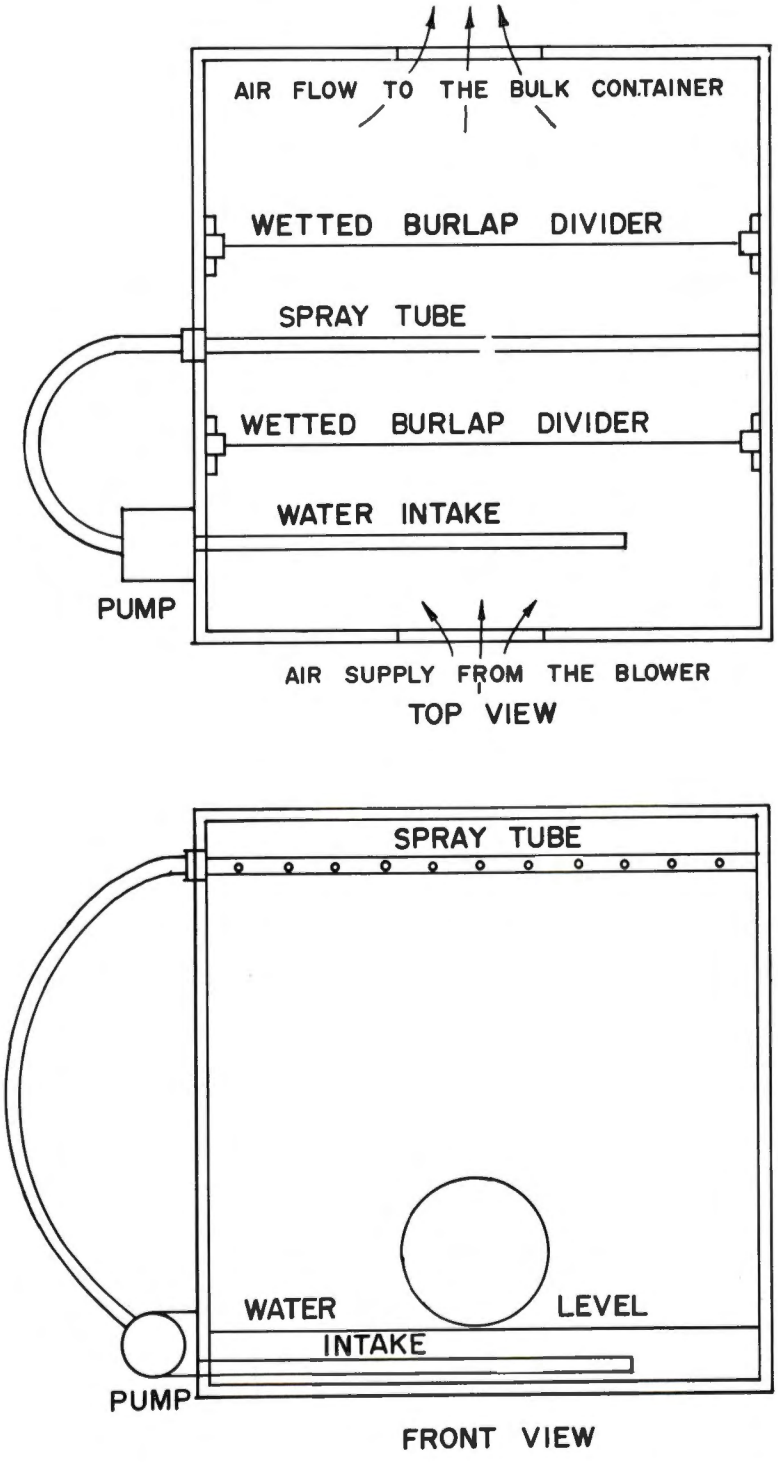


FIGURE 2. Evaporative cooling and humidifying chamber. Water is pumped from reservoir onto the burlap. Air is forced through the burlap picking up moisture.

Figure 3 is a photograph of the wick and thermocouple system used for wet-bulb temperature determinations at the fan intake. The top of the ventilated side of the box was covered except for a 15.0 cm diameter hole. This allowed the wet bulb determinations to be made on the air after it had passed through the beans. Additionally, temperature measurements were made within the beans as shown in Figure 4. Box wall surface temperatures and ambient air temperatures were also measured for use in energy balance calculations. The copper-constantan thermocouple temperature measurements were recorded by a 60 point digital data acquisition system.

Determinations of the color of the bean samples were made using a Hunter color-difference meter (Hunterlab Model D25 D2M/L). This device measured three parameters. The "L" value, measured lightness from 0 for black to 100 for white. The "a" value measured the degree of redness (positive values) or greenness (negative values). The "b" value indicated yellowness (+) or blueness (-). These three values locate a specific point on the three dimensional scale shown in Figure A2, in the Appendix. This method of determining color is widely used in the food industry (Francis and Clydesdale, 1975). For measuring the color of the snap beans, the meter was standardized using standard tile number C2-141 (green).

An Allo-Kramer shear press was used to determine the texture of the snap bean pods. The shear press cell contained a set of parallel vertical plates, which were forced through the sample to produce a measurable force. This force was an indication of pod texture. The shear press utilized in this study was incorporated into an Instron food

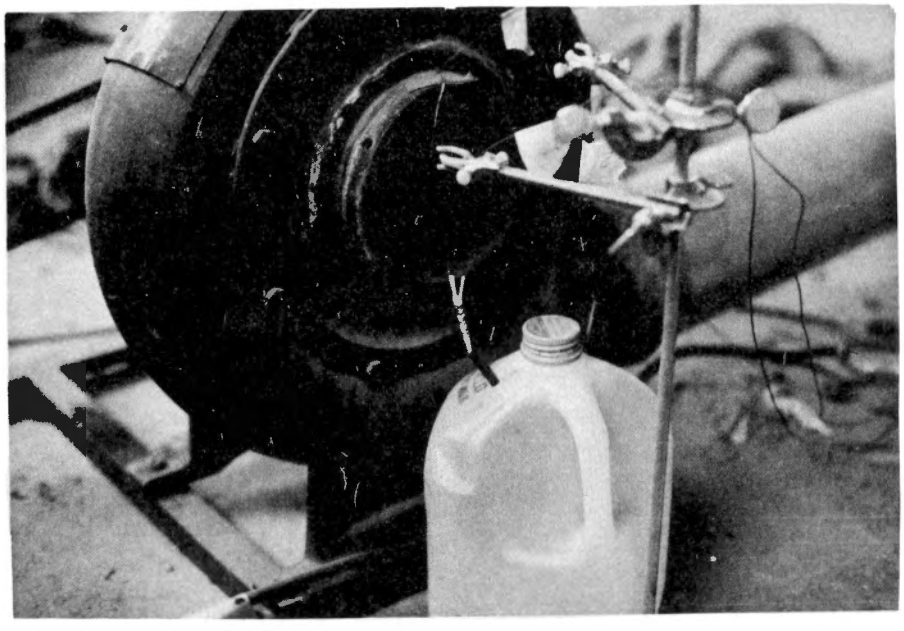


FIGURE 3. Wick and thermocouple system used for wet-bulb temperature determination at the fan intake.

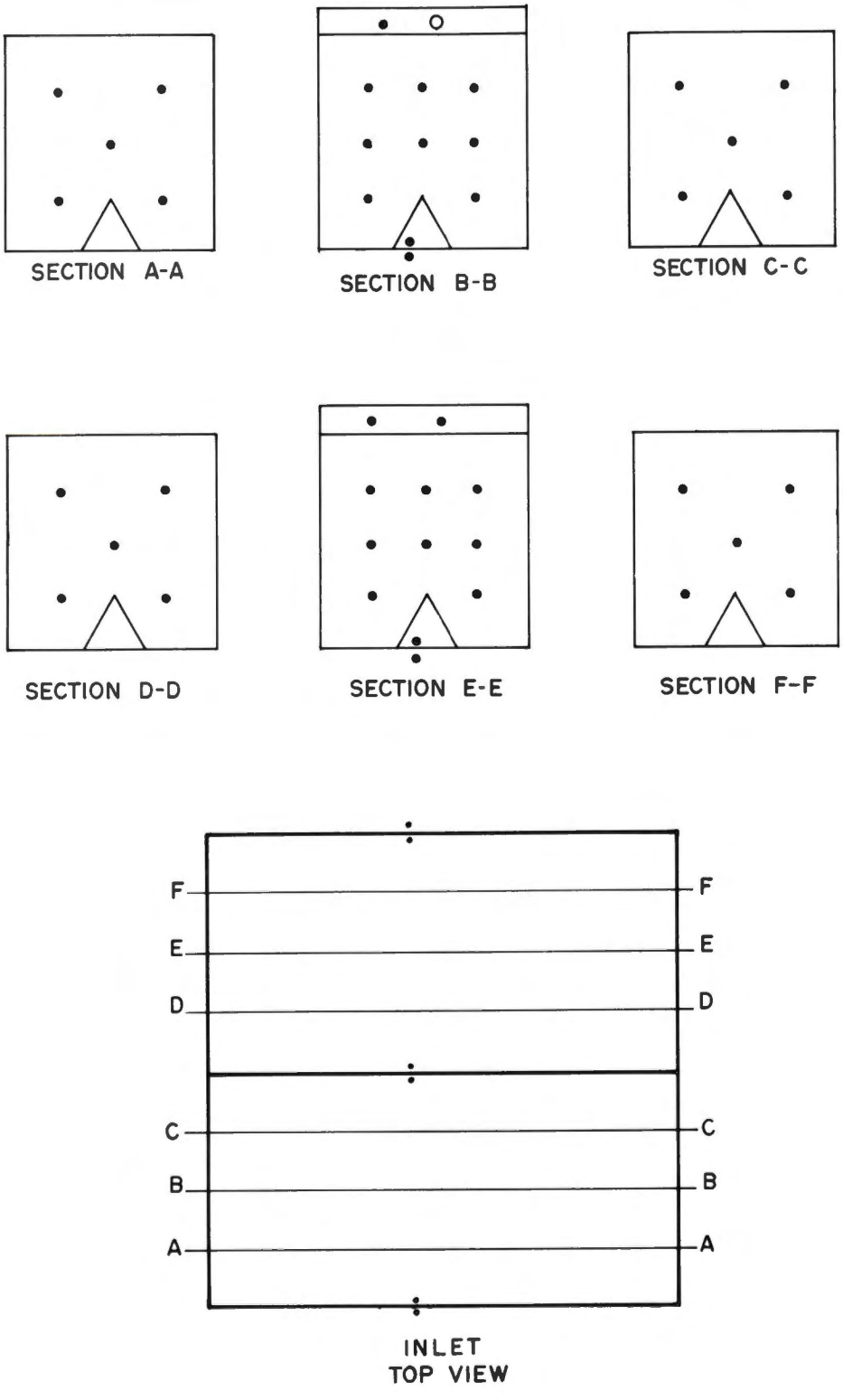


FIGURE 4. Identification of thermocouple and sampling locations within the container.

testing machine, Model 1132. This system allowed the force-displacement curve to be recorded, thus both the maximum shear force and work required to shear the sample were determined. A typical force-displacement curve is shown in Figure A3 in the Appendix. The peak represents maximum shear force and the area under the curve indicates work done by the shear press.

Moisture analysis was accomplished by use of a small drying oven and laboratory balance. Lowered oxygen content, caused by lack of air movement and the high respiration rate of the snap beans in the unventilated chamber, was determined by a Taylor Servomex Oxygen Analyzer (Type ØA250).

II. METHOD OF TESTING

The study consisted of six tests. Each test was conducted as follows. Both compartments of the container were filled with approximately 250 kg of snap beans. This completely filled the container. The blower was then turned on, ventilating one compartment. The other compartment received no forced air ventilation. These conditions were maintained for 24 hours, after which the beans were removed. During loading and unloading samples were taken and evaluated in terms of color, texture, and moisture content. The weight lost during the 24 hour test period was also determined. During the tests, the psychrometric properties of the ventilating and surrounding air were determined. The temperature of the snap beans in each container was also measured. The dates and starting times for each of the tests are shown in Table 1.

TABLE 1. Dates and starting times for the six tests.

Test Number	Date of Test	Starting Time
1	July 26, 1974	12:20 pm
2	August 8, 1974	10:36 am
3	August 12, 1974	12:20 pm
4	August 14, 1974	10:40 am
5	August 19, 1974	11:15 am
6	August 21, 1974	11:07 am

III. TECHNIQUE FOR CONDUCTING TESTS

This study was conducted at The University of Tennessee Plateau Experiment Station near Crossville, Tennessee. The apparatus was located in a storage and service building on the station. The complete apparatus is pictured in Figure 5. The bean container, humidifier, oxygen analyzer, temperature recorder, and air duct can be seen as they looked prior to loading. A panel covered the open front of the bean container during the tests. The beans were harvested using a Chisolm-Ryder two-row mechanical harvester (Bledsoe and Morgan, 1972). The beans were harvested and collected in burlap bags. Normally, each bag contained about 15 to 20 kg of beans. Harvesting was begun the morning of the test with the exception of test 2. In this test the beans were harvested the preceding afternoon and left outside overnight.

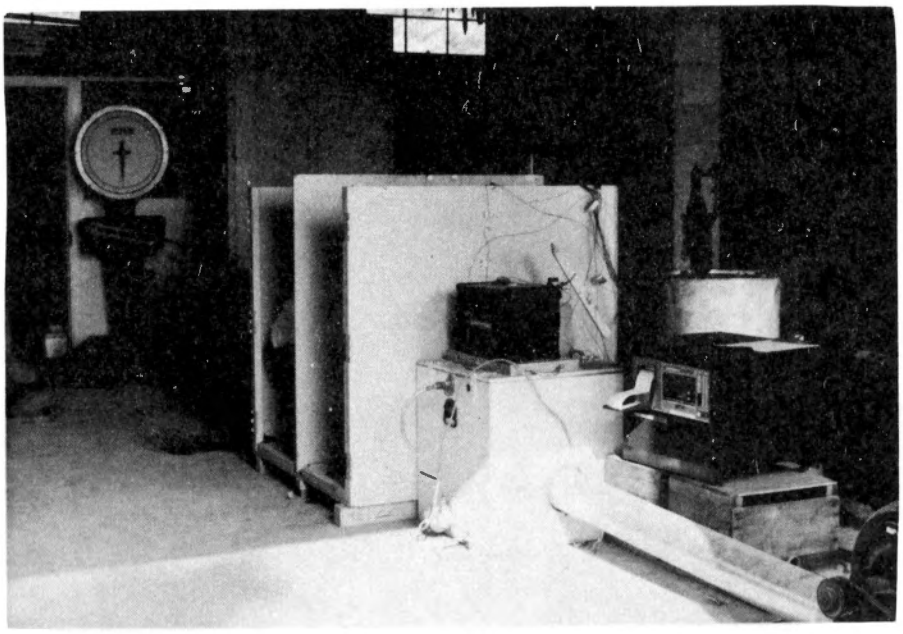


FIGURE 5. Apparatus in location prior to loading.

The beans under study were of marketable size, with a size distribution typical of mechanically harvested beans. The beans in test 2 were larger than the other tests, while test 5 was conducted using beans smaller than average. No great control was maintained over the varieties of the beans, but samples were of the same variety where possible.

The harvested beans were weighed, visually evaluated, and loaded into the container. Both compartments were loaded simultaneously. During the first three tests, samples were taken and thermocouples placed at each of the locations indicated in Table A1 in the Appendix. For the last three tests, wide mesh sample bags were filled and weighed prior to loading. These bags were then placed at the indicated locations along with the thermocouples. This made it possible to determine the weight lost by the beans during the test, and improved the consistency of sample selection.

The fan was started after both compartments were completely filled and the thermocouples were in place. Harvesting usually required two hours, and loading the container required one hour; thus, about three hours had elapsed before the first beans harvested were under test conditions. During the test period, temperatures were recorded at 20 minute intervals. The air flow was maintained at 4.5 m/s in the 15.2 cm duct. This is equivalent to 0.082 m^3/sec of air through the 1.22 m x 0.61 m area of the ventilated compartment.

The oxygen content at the bottom corner of both the ventilated and unventilated compartment, and the center of the unventilated compartment was measured during several tests. Air samples were drawn

from the sampling location through a tube into the oxygen analyzer, and analyzed. These measurements were usually taken about two hours after starting and two hours before ending a test.

The beans were removed after 24 hours. "Grab" samples were again taken at each location indicated in Table A1, in the Appendix, for the first three tests. For the last three tests, the sample bags were weighed to determine weight loss and these beans were used for all quality evaluations.

IV. EVALUATION OF QUALITY CHANGES

Moisture content was determined by weighing about 60 gm of fresh beans from each sampling location and drying 24 hours at 130°C in a drying oven. Normally, this yielded about 6 gm of dry weight. This determination was made within 1 hour after the beans were removed from the chamber.

It was necessary to transport the samples 80 miles to be analyzed for color and texture. In order to stabilize the quality of the beans until these evaluations could be made, the samples for these analyses were blanched and frozen. The beans were blanched for three minutes at 100°C. After which they were cooled with tap water. The beans were then frozen and transported in a portable freezer. The beans were kept frozen until they were to be analyzed. For analysis, the beans were thawed in tap water. Samples from the same location and test were analyzed simultaneously; thus, a sample from the unventilated compartment was analyzed with its corresponding sample from the ventilated compartment and a sample collected at the beginning of the test.

Two sub-samples were taken from each sample after thawing. These were washed, trash and stems were removed, and placed in a container for color analysis. Another two sub-samples were taken for texture analysis. The pods for this analysis were cut in 6 cm sections. Only the center portion of the pods were used. Ends were discarded. This length was chosen because it was about the width of the shear press cell and allowed the pods to be placed perpendicular to the shear plates. In all tests, except test 2, a 60 gm sample was weighed and tested on the Instron testing machine at a head speed of 10 cm/min. In test 2, the beans were tougher and it was necessary to reduce the test sample to 40 gm to avoid exceeding the capacity of the machine. The head speeds in all tests were the same.

V. ANALYSIS OF DATA

Statistical calculations were made by use of the SAS (Statistical Analysis System) computer program package developed by the Statistics Department at North Carolina State University (Service, 1972). Analysis of variance tables and means were computed by the SAS program for percentage moisture, weight loss, color difference values, maximum shear force, and shear press work. The effects of ventilation and location within each compartment were taken into account.

Energy balance calculations were accomplished by use of computer programs developed for calculation of psychrometric properties in S. I. units. These programs were developed by Wilhelm (1976)

in conjunction with this study. In addition to energy balance relations, bulk mean temperatures for each compartment were computed.

CHAPTER IV

RESULTS AND DISCUSSION

I. EFFECT OF VENTILATION ON BEAN TEMPERATURES AND ENERGY BALANCE

The primary goal in ventilating the beans was the removal of field heat and heat produced by respiration. Ambient air at a sufficient rate of flow could have accomplished this without the evaporative cooler, and bean temperatures that were equal to outside air temperatures could have been maintained. However, any additional cooling would have resulted in dehydration of the beans.

The cooling effectiveness of the evaporative cooler may be seen in Figures A4 through A9 in the Appendix. These curves show the bulk mean temperatures of the ventilated beans to be consistently lower than that of the ambient air. Normally, the temperature difference was about 2°C to 3°C; however, the importance of ambient relative humidity is clearly illustrated in test 1 (Figure A4 in the Appendix) where an afternoon thundershower caused a rapid drop in temperature and increase in relative humidity. This occurred at about the third hour of the test and is represented on the graph by a rapid decrease in ambient temperature to within 0.5°C of the ventilated bean temperature.

The effectiveness of ventilation becomes even more obvious when the curves representing the bulk mean temperatures of the ventilated and unventilated beans are compared. This information is also found in

Figures A4 through A9 in the Appendix. The temperature of the unventilated beans tended to increase for at least the first ten hours of each test. The maximum temperatures reached by the unventilated beans were sometimes above 30°C (tests 1 and 5). This can be compared to maximum temperatures of 25°C for test 1 and 23°C for test 5 for the ventilated beans. In fact, the average difference in the bulk mean temperatures of the ventilated and unventilated beans was 6°C. This included the initial period when temperatures were almost the same. This shows that ventilation with air that has been evaporatively cooled can be effective in maintaining lower temperatures of snap beans handled in bulk.

This temperature difference should have resulted in lower respiration rates and subsequently lower rates of heat evolution by the respiring beans. Based upon values calculated using Equation 1, page 5, and presented along with other energy balance relationships in Table 2, it appears that this was the case. The average heat produced by respiration as calculated was 87 percent greater for the unventilated beans; however, the equation used to calculate these values may be inaccurate at high temperatures and fails to include all pertinent factors, as will be discussed later. The heat of respiration was determined using the measured bean temperatures and Equation 1. The conductive heat transfer was determined from temperature measurements made on the box wall and bottom surfaces, and the thermal conductivity of the box material. Heat gained due to increasing bean temperatures or lost by the beans as their temperatures decreased was determined by measuring bean temperatures and using the coefficient of thermal capacity of snap

TABLE 2. Summary of heat flow relationships.

	Test Number					
	1	2	3	4	5	6
Ventilated Beans						
Weight of Beans (kg)	247	264	292	256	242	225
Heat produced by respiration (kJ)[a]	20,300	16,200	20,200	19,100	16,800	14,300
Heat lost by conduction (kJ)	-80	-70	-80	-90	-110	-80
Heat removed by temperature change (kJ)[b]	3,200	210	2,100	800	3,100	2,800
Heat removed by ventilation (kJ)	20,200	15,500	25,400	18,100	12,400	14,900
Unventilated Beans						
Weight of Beans (kg)	250	257	285	258	245	230
Heat produced by respiration (kJ)[a]	40,900	27,600	34,600	34,200	33,600	29,300
Heat lost by conduction (kJ)	120	80	80	70	60	100
Heat removed due to temperature change (kJ)[b]	-390	-470	-4,500	-6,900	-2,700	-2,400

[a]Calculated using Equation 1 and bulk mean temperature of the beans at 20 minute intervals.

[b]Using a coefficient of thermal capacity of 3.81 kJ/(kg·°C).

beans as indicated by Lutz and Hardenburg (1968). The heat removed by ventilation was calculated using the psychrometric properties of the flowing air.

For the ventilated beans the sum of the heat produced by respiration, gained by conduction, and removed by temperature change should have been equal to the heat removed by ventilation. The data in Table 2 seem to confirm this. It might be noted that since the temperature of the ventilated beans was lower than ambient and the final temperature was lower than the initial temperature, the heat values for conduction and temperature change represented heat which was removed by ventilation. For the unventilated beans, conduction and temperature change partially accounted for the heat produced by respiration. However, the sum of these two factors represented on the average, less than 10 percent of the calculated heat produced by respiration. Another medium of heat transport from the unventilated beans was free convection from the open top. Unfortunately, no reliable method of measuring free convection was devised. However, it would seem unlikely that free convection could have resulted in substantial heat transfer from the unventilated beans. Therefore, the calculated values for the heat of respiration of the unventilated beans appear to be too high. The equation used to calculate the heat of respiration considers only the effect of temperature on the rate of respiration. As the temperature increased, other factors would have increasingly important roles in limiting respiration. One important factor was the amount of oxygen available. The oxygen concentrations at selected locations within both compartments are presented in Table A2 in the Appendix. These

measurements were made about two hours and twenty-two hours after the beans were loaded into the box. As can be seen from the table, the atmosphere of the unventilated compartment showed lowered oxygen concentrations at the two hour measurement. The minimum measured value was 17 percent. This was well above the necessary level for aerobic respiration, but could have caused a lower rate of respiration than predicted by the equation at the temperatures prevalent at that point. After twenty-two hours the oxygen levels had returned to normal. This indicates that the beans were respiring at a lower rate than in the first two hours. The high initial rate may have been caused by the higher metabolic activity as the wounds caused by harvesting healed. The lowered rate after several hours could have been due to the depletion of easily translocatable materials to respire, which would occur if high rates of respiration continued over a long period. Increasing levels of carbon dioxide may have also retarded respiration.

Whether these factors or other undetermined ones were responsible for the behavior of the unventilated beans in this study cannot be readily ascertained. Only careful monitoring of samples under highly controlled conditions can limit the variables sufficiently for this type of determination. However, the unventilated beans did experience higher temperatures which should have been detrimental to their quality.

II. THE PROCESS OF COOLING BY VENTILATION

The ventilating air was effective in cooling the beans. The process by which this cooling was accomplished in the system under study merits closer consideration.

The system may be considered to have consisted of three components which affected the psychrometric properties of the air. The first was the blower or centrifugal fan, which drew in ambient air and provided a pressure sufficient to maintain air flow through the beans. The effect of the blower was an increase in the enthalpy of the air with no change in the moisture content. The next component of the cooling process was evaporative cooling. This process should have been an adiabatic addition of moisture; however, the air usually experienced some change in enthalpy as it passed through the evaporative cooler. This enthalpy change was probably due primarily to heat transfer through the walls of the evaporative cooler. This contention is supported by the fact that the enthalpy change tended to fluctuate; sometimes representing a heat gain and sometimes representing a heat loss. Additionally differences in the temperature of the water in the evaporative cooler and the air passing through it, or errors in temperature measurements, could have been partially responsible for these fluctuations. Overall, this enthalpy change was of little consequence; and the evaporative cooler served well in its major functions, lowering the dry bulb temperature and increasing the moisture content of the cooling air. In the final component of the process the air passed through the beans. Normally both heat and water were removed from the beans by the air. However, there were instances of either heat or water or both being added to the beans. These instances are clearly illustrated in Figures A10 through A15, in the Appendix, where the heat and moisture removed from the beans by the flowing air are depicted graphically for each of the six tests. Also included on these

curves is the amount of moisture the evaporative cooler added to the air.

The heat curves exhibit similar trends for each of the six tests. Initially the rate of heat removal was quite high. This was followed by a short period of heat addition (Figure A10, Appendix) or low levels of heat removal as in Figure A12 in the Appendix. After this there was a long period of stability at moderate levels of heat removal. The final phase consisted of rapid fluctuations with heat addition again occurring.

The moisture removed from the beans follows the pattern of heat removal quite closely. Again great consistency from test to test was exhibited. The curves representing the moisture added to the air by the evaporative cooler were somewhat different. The amount of moisture added by the evaporative cooler followed the same pattern as the variations in the relative humidity of the ambient air. As was expected, the moisture added was less at higher ambient relative humidity levels.

Numerous factors must be considered to explain the curves representing heat and moisture removed from the beans. Generally, the beans had considerable surface moisture when they were loaded into the apparatus. This when combined with a higher respiration rate due to the healing of wounds caused by harvesting and handling, resulted in high initial values of heat and moisture removed. This led to decreasing bean temperatures and an increasing difference between ambient and bean temperatures (Figure A4, Appendix). Finally, all the surface moisture was evaporated. With no surface moisture available

for evaporative cooling in the beans, the cooling capacity of the air was limited to changes in specific heat. However, the air temperature was higher than the bean temperature. This resulted in the air giving up heat to the beans. The heat added caused an increase in bean temperatures which led to a higher rate of respiration, producing more heat and moisture. The balancing of this heat production with the cooling capacity of the air is represented by the fairly stable conditions occurring during the middle portion of the heat removal curves (Figures A10 through A15, Appendix). This period occurred during the night. Figures A4 through A9, in the Appendix, show both bean and ambient temperatures decreasing, indicating slower respiration for all tests during that period. Unstable conditions occurred again in the morning when ambient temperatures increased and gave up heat to the beans. Stability had not returned as each test ended.

The process of cooling may be summarized in terms of the psychrometric properties of the ventilating air by means of Figure 6. The blower represented by process 1-2, added heat in a constant moisture process. The evaporative cooler added moisture in a constant enthalpy process. In passing through the beans the air normally followed line 2-3, picking up heat and moisture from the beans. However, process 2-4 also occurred, with the beans receiving heat and moisture from the air. The processes depicted in Figure 6 are idealized and do not represent all possible conditions.

There were two equipment malfunctions during this study that had an effect on the results. During test 2 the temperature recorder malfunctioned and no temperatures were recorded from the eighteenth

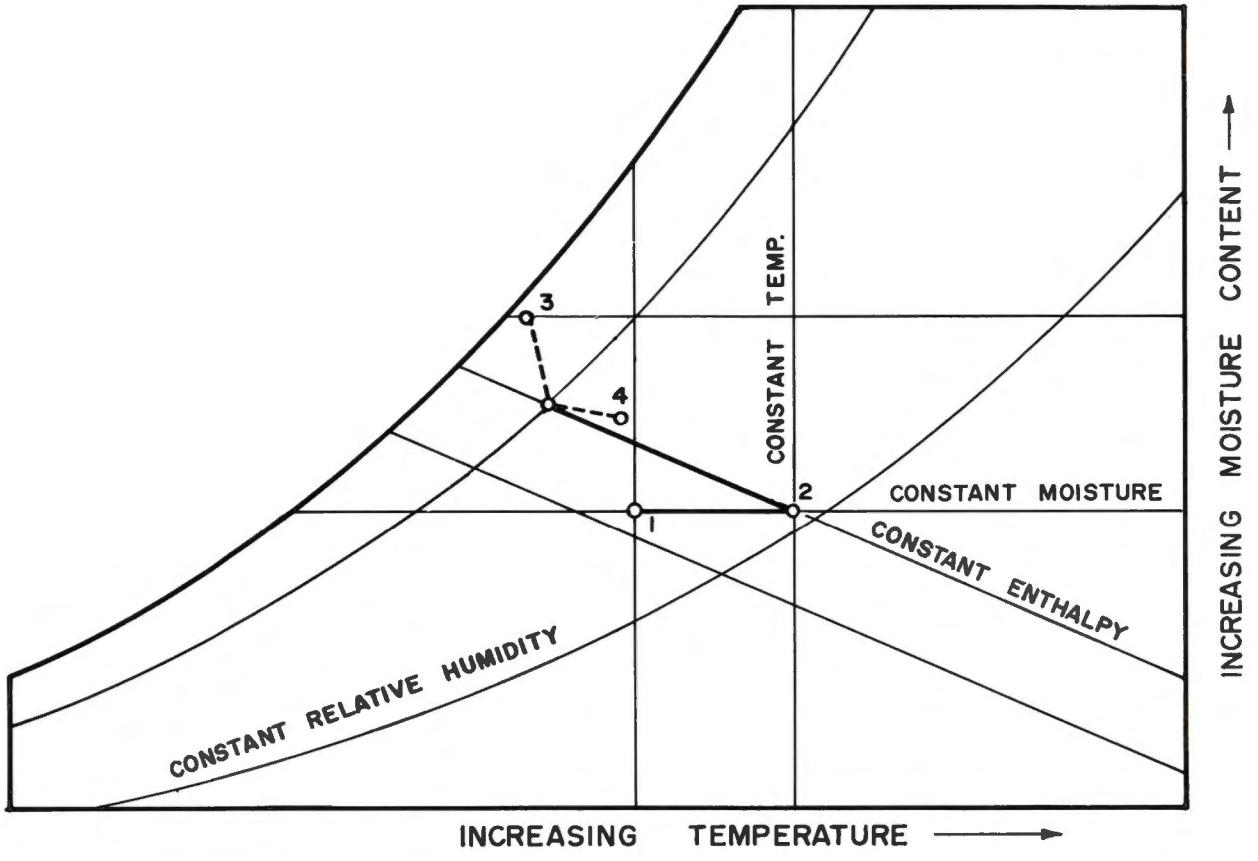


FIGURE 6. Psychrometric properties of the ventilating air as it flows through the system. Air is heated by the blower (1-2), cooled by the evaporative cooler, and then flows through the beans (2-3 or 2-4).

through the twenty-third hour. The data are shown as missing in Figure A5, in the Appendix, but were estimated in the rest of the analysis. In test 6 the blower did not function properly from the seventeenth to the twenty-second hour. During this period no forced ventilation cooling occurred.

Overall, evaporation of moisture was of great importance in the process of cooling. When surface moisture was available on the beans, the ventilating air removed it, causing a lower temperature. However, the evaporative cooler kept the moisture content of the air high enough to prevent dehydration of the beans and the resulting quality deterioration.

III. STATISTICAL ANALYSIS OF CHANGES IN PHYSICAL PROPERTIES

The effects upon bean quality of storage under ventilated and unventilated conditions were determined by the analysis of several physical properties. The results of these analyses are presented in Table 3. The analysis of variance tables associated with the means presented in Table 3 are in Table A3 in the Appendix. The experimental design was a randomized complete block with each test representing a replication. The treatment by test interaction was used as the error mean square in the test of treatment. The residual represents a pool of the variances associated with location of the samples, the interactions associated with location, and sampling within location. Differences between means at the 5 percent significance level ($\alpha = 0.05$) were determined by Duncan's New Multiple Range Test.

TABLE 3. Means of the measured physical properties by treatment.

	When Harvested	Ventilated for 24 Hours	Unventilated for 24 Hours
Weight Loss (g/100 g fresh weight)		3.3^{a}	3.6^{a}
Moisture Content (percent wet basis)	92.3^{b}	91.8^{b}	91.9^{b}
Peak Shear Force for a 60 g Sample (Newtons)	3621^{c}	3886^{d}	3850^{d}
Work to Shear 60 g Sample (Newton meters)	35.9^{e}	39.9^{f}	39.6^{f}
Color			
L (Lightness)	30.8^{g}	31.3^{h}	31.0^{gh}
a (Degree of greenness)	-11.5^{i}	-11.1^{ij}	-10.9^{j}
b (Degree of yellowness)	14.1^{k}	14.5^{l}	14.5^{l}

NOTE: Means with different superscripts are different ($\alpha = .05$).

As can be seen from Table 3 the fresh weight of the beans was reduced by about 3.5 percent over the 24 hour test period. The ventilated beans did not lose as much weight as the unventilated beans, but the difference was not significant. The moisture content of the beans was also reduced during the storage period, but there was no significant change caused by storage under either condition. Thus, the evaporative cooler prevented the beans from dehydrating excessively.

The peak shear force and work required to shear a 60 g sample showed a significant increase for beans stored 24 hours. The higher values indicate the stored beans increased in toughness during their storage period. Ventilation was not effective in limiting this increase in toughness. In fact, the ventilated beans required higher peak forces and more work to shear than the unventilated beans, but the differences were not significant. Test 2 was excluded from the peak shear force and work analysis in Table 3. The 40 g samples used in test 2 resulted in values considerably lower than those of the other tests. The treatment means for test 2 are presented in Table A4 in the Appendix.

In terms of color, the stored beans tended to be lighter, less green, and more yellow. There was no significant difference between the ventilated and unventilated beans for any of the color parameters measured. There was a significant difference in the "L" or lightness values for the ventilated bean when compared to those of the beans when harvested. The unventilated beans were not significantly different from freshly harvested beans for "L" values. The loss of greenness for the ventilated beans, as measured by "a" values, was not

significant. The "a" values for the unventilated beans were significantly higher than those of the beans when harvested. Storage for 24 hours caused significant increases in the degree of yellowness or "b" values whether the beans were ventilated or not.

Overall, ventilation was not shown to be greatly advantageous in the maintainance of the measured physical characteristics under the conditions encountered in this study. However, the dehydration caused by ventilation in previous studies (Wilhelm et al., 1973) was eliminated by the evaporative cooler.

The means of each of the physical properties by location within the ventilated and unventilated compartments were also analyzed. These analyses were conducted to establish whether the higher temperatures at some locations in the unventilated compartment or the uneven air flow in the ventilated compartment caused changes in quality. The results of the analyses are present in Tables A5 through A8 in the Appendix. No significant differences were found among location means.

The correlation coefficients associated with each pair of measured physical properties are presented in Table A9 in the Appendix. As expected, a significant correlation at the 5 percent level existed between each pair of the parameters indicative of color; darker beans were also less green and less yellow. The correlation coefficient between peak shear force and work done was also significant; samples with higher peaks required more work. Significant ($\alpha = 0.05$) correlation coefficients were calculated between moisture content and each of the following: peak shear force, "L" value, "a" value, "b" value, and weight loss. For peak shear force, lightness, and yellowness,

the correlation coefficient was negative. Thus beans that were higher in moisture tended to require less shear force, were darker and were less yellow. The positive correlation between moisture and greenness means that the greener beans tended to have a lower percentage moisture. The correlation coefficient between moisture content and weight loss was also positive, thus the beans which experienced a greater weight loss tended to have a higher percentage moisture as determined when the beans were removed from the container. This can be explained if the following is assumed. First, the pods tended to lose water at a faster rate than dry matter, and second; that the losses tended to make final moisture content percentages equal for all beans. The first supposition is reasonable if the final moisture content was lower than the initial moisture content; Table 3, page 37, supports this. The second supposition seems acceptable since the environment in the box was more homogeneous than the field environment. The lack of significant differences in moisture content means by location (Tables A6 and A8, Appendix) tend to support this contention. These two assumptions lead to the following conclusion. Those samples which had a high initial moisture content would have lost more weight and retained a higher moisture content than those samples with a low initial moisture content. Thus the process may be clearly understood, only if initial moisture content is included. This was impossible with the test procedures used in this study. Weight loss and greenness also had a significant correlation coefficient. Beans which were greener had lost less weight.

Temperature means at each sampling location within the ventilated and unventilated compartments were included in a correlation analysis. The results of this analysis are also given in Table A9 in the Appendix. For the unventilated beans, significant correlation coefficients were calculated for temperature and peak shear force, and temperature and work done by the shear press. This indicates that beans which had experienced higher mean temperatures tended to be tougher as well. For the ventilated beans, calculated correlation coefficients between mean temperatures and each of the following were significant: moisture content, peak shear force, work to shear the sample, lightness, and yellowness. Beans which had experienced lower mean temperatures tended to be less tough, less dark, more yellow, and lower in moisture content.

No cause and effect relationships can be ascertained from the correlation analysis. Much of the variation, particularly in the mean temperatures of the ventilated beans, was caused by the factors associated with replication or differences among tests. However, the significant correlation coefficients indicated that many of the properties measured were dependent on common factors in their variations.

IV. OTHER FACTORS AFFECTED BY STORAGE

Although no extensive analysis was conducted, several other features indicative of the condition of the beans were observed to have been affected by storage.

Usually the beans were wet and dirty when they were loaded into the container. Thus conditions were ideal for mold growth, and some mold growth was observed. The pockets of mold usually appeared to be centered around pods that had begun deterioration before harvest; there was normally some evidence of the diseased pod having been in contact with the ground. These pockets of mold occurred with equal frequency in the ventilated and unventilated compartments; however, the extent of damage in the ventilated compartment was usually less. Overall, the extent of damage by mold was minor.

The unventilated beans had a great deal of surface moisture and seemed to be limp as they were removed from the container. The ventilated beans had no surface moisture and appeared to be somewhat more turgid. It was also apparent that the ventilated beans were at a temperature below ambient, while the unventilated beans were warmer than ambient air.

After being frozen and thawed, the unventilated beans exhibited a greater tendency to slough the epidermal layer than either the ventilated beans or the beans frozen immediately after harvesting. The stored beans also tended to split along the ventral suture after being thawed. This tendency was slightly more prevalent in the ventilated beans.

CHAPTER V

SUMMARY AND CONCLUSIONS

Six tests were conducted under conditions similar to bulk transport. Each test lasted 24 hours. During the test period, one container of beans received forced ventilation of high moisture air. A similar container was unventilated. Temperatures within the beans and their surroundings were periodically recorded. Temperatures were also measured for the flowing air. These measurements were used to determine heat evolution characteristics for the beans under test conditions.

The ventilated beans maintained cooler temperatures and apparent lower respiration rates than the unventilated beans. The average temperature difference between the ventilated and unventilated beans was 6°C. Energy balance calculations showed the flow rate used in the study to be sufficient to maintain cooler temperatures. Observation of the heat and moisture removal curves for the study showed these characteristics to be fairly consistent from test to test and, thus, seemly predictable.

Samples were collected at the beginning and end of each test and evaluated in terms of several physical properties. After 24 hours, both the ventilated and unventilated beans were tougher and showed more yellow color. The beans in the unventilated compartment had lost some of their greenness during the test, while the ventilated beans had

become lighter. Twenty-four hours under both ventilated and unventilated conditions resulted in a weight loss, but no appreciable change in moisture content was measured. It was also observed that ventilation did not greatly affect mold growth, but that ventilated beans were more turgid than unventilated beans when removed from the container.

Forced ventilation cooling was effective in removing field heat and the heat of respiration of the snap beans. An average of 69.8 kJ/kg of heat was removed from the beans by forced ventilation over the 24 hour test period. This was the average for six bulk loads of snap beans during the 24 hours immediately following harvest. The ventilated bean temperatures were normally about two degrees Celsius below ambient, and averaged six degrees Celsius below comparable unventilated beans. The moisture added by the evaporative cooler allowed the beans to be cooled without excessive moisture loss. The relative humidity of the ambient air was shown to be important in the cooling effect.

The respiration rates of the ventilated beans were calculated to be lower than those for the unventilated beans, but the equation used appeared to be inaccurate at the temperatures experienced by the unventilated beans. This was due to the lack of data on snap bean respiration at high temperatures and exclusion of other factors, such as lowered oxygen concentrations, from the calculations. The unventilated beans did experience lowered oxygen levels during the initial hours of the tests.

The reduction in the changes in the physical properties of the beans expected by lowered respiration rates were not observed.

However, the reduced oxygen levels could have resulted in anaerobic respiration and the formation of undesirable chemical compounds in the unventilated beans. This would necessitate the use of some form of ventilation, making the use of the evaporative cooler important.

The conditions encountered during this study do not represent all the situations that might arise during the transportation of snap beans. The monitoring and measurement of procedures and conditions under actual transportation situations could be informative in this regard. This information combined with the results of this study could then be used to further refine the evaporative cooler and determine if its implementation could be justified under prevalent and predicted economic conditions.

The lack of an accurate equation for the prediction of the heat of respiration of snap beans at high temperatures suggests a study of the effects of high temperatures and specified environment, such as lowered oxygen concentration on snap beans. This would require careful monitoring of all input parameters and determination of the chemical composition changes caused by such an environment.

The curves representing the heat removed by the flowing air suggest a study of the system represented by the beans and flowing air as a dynamic heat transfer system. This would allow the determination of parameters that would be applicable for calculations in changing environments.

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APPENDIX

TABLE A1. Locations corresponding to samples collected for quality evaluations.

Sample Number	Location[a]		
	Plane[b]	Height	Area[c]
1	Inside	Top	Front
2	Center	Top	Front
3	Outside	Top	Front
4	Center	Top	Center
5	Inside	Top	Rear
6	Center	Top	Rear
7	Outside	Top	Rear
8	Center	Center	Front
9	Inside	Center	Center
10	Center	Center	Center
11	Outside	Center	Center
12	Center	Center	Rear
13	Inside	Bottom	Front
14	Center	Bottom	Front
15	Outside	Bottom	Front
16	Inside	Bottom	Rear
17	Center	Bottom	Rear
18	Outside	Bottom	Rear

[a]These locations apply to both the ventilated and unventilated compartments. Refer to Figure 4, page 19.

[b]The inside plane corresponds to Section C-C or Section D-D in Figure 4. The outside plane corresponds to Section A-A or Section F-F. The center plane corresponds to Section B-B or Section E-E.

[c]Front and rear are primarily for identification; effects should have been symmetrical.

TABLE A2. Oxygen concentrations in the bean container during the tests (percent).

	Test				
	1	3	4	5	6
After 2 hours					
Ventilated Bottom Center	21	21	21	21	21
Unventilated Bottom Center	17	20	19	20	20
Unventilated Center	19	21	20	18	17
Ambient	21	21	21	21	21
After 22 hours					
All Locations	21	21	21	21	21

TABLE A3. Analysis of variance summaries for the effect of ventilation on the measured physical properties.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F Value
Weight Loss				
Treatment	1	0.000238865	0.0002388650	0.29508
Test	2	0.035228141	0.0176140705	
Treatment x Test	2	0.001618976	0.0008094878	
Residual	102	0.088669871	0.0008693125	
Corrected Total	107	0.125755853	0.0011752883	
Moisture Content				
Treatment	2	0.001401538	0.0007007691	1.98779
Test	5	0.003559862	0.0007119725	
Treatment x Test	10	0.003525376	0.0003525376	
Residual	306	0.014239142	0.0000465331	
Corrected Total	323	0.022725918	0.0000703589	
Peak Shear Force				
Treatment	2	7292668	3646333.77	6.45579*
Test	4	12108918	3027229.56	
Treatment x Test	8	4518528	564815.95	
Residual	516	118924346	230473.54	
Corrected Total	530	142844459	269517.85	
Work to Shear Sample				
Treatment	2	1768.5814	884.290724	8.63469*
Test	4	2385.0647	596.266181	
Treatment x Test	8	819.2914	102.411419	
Residual	516	15836.3253	30.690553	
Corrected Total	530	20809.2628	39.262760	
"L" Value				
Treatment	2	26.25529	13.127645	5.19054*
Test	5	1183.12879	236.625757	
Treatment x Test	10	25.29150	2.529150	
Residual	588	2451.81975	4.169761	
Corrected Total	605	3686.49533	6.093381	
"a" Value				
Treatment	2	35.83506	17.917531	5.15711*
Test	5	759.11206	151.822412	
Treatment x Test	10	34.74334	3.474334	
Residual	588	2406.52380	4.092728	
Corrected Total	605	3236.21426	5.349114	

TABLE A3 (continued).

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F Value
"b" Value				
Treatment	2	20.70024	10.350122	9.44349**
Test	5	344.85738	68.971476	
Treatment x Test	10	10.96006	1.096006	
Residual	588	837.13092	1.423692	
Corrected Total	605	1213.64860	2.006031	

*Significant at the .05 level.

**Significant at the .01 level.

TABLE A4. Means by treatment for peak shear force and work to shear the sample for test 2.

	When Harvested	Ventilated for 24 Hours	Unventilated for 24 Hours
Peak Shear Force for 40 g Sample (Newtons)	2951	2934	3079
Work to Shear 40 g Sample (Newton Meters)	23.7	24.0	25.0

TABLE A5. Means of the measured physical properties and temperatures by location within the ventilated compartment.

Location	Temperature (°C)	Weight Loss (g/100 g)	Moisture Content (%)[a]	Peak Shear Force (N)	Shear Work (NM)	Color		
						L	a	b
1	21.8	3.8	91.5	3900	40.2	32.3	-10.8	15.1
2	21.9	3.6	92.0	3784	41.1	30.9	-12.0	14.5
3	21.8	2.5	92.0	3927	40.8	31.2	-11.5	14.6
4	21.6	2.9	92.1	3949	40.9	32.1	-11.4	15.1
5	21.5	2.7	92.1	3829	38.7	31.7	-10.6	14.5
6	21.7	2.2	92.4	3967	41.1	31.0	-10.3	14.0
7	21.8	4.3	92.1	3726	40.5	31.4	-10.1	14.2
8	21.6	2.7	91.6	3686	40.3	30.0	-11.0	14.0
9	21.4	4.0	91.9	3844	40.0	30.8	-12.6	14.6
10	21.4	1.9	91.8	3932	38.0	31.5	-12.5	15.0
11	21.5	0.0	91.7	4001	40.6	32.5	-11.5	15.0
12	21.6	4.3	91.8	3775	38.3	31.7	-10.8	14.6
13	21.6	6.8	91.3	3952[b]	39.3[b]	31.4[b]	-10.9[b]	14.4[b]
14	21.4	4.4	91.5	--	--	--	--	--
15	21.3	4.1	91.4	4001	38.1	30.9	-11.2	14.2
16	21.4	4.0	91.7	3942	40.4	31.1	-10.8	14.3
17	21.4	7.2	91.6	4084	40.4	31.7	-10.4	14.4
18	21.5	3.3	91.4	3794	38.9	29.9	-10.5	13.5

[a]Percentage moisture on fresh weight basis.

[b]Data for these parameters were not collected for location 14.

TABLE A6. Analysis of variance summaries for the effect of location within the ventilated compartment on the measured physical properties.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F Value
Weight Loss				
Location	17	0.013700162	0.0008058919	1.51189
Test	2	0.010893067	0.0054465333	
Location x Test	34	0.018123246	0.0005330366	
Corrected Total	53	0.042716474	0.000805972	
Moisture Content				
Location	17	0.000880480	0.0000517929	1.05208
Test	5	0.002821242	0.0005642484	
Location x Test	85	0.004184481	0.0000492292	
Corrected Total	107	0.007886203	0.0000737028	
Peak Shear Force				
Location	16	1971130.4	123195.65	0.43509
Test	4	5734442.3	1433610.59	
Location x Test	64	18121553.2	283149.37	
Residual	91	13702062.5	150572.12	
Corrected Total	175	39529188.5	225881.08	
Work to Shear Sample				
Location	16	184.95868	11.559917	0.18993
Test	4	1445.74732	361.436831	
Location x Test	64	3895.26556	60.863524	
Residual	91	1964.68549	21.589950	
Corrected Total	175	7490.65705	42.803755	
"L" Value				
Location	16	92.69751	5.7935941	1.07182
Test	5	415.14733	83.0294664	
Location x Test	80	432.43115	5.4053894	
Residual	100	267.17000	2.6717000	
Corrected Total	201	1207.44599	6.0071940	
"a" Value				
Location	16	97.401602	6.0876001	1.02641
Test	5	254.276281	50.8552563	
Location x Test	80	474.477810	5.9309726	
Residual	100	162.740000	1.6274000	
Corrected Total	201	988.89563	4.9198791	
"b" Value				
Location	16	37.637848	2.3523655	1.35647
Test	5	121.750438	24.3500875	
Location x Test	80	138.734487	1.7341811	
Residual	100	80.685000	0.8068500	
Corrected Total	201	378.807772	1.8846158	

TABLE A7. Means of the measured physical properties and temperatures by location within the unventilated compartment.

Location	Temperature (°C)	Weight Loss (g/100 g)	Moisture Content (%)[a]	Peak Shear Force (N)	Shear Work (NM)	Color		
						L	a	b
1	25.5	6.2	91.7	3905	40.4	32.5	-10.6	15.3
2	28.8	2.6	92.2	2815	40.6	30.7	-10.9	14.6
3	27.5	2.5	91.8	3905	40.0	31.0	-10.6	14.6
4	29.6	8.9	91.9	3566	37.4	32.4	-12.6	15.4
5	27.1	5.7	92.1	5040	41.4	32.0	- 9.9	14.7
6	28.7	3.3	92.3	3819	38.6	31.1	-10.0	14.3
7	26.8	2.8	91.9	3499	36.1	31.2	- 9.9	14.3
8	28.3	2.7	92.3	3882	41.9	30.5	-10.5	14.1
9	27.6	2.3	91.9	3837	39.5	31.5	-12.3	15.2
10	29.2	1.9	92.2	4079	40.6	30.6	-12.0	14.4
11	28.6	2.3	91.8	3878	39.4	30.7	-10.8	14.3
12	27.6	2.7	91.8	3908	39.9	30.4	-11.0	14.3
13	25.5	2.1	92.0	3775[b]	38.8[b]	31.0[b]	-11.0[b]	14.0[b]
14	26.6	2.4	91.9	--	--	--	--	--
15	25.3	3.3	91.7	3810	38.8	30.2	-10.9	14.1
16	26.6	2.8	91.8	3848	39.2	30.9	-11.6	14.5
17	27.6	2.3	91.2	3902	40.4	30.9	-10.5	14.3
18	28.1	2.5	91.9	4030	40.9	29.8	-10.3	13.7

[a]Percentage moisture on fresh weight basis.

[b]Data for these parameters were not collected for location 14.

TABLE A8. Analysis of variance summaries for the effect of location within the unventilated compartment on the measured physical properties.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F Value
Weight Loss				
Location	17	0.016532804	0.0009725179	0.82021
Test	2	0.025954050	0.0129770250	
Location x Test	34	0.040313659	0.0011856959	
Corrected Total	53	0.0828005132	0.0015622738	
Moisture Content				
Location	17	0.000700456	0.0000412033	0.93464
Test	5	0.001298637	0.0002597275	
Location x Test	85	0.003747210	0.0000440848	
Corrected Total	107	0.005746303	0.0000537038	
Peak Shear Force				
Location	16	3736970.9	233560.68	0.80916
Test	4	3237374.9	809343.73	
Location x Test	64	18473434.9	288647.42	
Residual	93	19415428.7	208768.05	
Corrected Total	177	44863209.4	253464.46	
Work to Shear Sample				
Location	16	356.56384	22.285240	0.51067
Test	4	810.98046	202.745114	
Location x Test	64	2792.89805	43.639032	
Residual	93	2070.17544	22.259951	
Corrected Total	177	6030.61778	34.071287	
"L" Value				
Location	16	101.68687	6.3554292	0.87693
Test	5	436.61025	87.3220490	
Location x Test	80	579.78911	7.2473639	
Residual	102	285.95667	2.8045967	
Corrected Total	203	1404.04289	6.9164674	
"a" Value				
Location	16	122.47627	7.6547670	1.10646
Test	5	222.21377	44.4427549	
Location x Test	80	553.46059	6.9182574	
Residual	102	166.16167	1.6290359	
Corrected Total	203	1064.31230	5.2429178	
"b" Value				
Location	16	38.716438	2.4197774	0.92788
Test	5	119.860441	23.9720882	
Location x Test	80	208.628562	2.6078570	
Residual	102	91.850000	0.9004902	
Corrected Total	203	459.055441	2.2613569	

TABLE A9. Results of the correlation analysis of the measured physical properties and temperatures.

	Weight Loss	Moisture	Peak	Work	"L"	"a"	"b"
"b"	-0.187091	-0.321010*	0.006880	-0.016939	0.861072*	-0.649445*	
"a"	-0.222610*	0.146444*	0.088813	0.072118	-0.373200*		
"L"	-0.1345434	-0.364342*	0.077318	0.005167			
Work	0.150459	-0.054199	0.900751*				
Peak	0.187420	-0.133119*					
Moisture	0.205089*						
Mean Temperature Unventilated	-0.134444	0.063821	0.243055*	0.26883*	0.000116	-0.096805	0.005798
Mean Temperature Ventilated	0.076909	-0.461513*	0.428404*	0.372095*	0.351715*	-0.033872	0.206140*

*Significant at the .05 level.

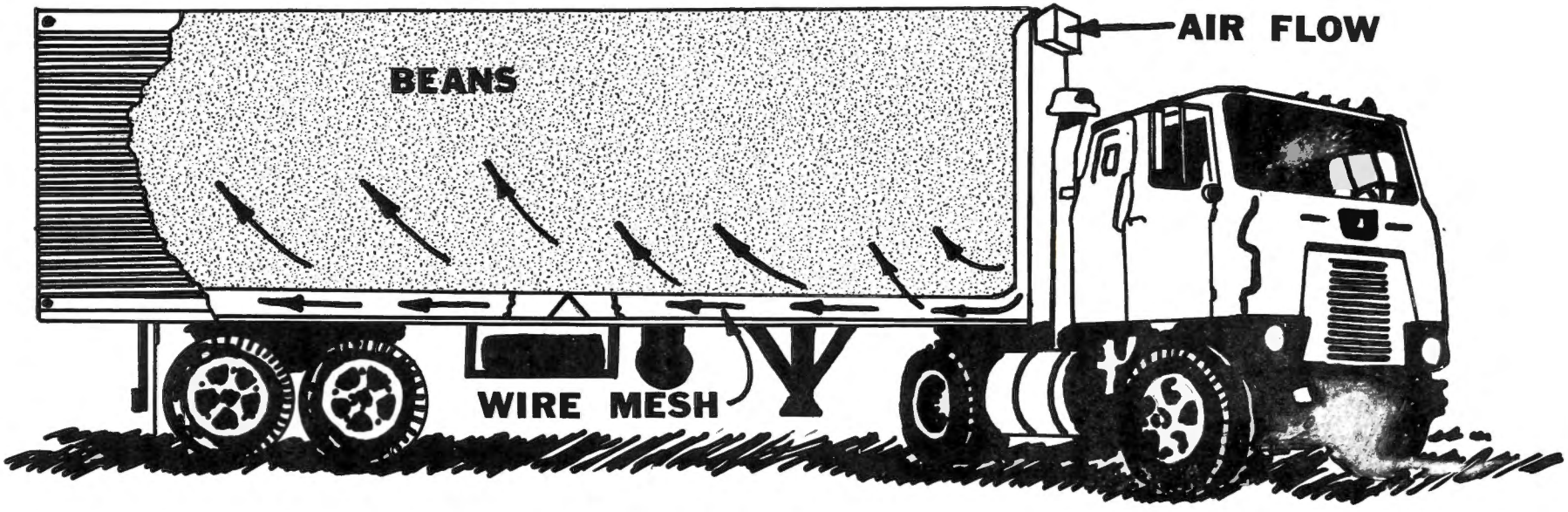


FIGURE A1. Truck used for transporting beans and equipped with an air scoop to utilize forced air cooling.

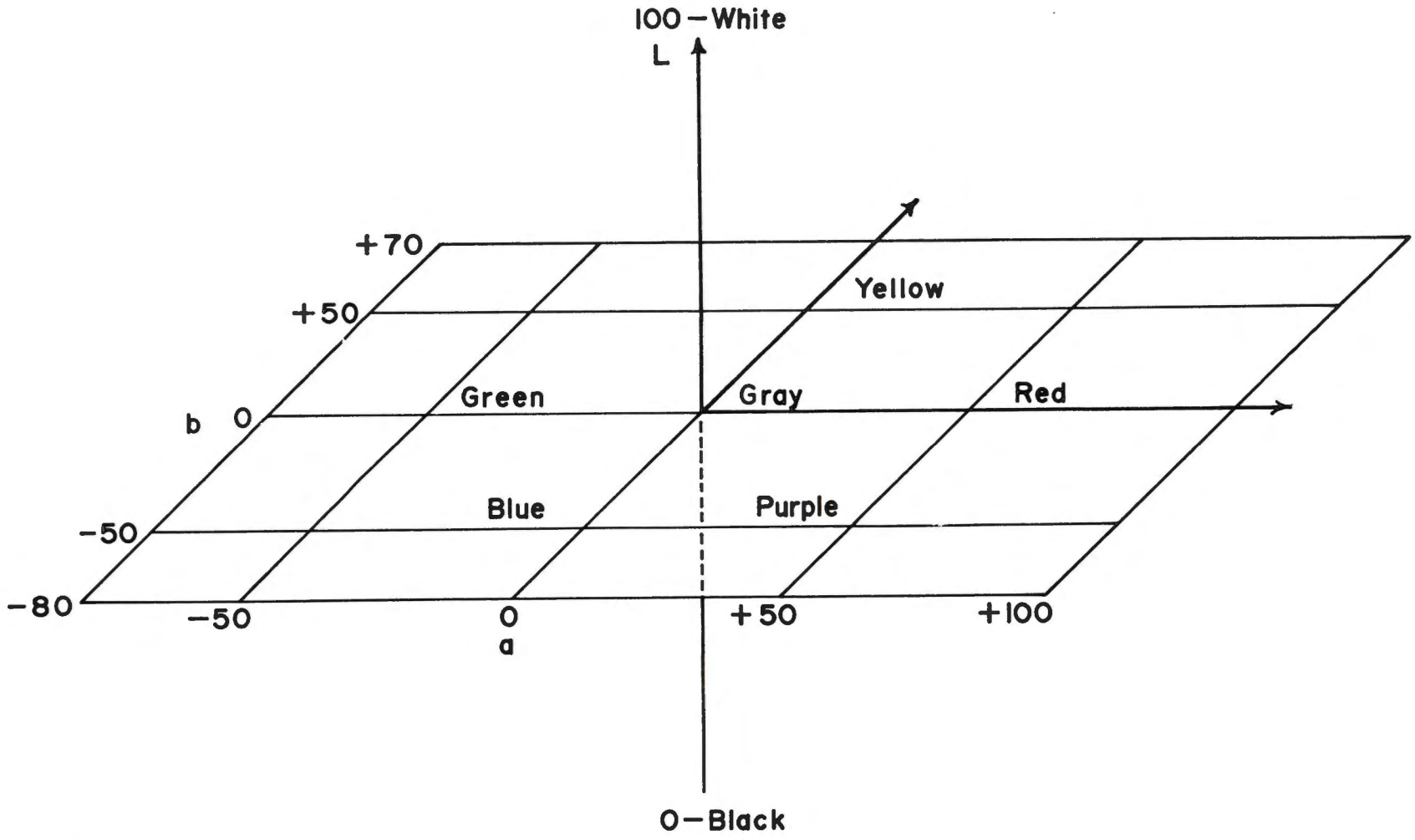


FIGURE A2. Diagram of three-dimensional scale for the Hunter color-difference meter.

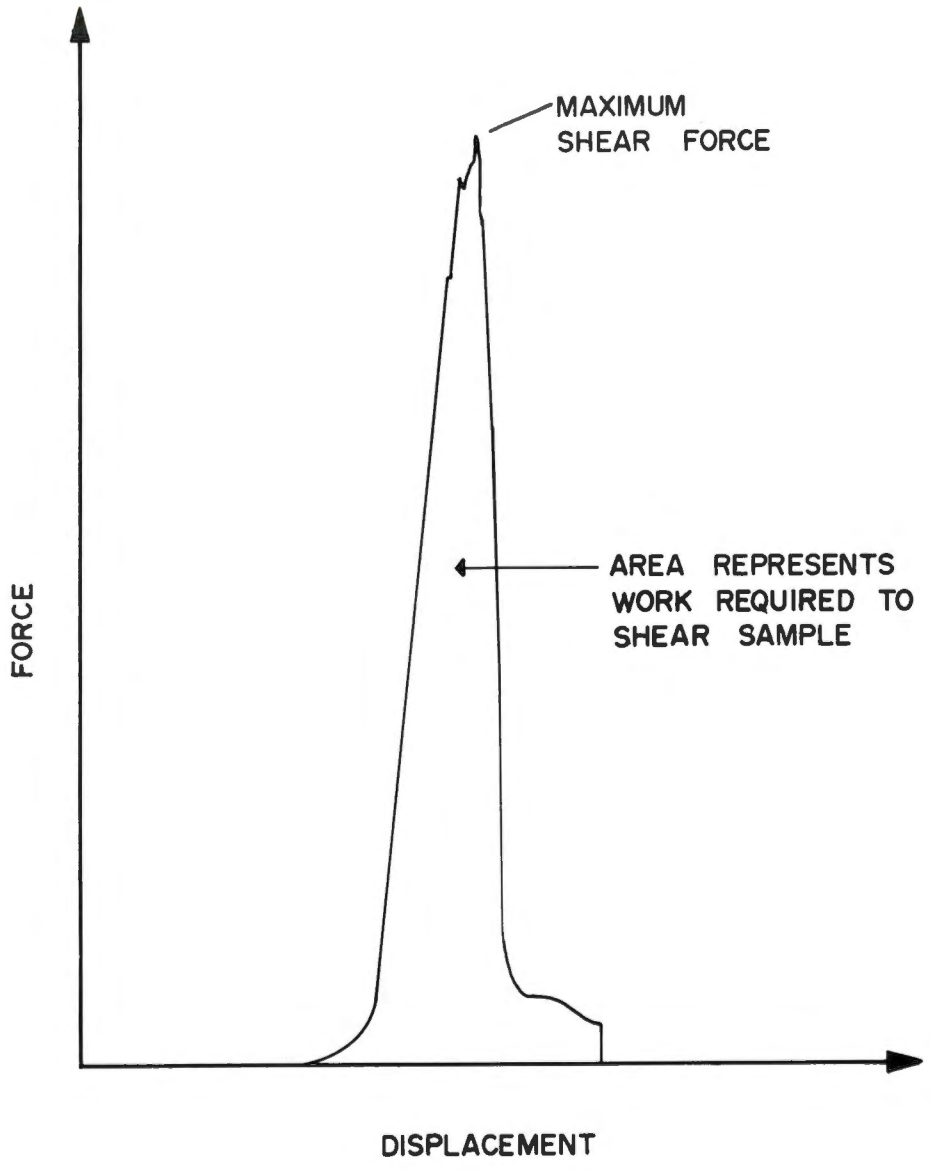


FIGURE A3. Typical force-displacement curve for a 60 g sample of snap beans using an Allo-Kramer shear press at a press speed of 10 cm/min.

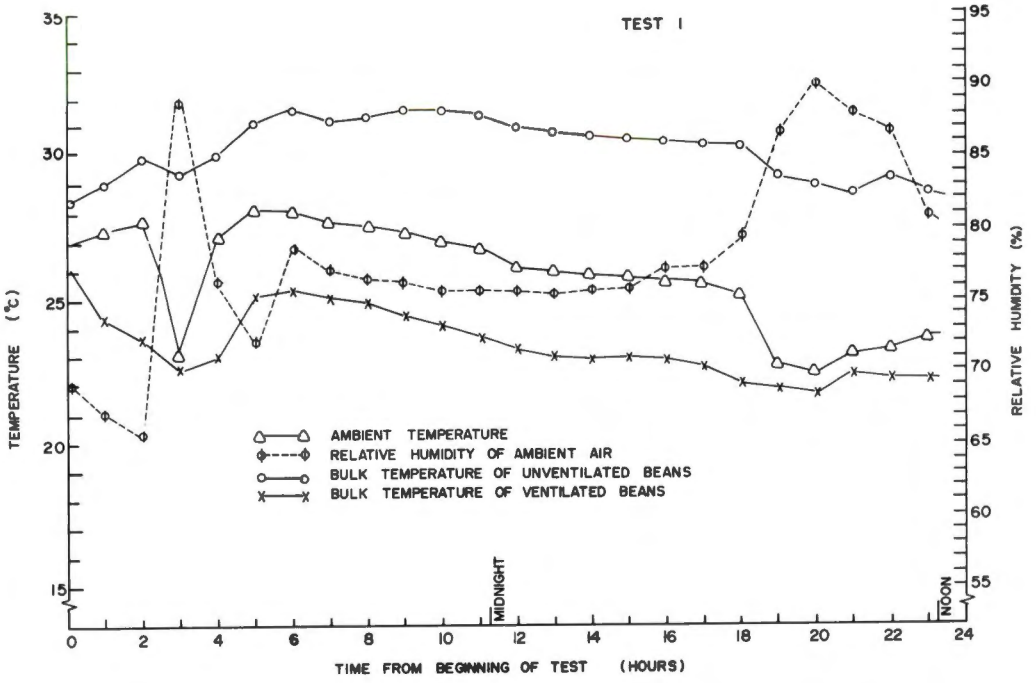


FIGURE A4. Temperature and relative humidity records over the 24 hour test period for test 1.

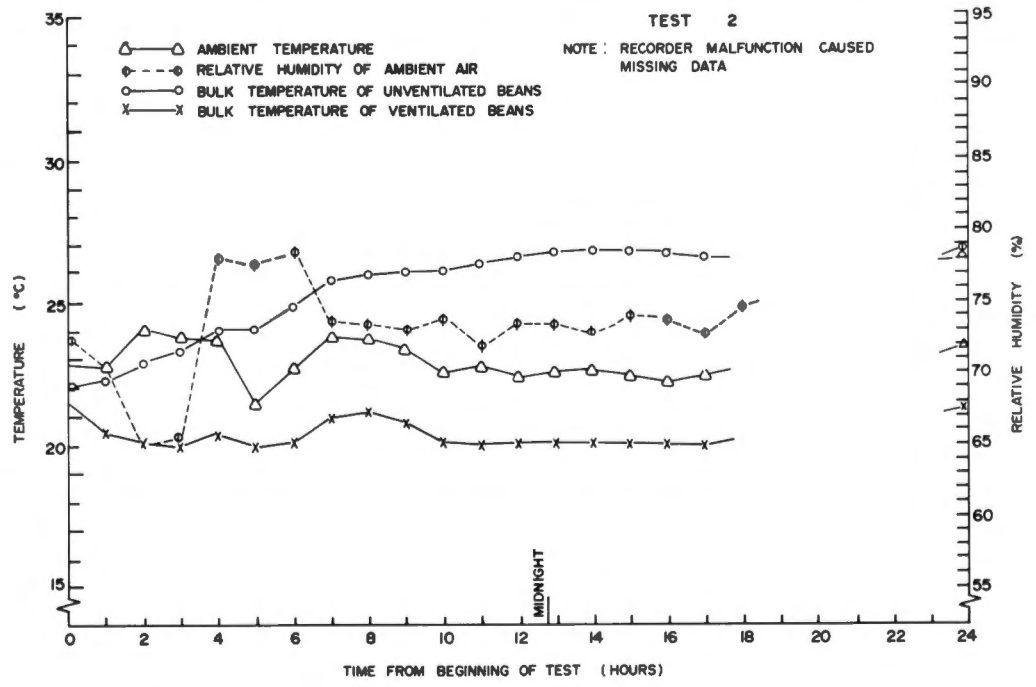


FIGURE A5. Temperature and relative humidity records over the 24 hour test period for test 2.

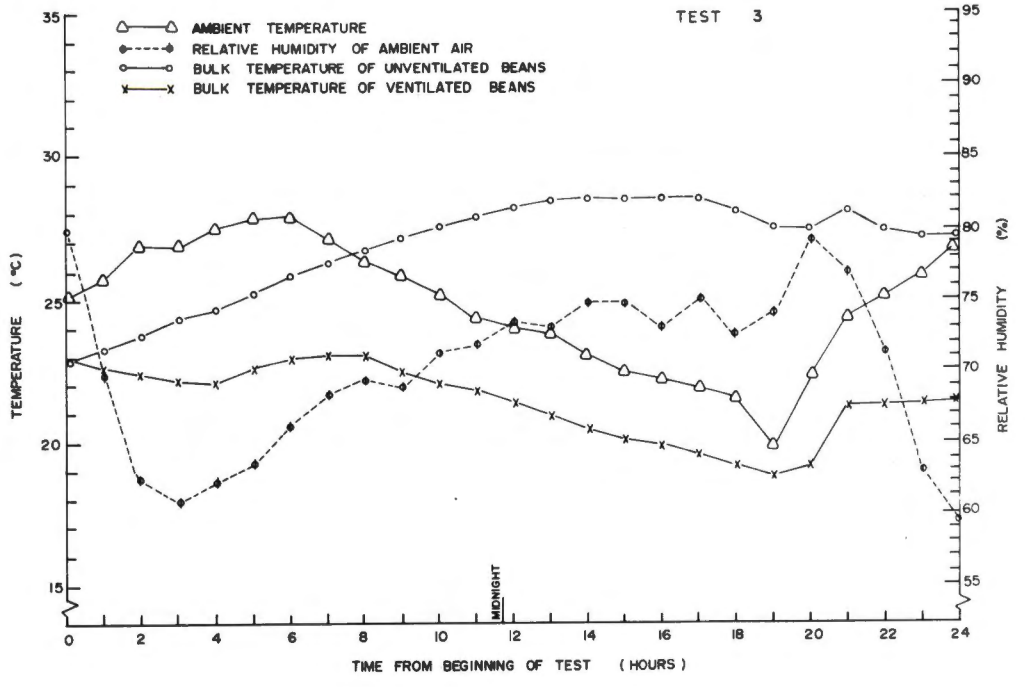


FIGURE A6. Temperature and relative humidity records over the 24 hour test period for test 3.

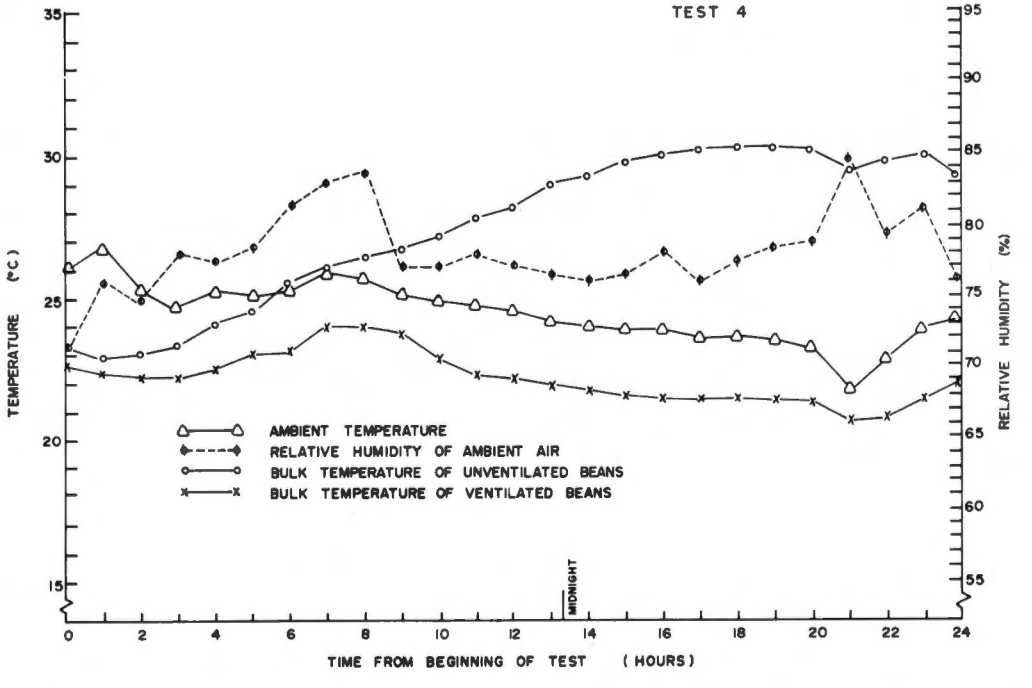


FIGURE A7. Temperature and relative humidity records over the 24 hour test period for test 4.

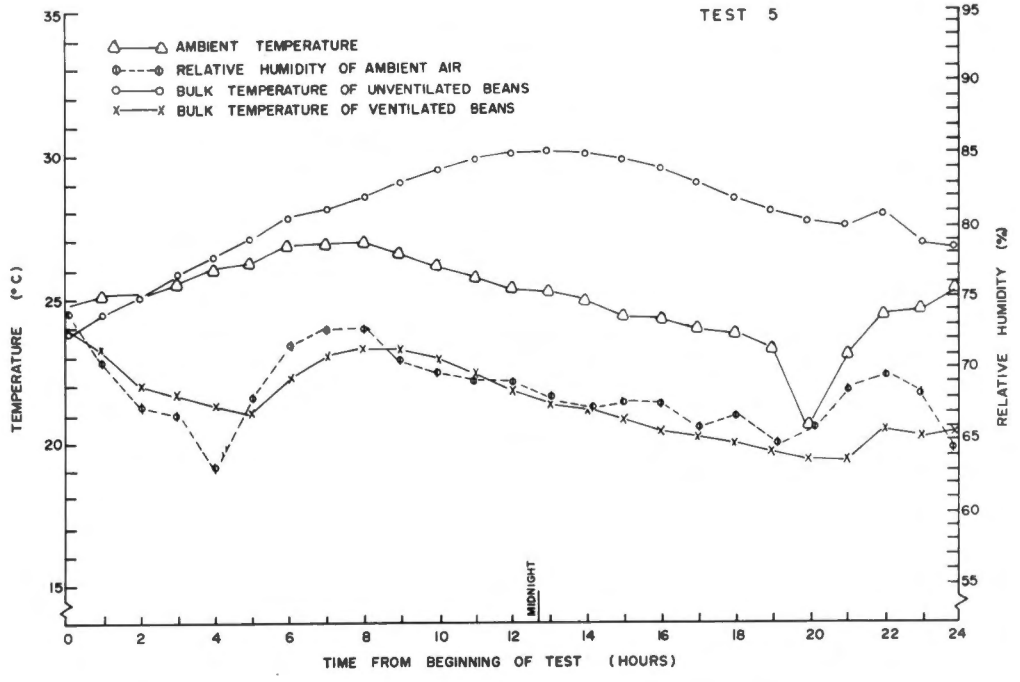


FIGURE A8. Temperature and relative humidity records over the 24 hour test period for test 5.

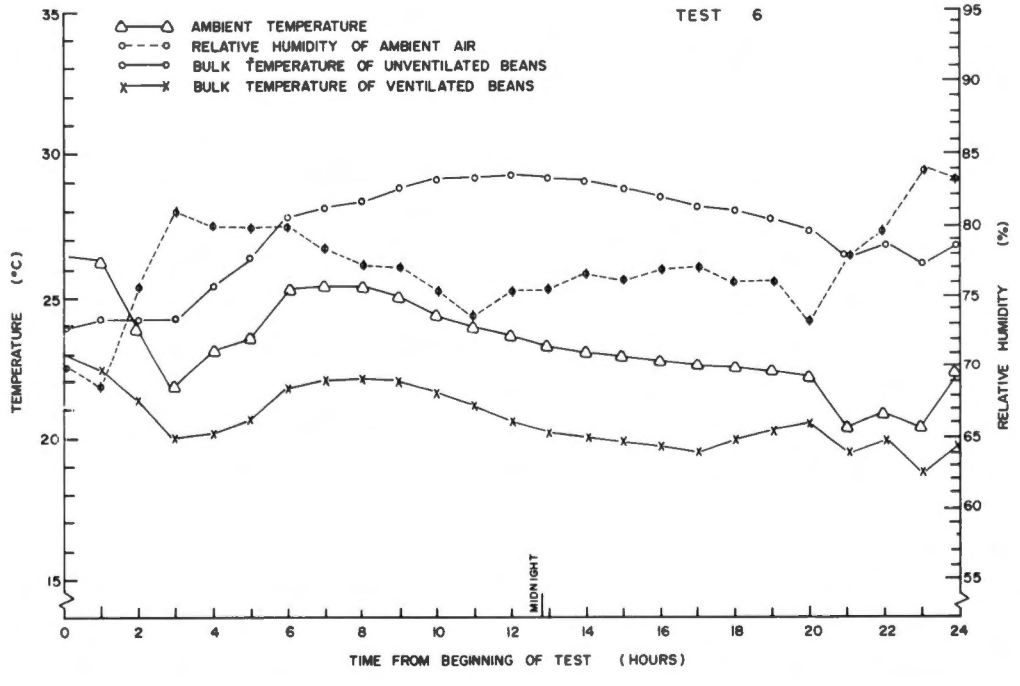


FIGURE A9. Temperature and relative humidity records over the 24 hour test period for test 6.

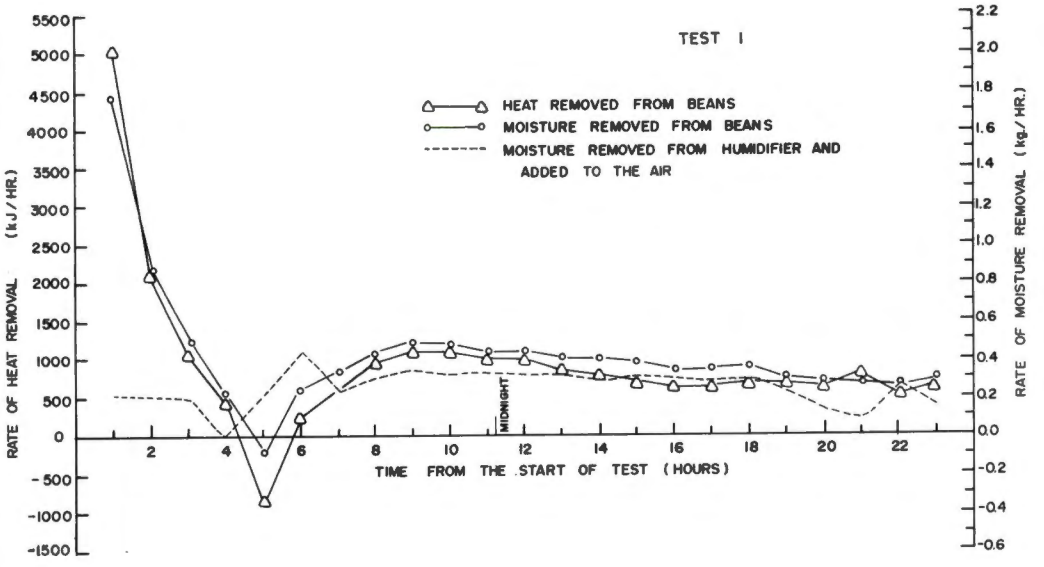


FIGURE A10. Heat and moisture removed from the beans by the ventilating air as a function of time for test 1.

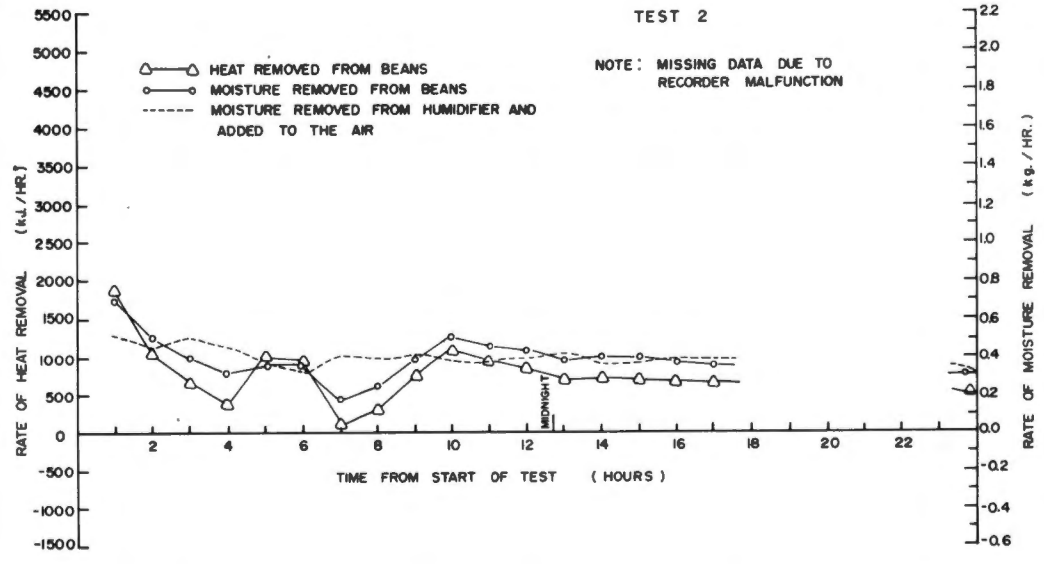


FIGURE A11. Heat and moisture removed from the beans by the ventilating air as a function of time for test 2.

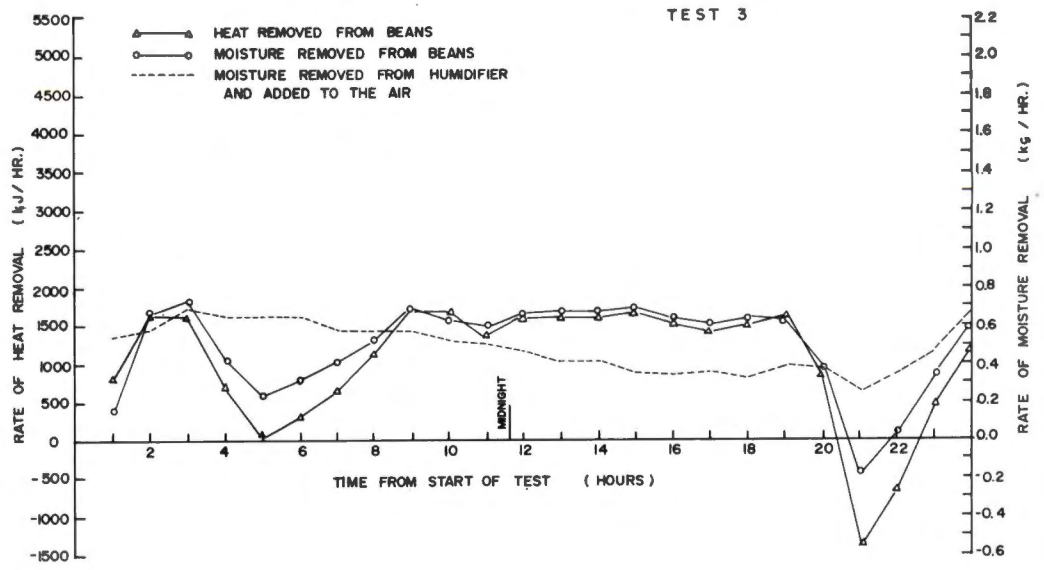


FIGURE A12. Heat and moisture removed from the beans by the ventilating air as a function of time for test 3.

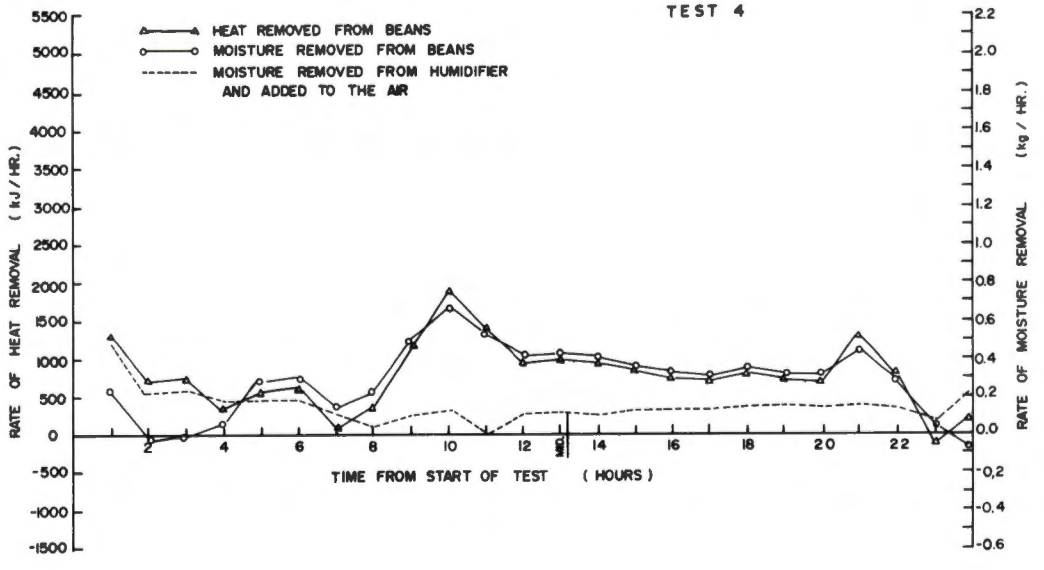


FIGURE A13. Heat and moisture removed from the beans by the ventilating air as a function of time for test 4.

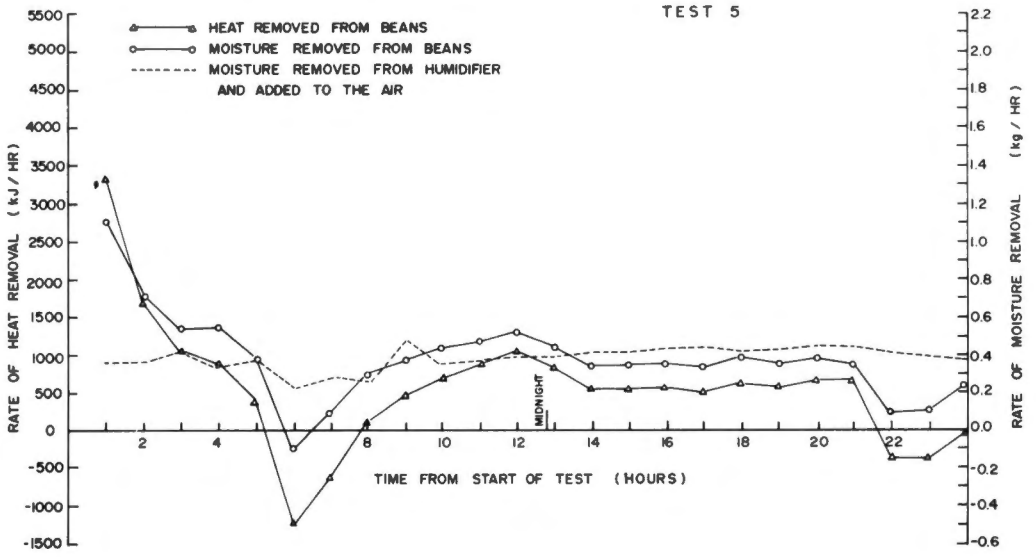


FIGURE A14. Heat and moisture removed from the beans by the ventilating air as a function of time for test 5.

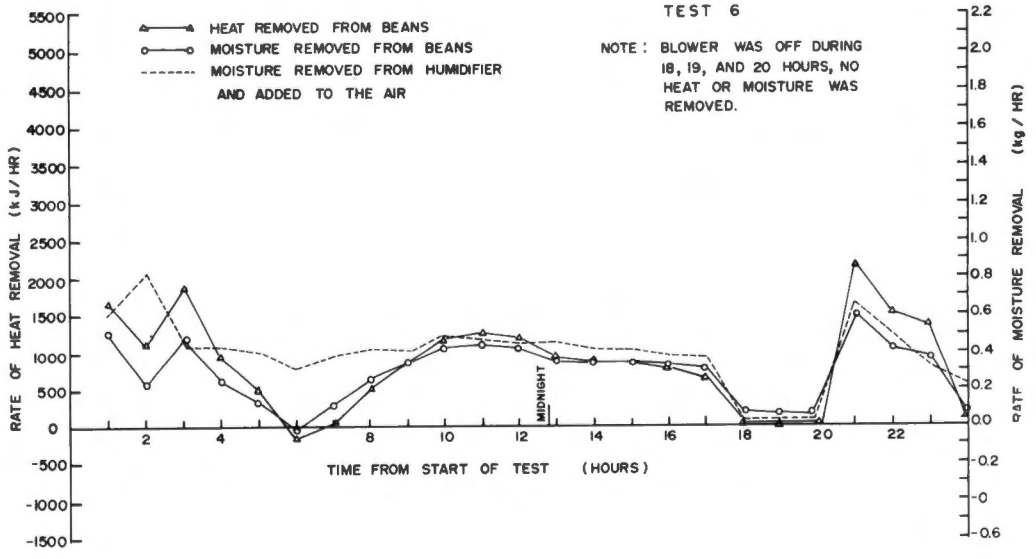


FIGURE A15. Heat and moisture removed from the beans by the ventilating air as a function of time for test 6.

VITA

John Richard Lehman was born June 10, 1950; the son of James Leonard and Dixie Winstead Lehman. He has two brothers, James Leonard, Jr., and Joseph Patrick; and a sister, Jeanine Webb. His early years were spent on a farm near McEwen, Tennessee. After attending St. Patrick School in McEwen, he graduated from McEwen High School. He enrolled in The University of Tennessee in September, 1968, where he majored in Agricultural Engineering. During his undergraduate tenure, he was active in the American Society of Agricultural Engineers Student Branch, and the Student Government Association. He is also a member of Tau Beta Pi, and Alpha Zeta. After receiving his Bachelor of Science degree in August, 1973, he accepted a Graduate Research Assistantship at The University and began graduate work toward a Master of Science degree in Agricultural Engineering. He received his Master of Science degree in March, 1977.

He is married to the former Melissa Elaine Florence of McEwen, Tennessee. They have one son, Paul Richard.