

THEOREM



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CONTINUOUS-FLOW DRYING OF SOYBEANS

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Valdecir Antoninho Dalpasquale

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CONTINUOUS-FLOW DRYING OF SOYBEANS

By

Valdecir Antoninho Dalpasquale

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ABSTRACT

CONTINUOUS-FLOW DRYING OF SOYBEANS

By

Valdecir Antoninho Dalpasquale

The feasibility of drying soybeans continuously at high temperatures is the main topic of this study. In the United States, the adoption of this practice will permit harvesting of soybeans at higher moisture contents, thus reducing the losses at harvesting. Field losses due to adverse weather conditions will also be reduced. In Brazil, besides the advantages already mentioned, early harvesting will make the practice of double cropping (soybeans-wheat) more attractive.

A one-stage concurrent flow dryer was used in the laboratory to dry soybeans at different temperatures. In the first test, soybeans at 14.18 percent wet basis moisture content were dried at 121.1°C for 2.5 hours. In the second test, two stages were simulated by letting the soybeans to temper for two hours between runs. For the first stage, 121.1°C was used as the drying air temperature, and for the second stage, 93.3°C. In the third test, two stages were simulated and the inlet drying air temperatures were 148.9°C and 121.1°C for the first and second stages, respectively. In all tests, the overall dryer efficiencies fell between 4200 and 5100 kJ/kg of water removed. Germination, cracks and splits were the quality parameters evaluated; the

obtained values after drying were considered satisfactory.

Continuous flow drying of soybeans was also studied by the use of a newly developed crossflow dryer computer model. The lack of precise thin-layer drying equations and equilibrium moisture content equations was noted. Nevertheless, an acceptable crossflow dryer model was developed for air and soybean conditions typical of the United States as well as Brazil.

F.W. Bekker, Arkansas
Major Professor
5-16-1979

D.R. Heldman
Department Chairman

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LIST OF SYMBOLS

c_a	heat capacity of dry air, BTU/lb °F or otherwise specified
c_p	heat capacity of dry product, BTU/lb °F or otherwise specified
c_v	heat capacity of water vapor, BTU/lb °F or otherwise specified
c_w	heat capacity of liquid water, BTU/lb °F or otherwise specified
e	efficiency rating, lbs of water removed by 1000 BTU of fossil energy
E	energy consumption, BTU
EMC	equilibrium moisture content, dimensionless
G_a	dry airflow rate, lb/hr-ft ²
G_p	grain flow rate lb/hr-ft ² or kg/hr-m ²
h_{fg}	latent heat of water in grain, BTU/lb or kJ/kg
H	humidity ratio, lb of water/lb of drying air
M	moisture content, decimal wet basis or otherwise specified
M_e	moisture equilibrium, decimal dry basis or otherwise specified
M_o	initial moisture content, decimal wet basis or otherwise specified
$P_{vs} - P_v$	air water vapor pressure deficit, kg _f /m ²
Q_a	volumetric airflow, cfm/bu
R	universal gas constant, 1.987 cal/kg °K
R_e	Reynolds number, dimensionless

RH	relative humidity of drying air, decimal or otherwise specified
RH_{amb}	ambient air relative humidity, decimal
RM	moisture removal, lb
SP	static pressure due to airflow, inches of water
T	drying air temperature, °F or otherwise specified
t	drying time, hr
T_{abs}	drying air temperature, °R
T_{amb}	ambient temperature, °C
X	node position
X_1	column depth, ft
W	weight of grain at moisture M, lb
θ	grain temperature, °F or otherwise specified
ρ_p	dry bulk density of grain, lb/ft ³

CHAPTER I

INTRODUCTION

Artificial drying of a wide variety of crops is a practice that gives satisfactory results for most uses. Drying soybeans (Glycine max, L., Merrill) requires the knowledge of the parameters which determine the quality of the dried product. Some requirements are already known. For instance, several studies showed that at low air humidity (below 40 percent RH) cracking of the seed coat and separation of the cotyledons are likely to happen to soybeans. Preserving the seed quality during the drying process results in a better product for storage, avoids seeds with low germination and, consequently, low yields.

1.1 Production, Perspectives and Importance of Soybeans in the United States and Brazil

In the United States, soybeans are planted by about 600,000 farmers. It is the second largest crop by volume. The production has increased over the years to 1.81 billion bushels in 1978 (approximately 49 million metric tonnes). Most of this is used as animal feed but it is also consumed as human food. Soybeans and soybean derivatives exported in 1978 generated \$4.75 billion, i.e., 17.4 percent of the value of all agricultural products exported during that

period of time. The future trend is likely to be a smooth increase in the production due to better yields through the adoption of more sophisticated agricultural techniques.

In Brazil, soybean production has increased by more than ten times since 1968, when it was a practically unknown culture. In 1978, 9.35 million metric tonnes of soybeans were grown on Brazilian farms and the projection for 1979 is a record production of more than 12.0 million tonnes. The Brazilian economy is greatly dependent on agricultural products with soybeans playing a major role. As in the United States, the production tends to increase each year but at higher rates mainly because Brazilian farmers are expanding their acreages by expanding the country's frontiers.

Table 1 presents the American and Brazilian soybean production during the last ten years. In 1968 the Brazilian production was about 2 percent of that produced in the United States; this proportion has increased to about 19 percent ten years later.

1.2 When and Why Soybeans Must Be Dried

Soybean drying is a practice that can usually be avoided by American farmers because of the favorable weather conditions at harvest time. The crop is left in the field until the moisture content reaches a level that is safe for storage, i.e., around 11-12 percent or even less, depending on the storage time. Rather recently, some soybean growers in the Corn Belt have started harvesting at 15-17 percent moisture content followed by artificial drying to about

Table 1: Production of soybeans in the United States and Brazil during the period of 1968 to 1978.

Year	United States	Brazil
	In 1000 ton	
1968	30,121	655
1969	30,833	1,057 ^a
1970	30,669	1,509 ^a
1971	32,000	1,977 ^a
1972	34,575	3,223 ^a
1973	42,100	5,135 ^a
1974	33,156	7,876 ^a
1975	42,071	9,892 ^a
1976	35,048	10,810
1977	47,946	12,000
1978	49,252	9,350

Source: Agricultural Statistics, USDA (1978) and
a: Os Verdadeiros Numeros do Brasil, ed Bloch (1975).

12 percent. Low temperature drying has been most often used.

The Brazilian situation is quite different. Almost all soybeans must be artificially dried in one way or another after harvesting. Since a significant percentage of the soybean growers double crop wheat, the time between the harvest of soybeans and the planting of wheat is not long enough to permit drying of the soybeans in the field. Another important point is that the sooner the product is sold, the better is the market price and the less interest is paid for the borrowed money. Brazilian farmers are more concerned about interest because it is much higher in Brazil than in the United States. In fact, it may determine the profitability of the business.

Drying soybeans in Brazil is an operation practiced mainly by the cooperatives and by the processing industry. Only a very small amount is dried and/or stored on farms. This is due to the lack of knowledge of post-harvest techniques on the part of the farmers and because of the high initial investment of the necessary equipment. In general, soybeans require better controlled storage conditions than other crops such as corn and wheat. At tropical conditions these requirements are more pronounced.

1.3 How Soybeans Are Dried

The conventional field drying practiced in the United States is satisfactory as far as keeping quality and storage are concerned. However, it is a weather dependent practice

and often leads to excessive losses because of the brittleness of the bean stalks and pods. Under unfavorable conditions of humid weather, the beans suffer deterioration prior to the harvest.

Harvesting soybeans at high moisture content levels requires that the amount of water in the beans is decreased down to safe storage quantities. This can be done in several ways.

The oldest drying method, which is still extensively used in the United States, is natural drying in the field. It is highly dependent upon the weather conditions. Artificial drying is a safer method to decrease the excessive moisture in the crop. There are several methods which fall in this category. Forced air is the most common. The resulting drying rate is a function of the product moisture content, product equilibrium moisture content, mass flow rate, air temperature and relative humidity. The equilibrium moisture content of a product is the lowest moisture which the product can reach under given air conditions. The rate of drying is controlled by the amount of heat that is added to the air. The drying process falls into two categories: low- and high-temperature drying.

The low-temperature process is being used specially for seed drying where the viability of the crop must be preserved. With the increase in energy costs, this method is being preferred by some researchers. In some cases, no heat is added, and ambient (natural) air is used. When the

initial moisture content of the crop is high and the weather is unfavorable, the drying time during natural air drying may be so long that some deterioration takes place before the desired low moisture level is reached.

High-temperature drying is a faster process and is less dependent upon the weather conditions. The raising of the air temperature is expensive and creates a management problem. If too high, the soybeans may crack, thereby increasing the chances of molding and deterioration and making storage more difficult. If too low, the water removed will be less than the desirable amount, i.e., the end product will not have the desirable quality.

Low- and high-temperature processes have advantages and disadvantages. The utilization of one or the other will be decided by the particular characteristics of each situation.

CHAPTER II

OBJECTIVES

The general objective of this thesis is to retain the soybean quality during continuous flow drying at high air temperatures.

The specific objectives are:

1. To verify the feasibility of continuous-flow high-temperature drying of soybeans in a concurrent flow dryer.
2. To maintain soybean quality at high drying temperatures using the concurrent flow dryer.
3. To develop a computer model for simulating soybean drying in a continuous cross flow dryer to be used in optimization studies.

CHAPTER III

LITERATURE REVIEW

3.1 Soybean Quality

Soybeans are classified in different grades according to their visual and physiological conditions. The latter is represented mainly by the germination capability of the seeds although the amount of free fatty acids is sometimes considered. By the visual conditions is meant the external appearance of the seeds, including cracking of the seed coat and broken and/or separated cotyledons.

Several investigators have studied the factors which alter the quality parameters. White et al. (1978) carried out thin-layer experiments using three initial moisture contents (16, 20 and 24 percent, wet basis), seven dew-point temperatures ranging from 8 to 38°C, and five drying temperatures (from 30° to 70°C). Drying data was analyzed by fitting an exponential drying model containing two empirical drying parameters. The drying damage was analyzed and classified according to seed coat and cotyledon or cleavage cracks. Seed coat cracks were found to be correlated to the initial moisture content, drying air relative humidity, the difference between the vapor pressure of the drying air and the saturated vapor pressure at the wet bulb temperature,

the dew-point depression, the difference between the initial and equilibrium moisture content, and the two empirical drying values contained in the drying model.

The relative humidity of the drying air must be kept above 40 percent, regardless of the air temperature, if soybeans are to be used for seed. Below 40 percent relative humidity, severe cracking damage can occur to the beans, especially at high air drying temperatures. In order to avoid germination losses, the seed temperature cannot be greater than 43.33°C (110°F). To prevent cracking, the temperature limit may be increased to 54.44-60°C (130-140°F), although some splitting will have occurred at that temperature level (Rodda, 1974).

Pfost (1975) studied the effects of varietal and environmental factors on the cracking of soybeans in the range of 90 to 150°F. Seventeen varieties were tested and significant differences were found among them. In general, cracking decreased with an increase in the final moisture content and relative humidity of the drying air, and increased with an increase in air temperature, drying rate and initial moisture content. For any given variety, the most significant factor affecting cracking was the relative humidity of the drying air. Pfost also observed that most of the cracks formed during the first five minutes of drying.

Ting et al. (1978) investigated the occurrence and extent of drying damage in remoistened soybeans at different depths in a laboratory-type deep-bed dryer. The position of

the soybeans in the bed was found to be the most significant factor affecting the drying damage. The farther the soybeans were located from the air inlet, the lower the damage. Thus, the drying damage produced in soybeans at varying locations in a deep-bed dryer will be different. Besides the position in the drying bed, initial moisture content, air flow rate and air drying temperature were all found to significantly affect the drying damage.

Sabbah et al. (1976) applied the reversed-direction-air-flow technique to a batch-in-bin drying system and claimed considerable improvements in soybean seed quality over the conventional one-direction-air-flow method. In this system, the final moisture content was uniform throughout the bed due to the periodic reversal of the air flow direction.

Due to the better uniformity of the moisture content, fewer overdried and underdried seeds were observed. This resulted in less cracking and mold activity inside the mass of beans. Another advantage of this drying method is the avoidance of mechanical stirring equipment which is frequently used in order to obtain a more uniform final moisture content. Stirring of a bin of soybeans usually increases the mechanical damage of the dried product.

White et al. (1976) reported that the physical damage experienced by soybeans when dried with heated air can have pronounced effects on their long term storability and quality. Soybeans dried by means of high air temperature are more prone to mold development and, also, to an increase in the fatty acid content.

Chanchai et al. (1976) studied the influence of heated air drying on soybean impact damage using temperatures from 75 to 165°F. Heated air drying resulted in considerable damage to the soybeans and was related to subsequent impact damage during handling. Tests showed that the higher the drying temperature, the higher the number of cracks and splits. However, Hall (1974) studying damage caused by handling of soybeans, observed that artificial drying will not cause an increase in damage during handling. A similar observation was made by Matthes and Welch (1974) who concluded that it is feasible to dry high moisture content soybean seeds with heated air and obtain a finished product of acceptable quality.

Soybean seeds which did not lose quality significantly during the drying process still can be deleteriously affected if subsequent handling and storage operations are not properly performed. Rodda and Ravallo (1978) stored soybeans in four types of containers at ambient temperatures and in sealed metal containers at constant temperatures. Samples at low initial moisture content maintained the original characteristics satisfactorily under tropical conditions. On the other hand, samples with poor initial quality did not store well even at temperatures as low as 3°C.

3.2 Continuous-Flow Drying

For the purpose of this thesis, only cross flow and concurrent flow drying processes will be considered. Cross flow drying is the most commonly used continuous-flow drying

technique. The concurrent flow dryer has recently been developed.

In a cross flow dryer, the directions of the grain and air flow are perpendicular. As a rule, grain nearest the air exhaust tends to remain wet, and grain near the air inlet tends to overdry and overheat. However, commercial cross flow dryers with air recycling and reversed air flow overcome these disadvantages somewhat. These so-called modified cross flow dryers reduce the moisture and temperature gradient problems and are also more efficient than the conventional cross flow dryers (Lerew et al., 1972). Additional changes in the basic cross flow dryer design will be needed in order to overcome the problems related to energy efficiency and the quality of the end product. A diagram of a modified cross flow dryer is presented in Figure 1.

In a concurrent flow dryer, air and grain flow in the same direction, resulting in an equal drying treatment of the product. The air temperature decreases rapidly because the warmest air encounters the wettest grain causing evaporation to occur at high rates. The reason for the popularity of this kind of dryer is the advantage it represents over the conventional cross flow dryer with regard to energy efficiency, product quality and air pollution. A diagram of a two-stage concurrent flow dryer is presented in Figure 2.

A grain dryer is a device which uses ambient air and a source of heat to create a flow of heated air to remove water from a grain. Its performance is affected by several

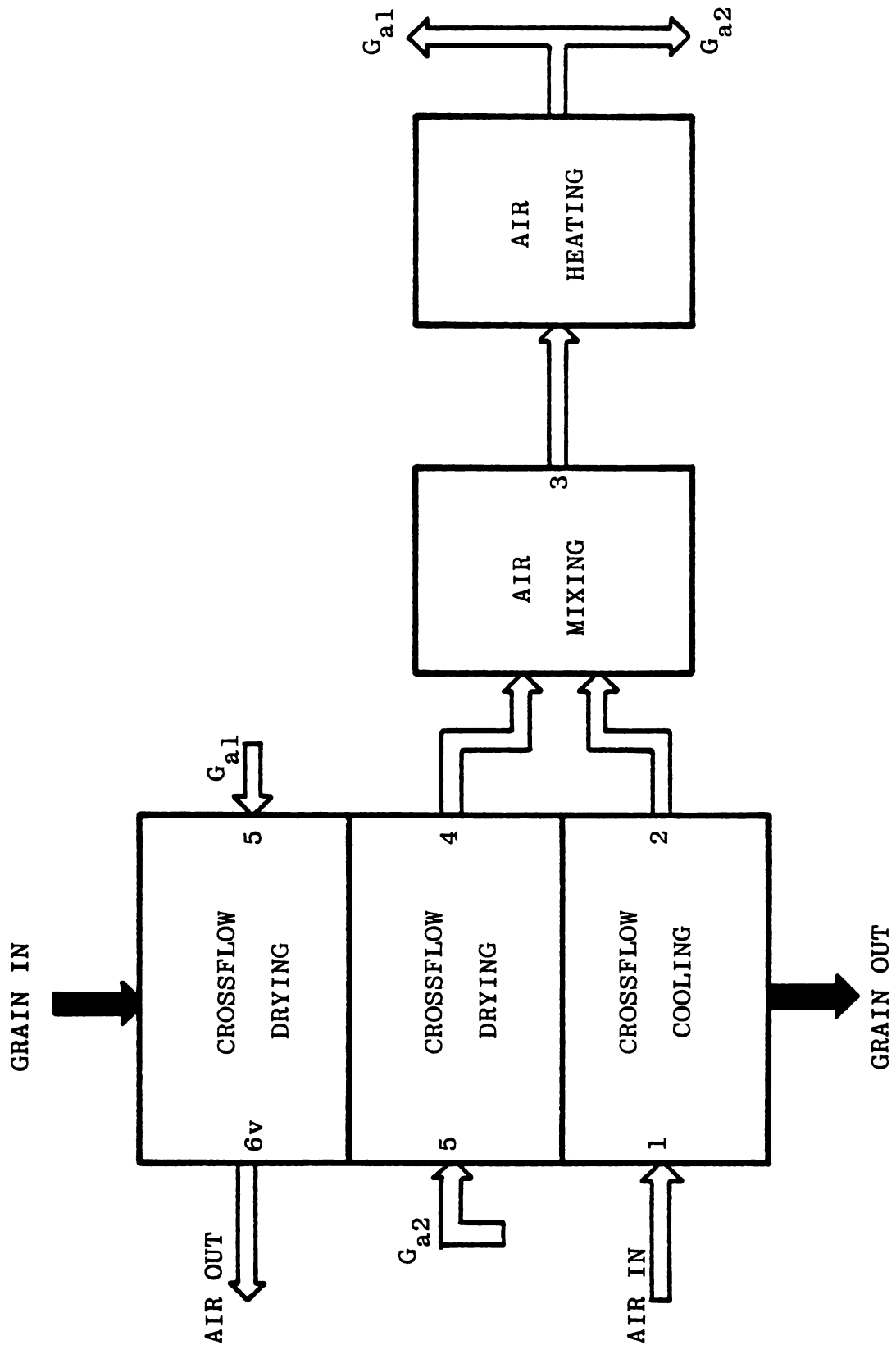


Figure 1: Block diagram of a 3-stage cross flow dryer with partial air recycling (Lerew et al., 1972).

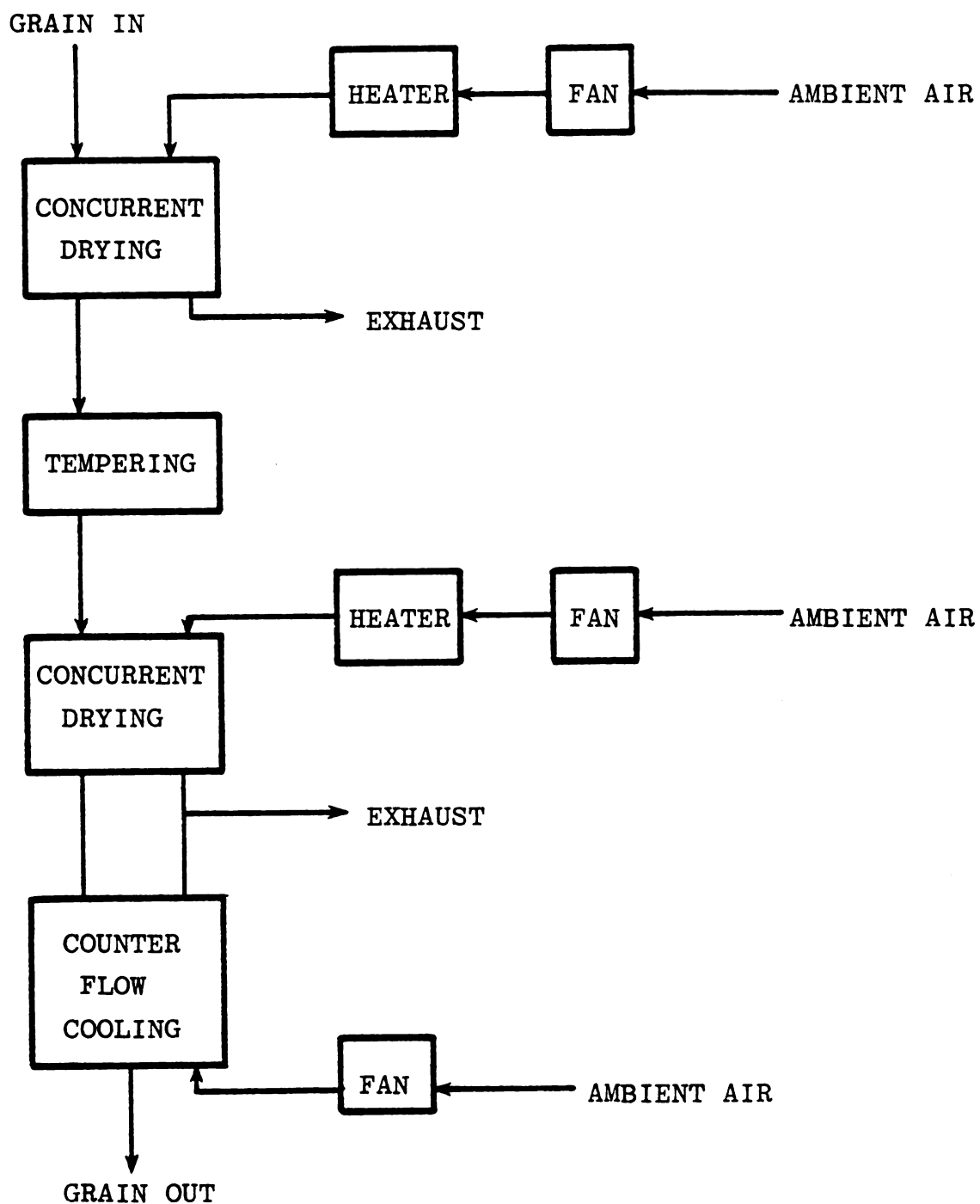


Figure 2: Block diagram of a 2-stage concurrent flow dryer with counterflow cooler (Brook, 1977).

factors including: (1) the air temperature and relative humidity, (2) the initial grain temperature, (3) the initial and final moisture content of the grain, (4) the resistance to air flow through the grain mass, (5) the throughput of the dryer, (6) the grain variety, and (7) the design factors of the burner, fans, and ducting systems. All these parameters act together.

Generally, the higher the initial moisture content of the drying product, the faster the drying rate will be in terms of water removed vis-a-vis energy inputs. This is explained by the fact that at higher moisture contents water is removed more easily from the individual grain kernel, i.e., water is less highly held by the grain. Figure 3 shows the relation between energy required and the initial moisture content of rice when the drying air temperature was 48.89°C (120°F). As expected, at the higher initial moisture contents less energy per pound of water removed was required than at lower moisture contents.

The air conditions can drastically alter the drying efficiency. They are the most easily manageable parameters in a drying system, especially the temperature. Together with the air flow, the air condition is responsible for the amount of water removed in a dryer and also determines the quality of the end product.

Air flow resistance, usually expressed as the pressure drop across a bed of the drying product, can have a significant effect on the airflow rate and thus on the drying rate.

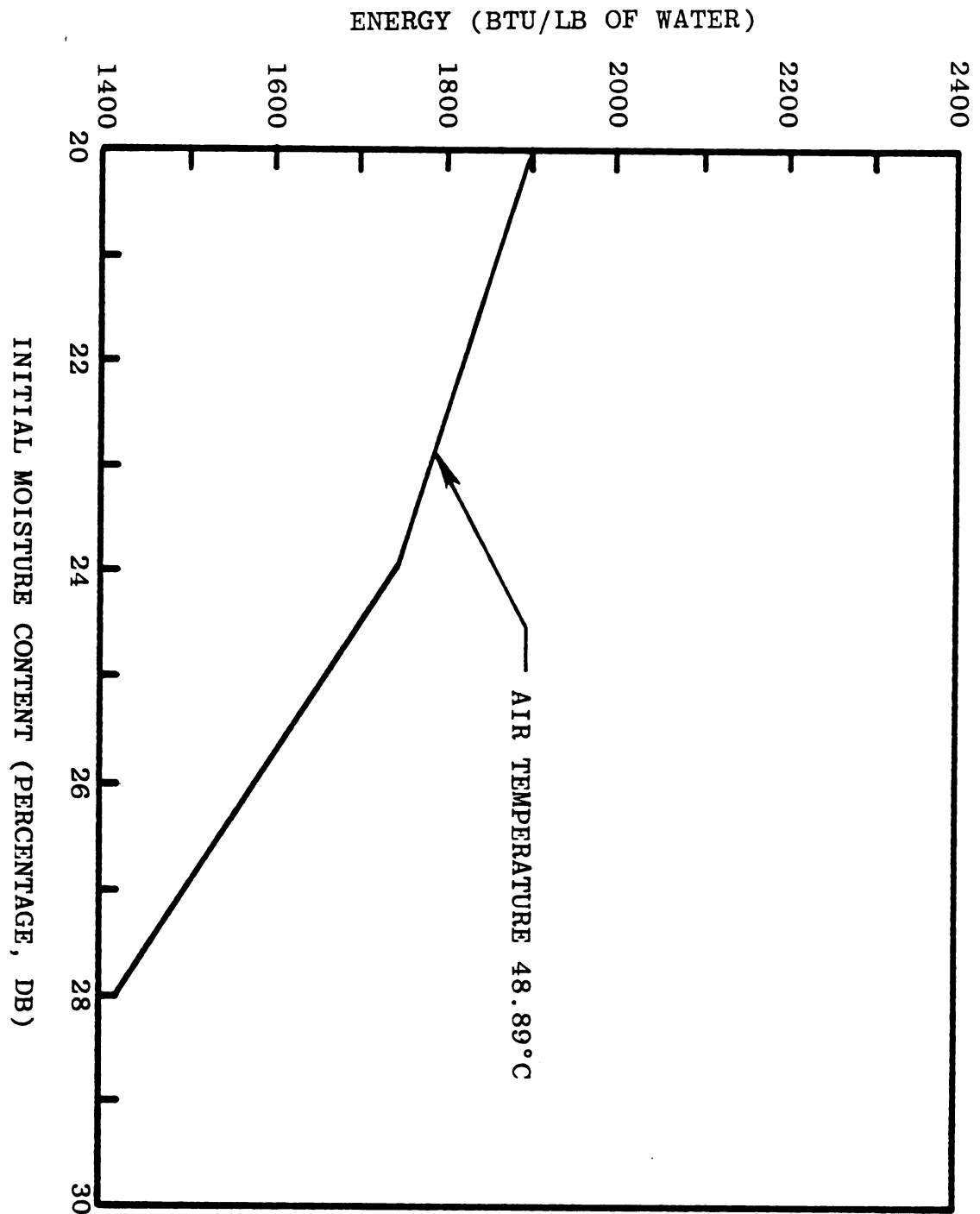


Figure 3: Relation between energy required and initial moisture content of rice when the drying air temperature is 48.89°C (120°F) (Bakshi et al., 1978).

For a given fan size, the cleaner the mass, the higher the airflow and the drying rate will be.

The grain variety may affect the total water removed by a dryer. Bakker-Arkema et al. (1978) observed that some corn varieties dry at different rates. They defined a new quantity, named the "hybrid drying factor", which accounts for the characteristic drying behavior of a lot of corn. This factor is the ratio of the specific drying rate to the standard drying rate of a lot of corn used in an experimental dryer test. Similar observations were made by Keener and Glenn (1978). Tests to determine thin-layer drying constants will result in specific values for each hybrid corn variety. The hybrid factor should be defined for other crops than corn and thus also for soybeans.

A standard method for testing grain dryer performance has not been established. The importance of such a method cannot be overemphasized since comparison between different dryers will only be realistic if the dryers are tested under the same conditions.

Bakker-Arkema et al. (1978) proposed standard conditions for the performance evaluation of automatic batch and continuous-flow dryers. The variables that have to be monitored are the inlet and outlet grain moisture content and temperature, the ambient air temperature and relative humidity, the presence of foreign materials and the time period of testing. The proposed values for drying shelled corn are listed in Table 2.

Table 2: Proposed standard conditions for the performance evaluation of automatic batch and continuous-flow grain dryers, drying shelled corn.

Average inlet grain moisture content, % wb	25.0 ± 1.5
Average outlet grain moisture content, % wb	15.0 ± 0.5
Average ambient air temperature, °F	50 ± 10
Average ambient air relative humidity, %	50 ± 10
Average inlet grain temperature, °F	50 ± 10
Inlet grain BCFM, %	3.0
Outlet grain temperature, °F above ambient	15
Time period of testing, h	24

Source: Bakker-Arkema et al. (1978).

Keener and Glenn (1978) proposed a method to standardize the measurement of performance of crop dryers using rates of moisture removal and energy requirements. The following formulas are suggested in the evaluation of these parameters.

$$RM = \left(\frac{M_o}{1-M_o} - \frac{M}{1-M} \right) \cdot (1-M) \cdot W$$

$$E = 3 \cdot 3414 \cdot \text{electrical energy (kwh/test)} + \text{heat of combustion of fossil fuel per test}$$

$$e = 1000 \cdot RM \cdot E$$

where,

RM = moisture removal (lbs)

M_o = initial moisture content (w.b., decimal)

M = final moisture content (w.b., decimal)

W = weight of grain at moisture M dried by the system during the test (lbs)

e = efficiency rating (lbs of water removed by 1000 Btu of fossil energy)

Bakshi et al. (1978) compared various drying conditions in an attempt to evaluate the energy needed for drying rice in a cross flow dryer. A laboratory-scale model was used and results checked against the Michigan State Cross Flow computer model. Good results were attained especially when the exhaust air was recycled. Recycling resulted in lower energy requirements for rice drying and affected the milling yields beneficially.

Walker (1978) reported that rice can be dried at temperatures as high as 65.55°C (150°F) as long as the air flow

is less than $0.17 \text{ m}^3/\text{hr}$ and the grain flow rate higher than $2.27 \text{ m}^3/\text{min}$. A single-stage concurrent flow pilot-scale dryer was used but two- and three-stage dryers were simulated. Satisfactory energy efficiencies were achieved.

Bakker-Arkema et al. (1977) conducted tests in one-, two- and three-stage laboratory concurrent flow wheat dryers at high temperatures. Results showed that hard wheat can be dried in concurrent flow dryers at temperatures as high as 121°C (525°F) provided the kernel temperatures remain below 63°C (145°F). At the same time, comparisons of the three kinds of dryers tested indicated that multistage concurrent-flow dryers have advantages over a single-stage model. The advantages are: (1) higher energy efficiency, (2) higher capacities, (3) lower operating costs, (4) lower investment per unit of capacity, and (5) improved grain quality.

Brook and Bakker-Arkema (1977) investigated the optimum operational parameters and dimensions of multistage concurrent flow dryers. A dynamic programming optimization scheme was used. It was concluded that, on a per-square-meter-of-column-area basis, the single-stage concurrent flow dryer is more expensive to operate than a two- or three-stage similar model. This was attributed to the increased grain flow rate used in the multistage units. When compared with a cross flow dryer, the concurrent flow dryer is less costly and also produces an end-product of better quality. With regard to energy costs, the three-stage concurrent flow

dryer, with recirculating air, presented advantages over the two-stage dryer. The added capital required for the equipment necessary for conducting the exhaust air was not considered. Although these conclusions are drawn for corn, similar results may be expected for soybeans.

CHAPTER IV

CONCURRENT FLOW DRYING

Concurrent flow drying is one of the three main grain drying techniques. The other two, cross flow and counter flow, will not be discussed here.

The characteristic behavior of concurrent flow drying is schematically represented in Figure 4. Due to the high rates of evaporation and the short period of time during which the product is exposed to the high drying temperatures at the grain inlet side of the dryer, the kernel temperature remains considerably below the air temperature in that region (Farmer et al., 1972). In the subsequent portions of the dryer, the grain and the air temperatures both slowly decrease. This tempering process is an important characteristic of the concurrent flow dryers because it leads to a uniform high quality product at the end of the drying process. The end-product has fewer stress cracks and has also less tendency to mechanical damage by subsequent handling. In short, concurrent flow drying results in superior grain quality.

The high evaporation rate which occurs in the first layers of the dryer permits the use of inlet temperatures as high as 121.11°C (250°F) in the concurrent flow dryer

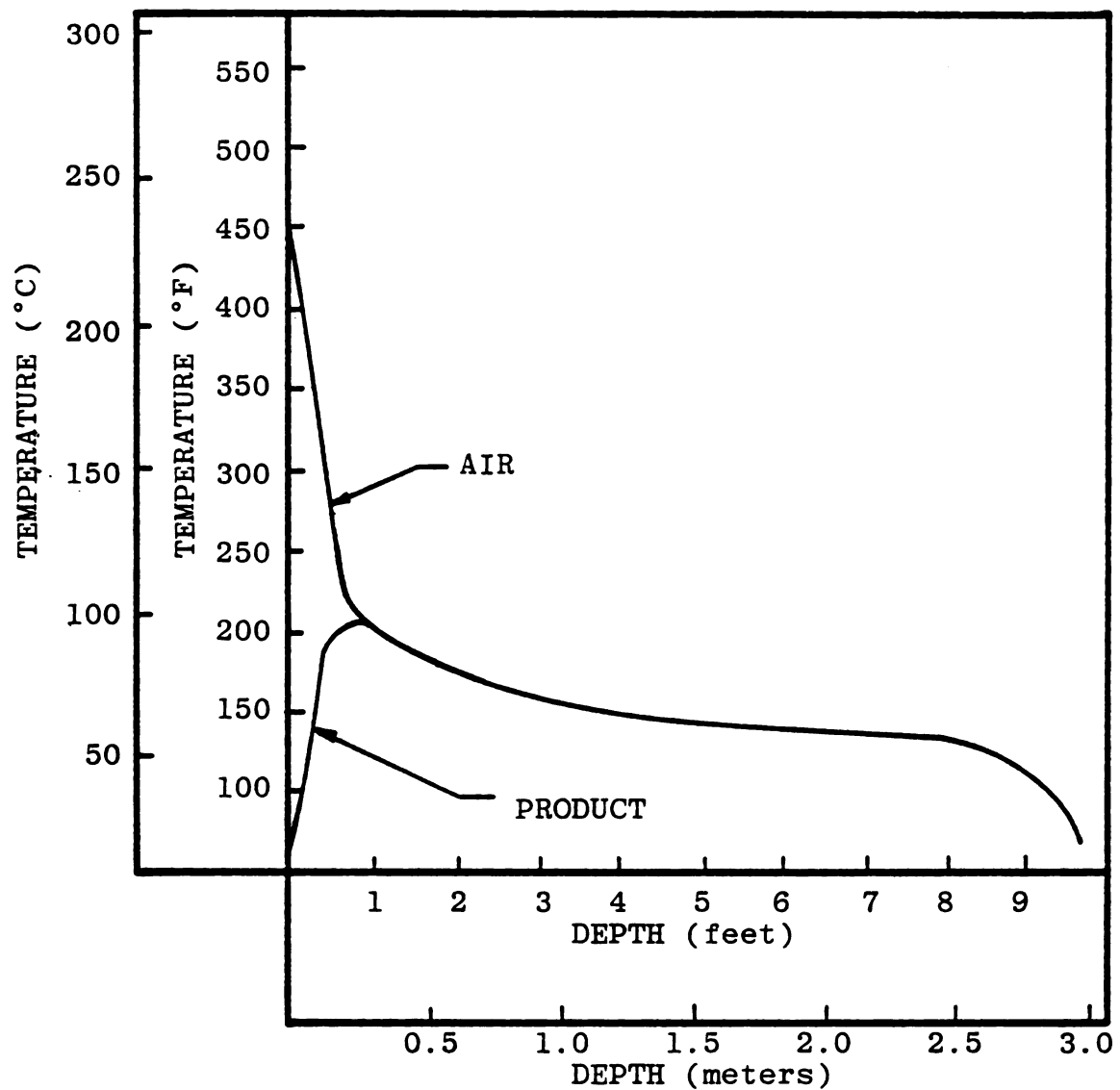


Figure 4: Product and air temperatures versus depth for a single-stage concurrent flow dryer (Brook, 1977).

without damaging the grain mass, when corn is used. The use of high drying air temperatures results in better energy efficiencies for the dryer. Brook (1977) reported that energy efficiencies between 4185 (1800 BTU/lb) to 5120 (2200 BTU/lb) kJ/kg of water evaporated are common for concurrent flow grain dryers.

4.1 Experimental

During the fall of 1978, soybeans were dried in a single-stage concurrent flow dryer in the laboratory. Two-stage drying was also simulated.

4.1.1 Dryer

Soybeans were dried in a pilot scale concurrent flow dryer in the Processing Laboratory in the Agricultural Engineering Department at Michigan State University. The dryer consists of a single-stage concurrent flow dryer with a counter flow cooling section. The cross sectional area is 0.00366 m^2 (1.0 ft^2) and the concurrent drying section has a length of 0.91 m (3.0 ft). The dryer is represented schematically in Figure 5.

4.1.2 Soybeans

An unknown variety of soybeans harvested during the 1978 season served as the drying material for the experiments. The beans were stored in a cold room at 4°C for several weeks before the tests were performed. By the time the soybeans were dried, the initial moisture content varied from 13 to 15 percent w.b. The non-uniformity in the moisture level

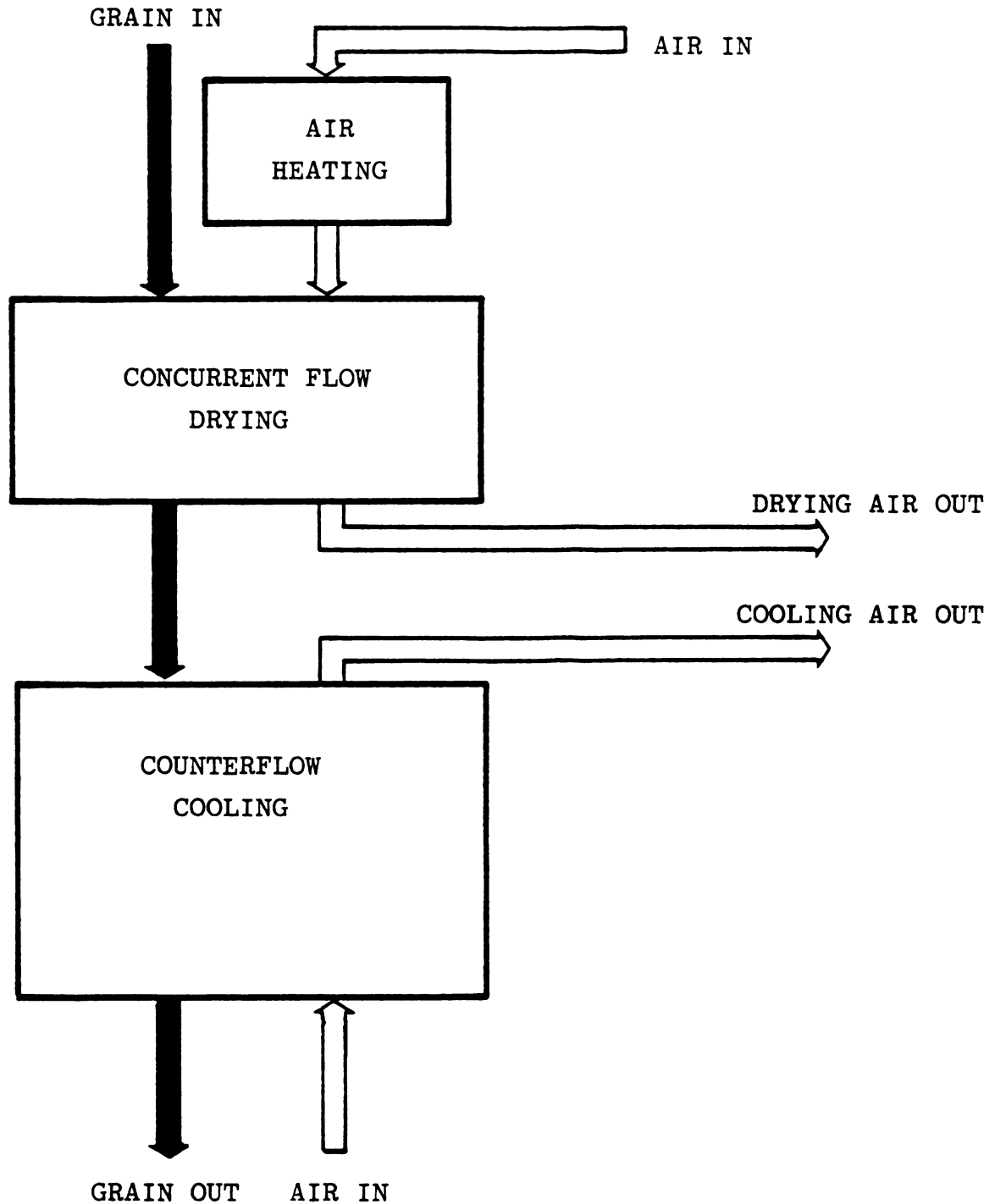


Figure 5: Block diagram of concurrent flow dryer with counter flow cooler (Brooker et al., 1974).

made the analysis among the tests more difficult because the energy required (Figure 3) and the end product quality are functions of the initial moisture content.

4.1.1.3 Soybean flow rate

An AC motor (1750 rpm) powers the cross auger from the base of the concurrent section. This system is responsible for the control of the mass flow rate. Previously, the auger was attached to a variable speed DC motor which allowed mass flow rate variations. However, problems with the motor speed control forced the change to the AC motor. As a result, only one mass flow rate (432.48 kg/hr) could be used. Determination of the mass flow rate was accomplished by recording the weight of the soybeans and the unloading time.

According to Kalchik (1977), the designer of the dryer, 0.207 m^3 of soybeans are required to fill the dryer. In order to fill the cooler and the cross auger, an additional volume of 0.083 m^3 is required.

4.1.1.4 Temperature and relative humidity

The drying air temperature is sensed by an iron-constantan thermocouple (type J) which accuracy is $\pm 2.2^\circ\text{C}$ ($\pm 4.0^\circ\text{F}$). This thermocouple is connected to a two channel Texas Instrument recorder. The characteristics of this instrument and of the others used in this experiment are presented in Table 3. Copper-constantan thermocouples (type T), accuracy of $\pm 0.8^\circ\text{C}$ ($\pm 1.5^\circ\text{F}$), are used on the dryer; these temperatures are recorded by means of a 24 channel Texas Instrument

Table 3: Monitoring instruments.

INSTRUMENTS	DESCRIPTION-ACCURACY
1. Recorder	Texas Instrument twenty-four channel, Model EMWT6B, accuracy $\pm 0.75^{\circ}\text{F}$, linearity $\pm 0.3^{\circ}\text{F}$.
2. Recorder	Texas Instrument two channel, Model P 502 W6A, accuracy $\pm 2^{\circ}\text{F}$, linearity $\pm 0.3^{\circ}\text{F}$.
3. Moisture tester	Steinlite Model 400 G, accuracy $\pm 0.5\%$ moisture content wet basis.
4. Drying oven	Blue M Electric Company, Model OV510, mercury in steel thermometer, accuracy $\pm 2.5^{\circ}\text{F}$.
5. Pitot Tube	Accuracy 0.01 inch.
6. Scale	Toledo Scale Company, style 0891, accuracy ± 0.25 lb.
7. Scale	Mettler P160N, accuracy ± 10 mg.
8. Scale	Mettler, accuracy ± 0.1 mg.

recorder. The soybean temperature was evaluated by inserting a mercury-in-glass thermometer (smallest division 1.11°C) into the grain mass as it left the dryer.

The inlet dry and wet bulb air temperatures are measured in three different positions. First, at the inlet air stream of the fan. This position was chosen in such a way that no turbulence was present, i.e., directly on the inlet air streamlines. The second point is located after the fan outlet and before the laminar flow element. The thermocouples detect the rise in temperature of the air due to turbulence inside the fan. Whenever the inlet air temperature is used in energy efficiency calculations, this temperature is used. A third thermocouple is placed after the burner in the plenum before the concurrent drying section. This is the only iron-constantan thermocouple used in the tests.

Dry and wet bulb temperatures are also sensed at the drying air outlet and at the cooling outlet. By periodically checking these temperatures during the tests, it is possible to calculate the exit air relative humidity and, consequently, the amount of drying in the concurrent section and in the cooler. Dry bulb temperatures are measured at three levels in the concurrent section, at 15.24 cm, 30.48 cm and 60.90 cm from the grain inlet. In addition, two thermocouples are installed above the concurrent section, one at 30.48 cm from the top of the dryer and the other at 91.44 cm from the same position. The latter one served as a check for air leakage through the hopper. Air leakage is possible if the

Figure 6: Schematic of the pilot-scale concurrent flow dryer used in the laboratory, showing the thermocouple locations (dots) (Walker, 1978).

- Legend:
1. Bucket elevator
 2. Grain storage hopper
 3. Natural grain airlock
 4. Heating air and grain boundary area
 5. Concurrent drying section
 6. Dryer exhaust
 7. Burner
 8. Grain flow rate metering auger
 9. AC motor
 10. Cooler exhaust
 11. Cooling section
 12. Cooling air entrance
 13. Cooling section discharge auger
 14. Cooler base

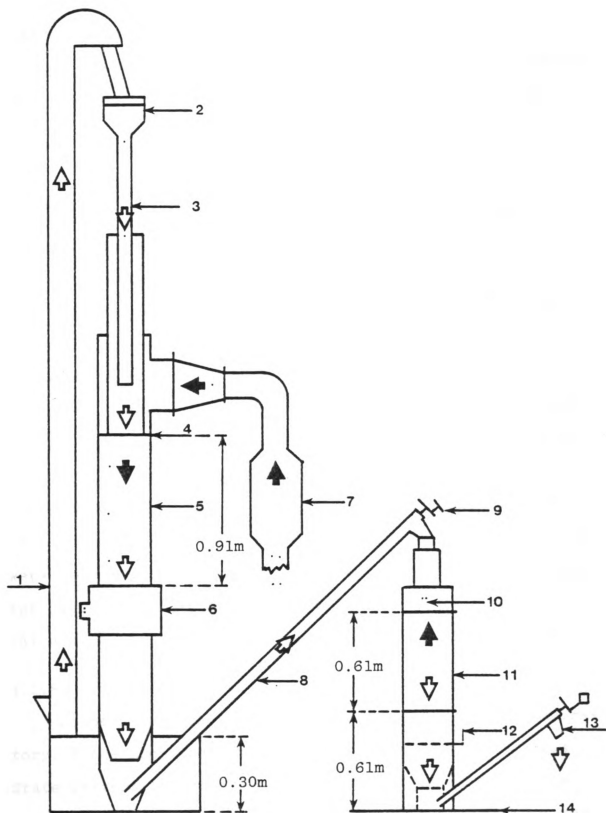


Figure 6: Schematic of the pilot-scale concurrent flow dryer used in the laboratory, showing the thermocouple locations (dots) (Walker, 1978).

is now possible because the new regulator allows very accurate adjustment of the gas flow rate.

In order to find the quantity of gas used in a complete run, the gas tank was weighed before and after each run.

4.1.7 Moisture content

The original moisture content was obtained by sampling the soybeans as the dryer was being filled. Subsequent samples were taken during the tests by collecting material at the unloading auger at a regular time interval.

A Steinlite electronic moisture tester served as an indicator of the soybean moisture content. These moisture values were used as a check for the amount of drying that was being carried out. The soybean moisture contents used in the results of this experiment were evaluated according to the Service and Regulatory Announcements No. 147 of the United States Department of Agriculture. Ground samples of 4-5 grams were dried at 130°C for one hour. The samples were cooled at room temperature inside a silica-gel containing jar. The final moisture content of the samples was calculated from the moisture loss during the oven drying.

4.1.8 Germination tests

Soybean germination tests were conducted in the laboratory of the Crop and Soil Sciences Department at Michigan State University. Two hundred seeds of each dried sample were germinated in two 100-seed lots. Normal seedlings and the seeds which had begun germinating without abnormal

symptoms were counted as germinated. All others were classified as dead seeds because of their incapacity to produce normal seedlings. Seeds that showed any sign of viability loss were avoided in order to eliminate the influence of elements other than temperature in the final results.

4.1.9 Cracks and splits

In this thesis, soybeans are classified as falling in one of the following categories:

- a. undamaged -- no visual evidence of physical damage;
- b. cracked -- a crack in the seed coat of the soybeans with the seed coat still on the bean and the cotyledons intact;
- c. split -- a crack which has advanced to the cotyledons, with the seed coat off and the cotyledons separated into two individual parts, and small broken or fractured parts of the beans.

Two samples of 25-35 grams each were obtained for each moisture content sample. After being weighed on a Mettler Pl60N scale, the material was separated and classified. Any foreign material was removed from the original samples. The quantity of soybeans in each category was recorded and the corresponding percentages evaluated. All tests were performed by the author in order to maintain consistency throughout the tests.

4.2 Test Procedure

Dryer operations involved only one person after a small modification was performed at the bucket elevator inlet. A bean storage hopper was installed at the inlet which allowed the operator to take samples and check temperatures and instrumentation between consecutive fillings of the inlet hopper to the dryer.

To start the drying process, the concurrent section was filled with soybeans until the micro-switches on top of the dryer indicated that it was full. The fan on the concurrent section was turned on and the burner ignited and adjusted to the desired temperature by manual regulation of the liquid propane (LP) gas controls. By this time, all recorders had been switched on, as well as the cross auger.

The dryer can be used in simulating a multi-stage concurrent dryer because the output from the concurrent section can be diverted from the machine before the beans reach the cooler. A description of the procedures for simulating this system follows.

Soybeans were dried without cooling to a moisture content below 13 percent and were placed in a container to temper for about two hours. During this time, the moisture diffuses uniformly inside the beans. The drying operation was then repeated with the cooling section used during the second drying operation.

Samples were taken at regular time intervals during a dryer test and conditioned in sealed plastic bags, identified

and stored in a cold room at 4°C. Moisture content and germination tests were determined later as was the evaluation of cracks and splits.

In this thesis, a pass means each time the soybeans go through the dryer once, and a run means one of the three tests performed. Using these definitions, it is necessary to point out that several passes were needed before a complete run was completed.

CHAPTER V

CROSSFLOW DRYING

Among the continuous-flow grain dryer configurations, the crossflow is the most common and, therefore, has been the topic of much research.

In the crossflow configuration, air and product flow in perpendicular directions. The product usually uses gravity to move through the dryer; the air passes through the grain horizontally.

In order to overcome the efficiency and quality problems of the basic crossflow configuration, many modifications have been tested. One of them is the use of the warm exhaust air from the cooling section as the heater inlet air for the drying section. The advantage of this process is an increase in the dryer efficiency, since part of the sensible heat of the grain is recovered (Brooker et al., 1974). The technique of reversing the airflow halfway through the drying section was tested and, although a reduction of 60-75 percent in the moisture content gradient across the column of the dryer was reported, there was also a decrease in the dryer efficiency and capacity. An advantage of reversing airflow is the lower average grain temperature (Bakker-Arkema et al., 1978).

Figure 1 presents a block diagram of a three-stage crossflow dryer with reversing airflow and air recycling. This dryer, commercially available, uses the mixture of the exhaust air from the second drying section and the first cooling section (after re-heating) as the inlet drying air for the first and second drying sections. As a result, the energy use is approximately half that used in the basic crossflow configuration. The moisture content gradients at the outlet are significantly smaller than of the conventional crossflow dryer (Bakker-Arkema et al., 1978).

5.1 Crossflow Model Development

Thompson et al. (1969) developed a series of semi-theoretical grain dryer models which have been used successfully. More general and fundamental models have been developed by researchers at Michigan State University, starting in 1966. These models are based on the basic laws of heat and mass transfer and, because of their theoretical nature, are described by a rather complicated system of differential equations. The solution to these systems of equations can be obtained numerically with the help of a digital computer.

Bakker-Arkema et al. (1976) studying in-bin solar drying, concluded that the air and product temperatures can be set equal at the low airflow rates used in solar drying. Later research with crossflow dryer models led to similar conclusions. The same simplification is used in the present thesis. The advantage of this assumption is that considerable

computer time is saved in the simulation of the model.

The three basic equations describing heat and mass transfer in a crossflow dryer are (Bakker-Arkema et al., 1976):

$$\rho_p (c_p + Mc_w) \frac{\partial T}{\partial t} + G_a (c_a + Hc_v) \frac{\partial T}{\partial x} + g_a [(c_w - c_v) (212 - T) + h_{fg}] \frac{\partial H}{\partial x} = 0 \quad (1)$$

$$\rho_p \frac{\partial M}{\partial t} + G_a \frac{\partial H}{\partial x} = 0 \quad (2)$$

$$\rho_p \frac{\partial M}{\partial t} = f(T, H, M, t) \quad (3)$$

Equations (1) through (3) can be written in finite difference form and rearranged as explicit functions of $H_{x,t}$, with x being the node position in the dryer width, and t being the drying time.

The basic finite difference equations of the crossflow model used in this thesis are:

$$\begin{aligned} & -\Delta t G_a (h_{x,t} - H_{x-\Delta x,t}) (h_{fg} + 212(c_w - c_v)) \\ & + \rho_p \Delta x (c_p + c_w M_{x,t-\Delta t}) T_{x,t-\Delta t} + G_a \Delta t (c_a + c_v H_{x-\Delta x,t}) \\ & T_{x-\Delta x,t} \\ T_{x,t} = & \frac{\quad}{-G_a \Delta t (H_{x,t} - H_{x-\Delta x,t}) (c_w - c_v) + \rho_p \Delta x (c_p + c_w M_{x,t-\Delta t})} \quad (4) \\ & + G_a \Delta t (c_a + c_v H_{x-\Delta x,t}) \end{aligned}$$

$$H_{x,t} = H_{x-\Delta x,t} - \frac{\rho_p \Delta x}{G_a \Delta t} (M_{x,t} - M_{x,t-\Delta t}) \quad (5)$$

$$M_{x,t} = f(T_{x,t}, H_{x,t}) \quad (6)$$

Other assumptions (besides the product and air temperatures being equal) made in the development of the present crossflow dryer model simulation are:

1. There is no volume shrinkage during the drying process;
2. The grain flow and airflow are uniform (plug-type);
3. The dryer walls are adiabatic, with negligible heat capacity;
4. $\partial T/\partial t$ and $\partial H/\partial t$ are insignificant as compared to $\partial T/\partial x$ and $\partial H/\partial x$;
5. There is no temperature gradient within the individual grain particles;
6. The heat capacities of grain and of the moist air do not vary over short periods of time;
7. All transfer processes are reversible without hysteresis.

5.1.1 Thin-layer equations

The practical importance of the thin-layer equation in the dryer simulation models is considerable. The equations are obtained from data obtained in thin-layer drying experiments in which a very small quantity of the original material is used. In simulation, the drying process is described by assuming the entire mass to consist of a series of thin layers of the product. An accurate equation describing the moisture behavior of the thin layers is thus very important in order to accurately simulate the multi-layer drying process.

Sabbah et al. (1976) developed a thin-layer drying equation for soybeans based on the premise that the drying is controlled by the rate of diffusion within the seed and by the rate of mass convection at its surface. Two governing equations for convection and mass diffusion developed in the range 32.2-43.3°C are coupled, resulting in the following semi-empirical equation:

$$\frac{M-M_e}{M_o-M_e} = 0.608(1 - \exp(-K_2 t))(\exp(-K_1 t) + 0.25 \exp(-4K_1 t)) + \exp(-K_2 t) \quad (7)$$

The variable K_1 is evaluated by Equation (8):

$$K_1 = 4\pi^2 D/d^2 \quad (8)$$

The term d in Equation (8) is the equivalent seed diameter, assuming the seed to be a sphere. The validity of this assumption has been confirmed by Chu and Hustrulid (1968) who stated that two solids of different shapes can be considered equivalent for drying if their volume-to-surface-area ratios are the same provided none of the solids are originally spheres. Values for the seed equivalent diameter of soybeans can be obtained from the following empirical equation:

$$d = 0.6279 + 0.1255 \cdot M \quad (9)$$

where M is the moisture content expressed in decimal, dry basis. A second empirical equation was used to evaluate the mass diffusion coefficient D in Equation (8).

$$D = (0.0493 \exp(-0.59/(M_o - M_e)) + 0.0181(M - M_e)) \cdot \exp(-3137.6/(\theta + 273)) \quad (10)$$

K_2 , the convection parameter in Equation (7), is defined as:

$$K_2 = GF \cdot AF \cdot GAF \quad (11)$$

where GF is the grain factor:

$$GF = a \cdot S/B \quad (12)$$

$$a = 558.99 - 196.19 \cdot M \quad (13)$$

$$B = 675.10 + 464.54 \cdot M \quad (14)$$

$$S = 1.0 \text{ (shape factor)}$$

AF is the air factor:

$$AF = 1.342 \cdot 10^{-6} G_a RH^{-1} (T+273)^{1.54} / (0.514 + 0.0036 \cdot T)^{0.67} \quad (15)$$

and GAF is the grain-air factor:

$$GAF = x R_e^y (RH_{amb} - RH) / (M - M_e) \quad (16)$$

where

$$x = 0.91 \text{ and } y = 0.51 \text{ for } R_e < 50.0 \text{ and}$$

$$x = 0.61 \text{ and } y = 0.41 \text{ for } R_e \geq 50.0$$

Equations (7) through (16) were originally written in SI units.

The Sabbah equation was at first selected for use in this study because it was developed using a reversed-air drying system.

When the Sabbah equation was added to the MSU crossflow computer simulation program in order to fulfill the requirements of Equation (6), serious instability problems arose. A more careful evaluation of the Sabbah equation showed that the moisture ratio cannot decrease below 0.73, no matter how large the drying time becomes.

Brooker et al. (1974) presented a semi-theoretical drying equation with a logarithmic behavior:

$$\frac{M - M_e}{M_o - M_e} = \exp(-kt) \quad (17)$$

where k is a drying constant expressed in hr^{-1} or sec^{-1} .

Overhults et al. (1973) observed that a logarithmic drying model of the type in Equation (18) does not adequately describe the thin-layer drying process for soybeans. The following modified logarithmic model was proposed:

$$\frac{M - M_e}{M_o - M_e} = \exp(-(kt)^n) \quad (18)$$

M = moisture content (dry basis, decimal)

t = drying time (hr)

k and t are drying constants described by:

$$n = 0.3529 + 0.00136 \cdot T \quad (19)$$

T = drying temperature ($^{\circ}\text{F}$)

$$\ln k = 11.752 - 7912.7/T_{\text{abs}} \quad \text{if } M_o = 20\% \quad (20)$$

$$\ln k = 10.906 - 7357.0/T_{\text{abs}} \quad \text{if } M_o = 23\% \quad (21)$$

$$\ln k = 10.375 - 6779.3/T_{\text{abs}} \quad \text{if } M_o = 33\% \quad (22)$$

with

T_{abs} = absolute temperature ($^{\circ}\text{R}$)

In the development of the Overhults equation, drying data of hand-harvested soybeans at initial moisture contents in the range of 20-33 percent w.b. and with drying temperatures from 37.8-104.4 $^{\circ}\text{C}$ were used.

White et al. (1978) derived two empirical equations for evaluating the n and k parameters in the Overhults equation:

$$n = 0.33 + 0.0025 \text{ RH} + 0.003 T \quad (23)$$

$$k = -0.207 + 3.57 \cdot 10^{-3} T + 2.16 \cdot 10^{-3} M_o + 2.61 \cdot 10^{-3} RH + 3.202 \cdot 10^{-6} M_o T \quad (24)$$

where

RH = relative humidity (percent)

T = temperature (°C)

M_o = initial moisture content (percent d.b.)

Air temperatures for the White et al. experiments varied from 30–70°C, initial moisture contents from 16–24 percent, wet basis, and dew point temperatures from 8–38°C.

Pinheiro-Filho (1976) also developed empirical equations to evaluate the parameters n and k in the Overhults equation for two temperatures (32 and 54.5°C) and two levels of moisture content (15 and 19 percent, w.b.):

$$n = 0.5526 + 1.7742 \cdot T^{-1} \quad (25)$$

$$\ln k = 03.5187 + 0.3333 \cdot 10^{-1} \cdot T \quad (26)$$

T = drying temperature (°F)

Pinheiro-Filho pointed out that some restriction must be put on these equations because of the small number of experiments on which the regression was based.

Roa and Macedo (1976) obtained a thin-layer drying equation for carioca beans:

$$\frac{M - M_e}{M_o - M_e} = \exp(-m(P_{vs} - P_v)^n t^q) \quad (27)$$

where

M = product moisture content (decimal, dry basis)

M_o = initial moisture content (decimal, dry basis)

M_e = equilibrium moisture content (decimal, dry basis)

$P_{vs} - P_v$ = air water vapor pressure deficit (kg_f/kg)

t = time (hours)

m, n and q = drying constants of the product

Roa et al. (1977) evaluated the drying constants of Equation (27) using drying data for soybeans obtained at 47.7°C and 28 percent relative humidity:

$$m = 0.01448$$

$$n = 0.47088$$

$$q = 0.51168$$

The Roa-Macedo soybean drying equation is presented in Figure 10 for five temperatures.

Initially, it was decided to use the Overhults equation as the thin-layer drying equation for the simulation in this study, together with White values for n and k (Equations (23) and (24)). After careful analysis, it was observed that the moisture ratio decreases as the air relative humidity increases. The opposite effect should be predicted by the equation. The behavior of the Overhults-White equations (Equations 18, 23, and 24) can be observed by comparing the results in Figures 7 and 8. It was finally decided to use Overhults equation as the thin-layer drying equation together with Equations (19) through (22) for the evaluation of its parameters. This equation is not affected directly by the air relative humidity, only by the air temperature. Its behavior at five temperatures is presented in Figure 9.

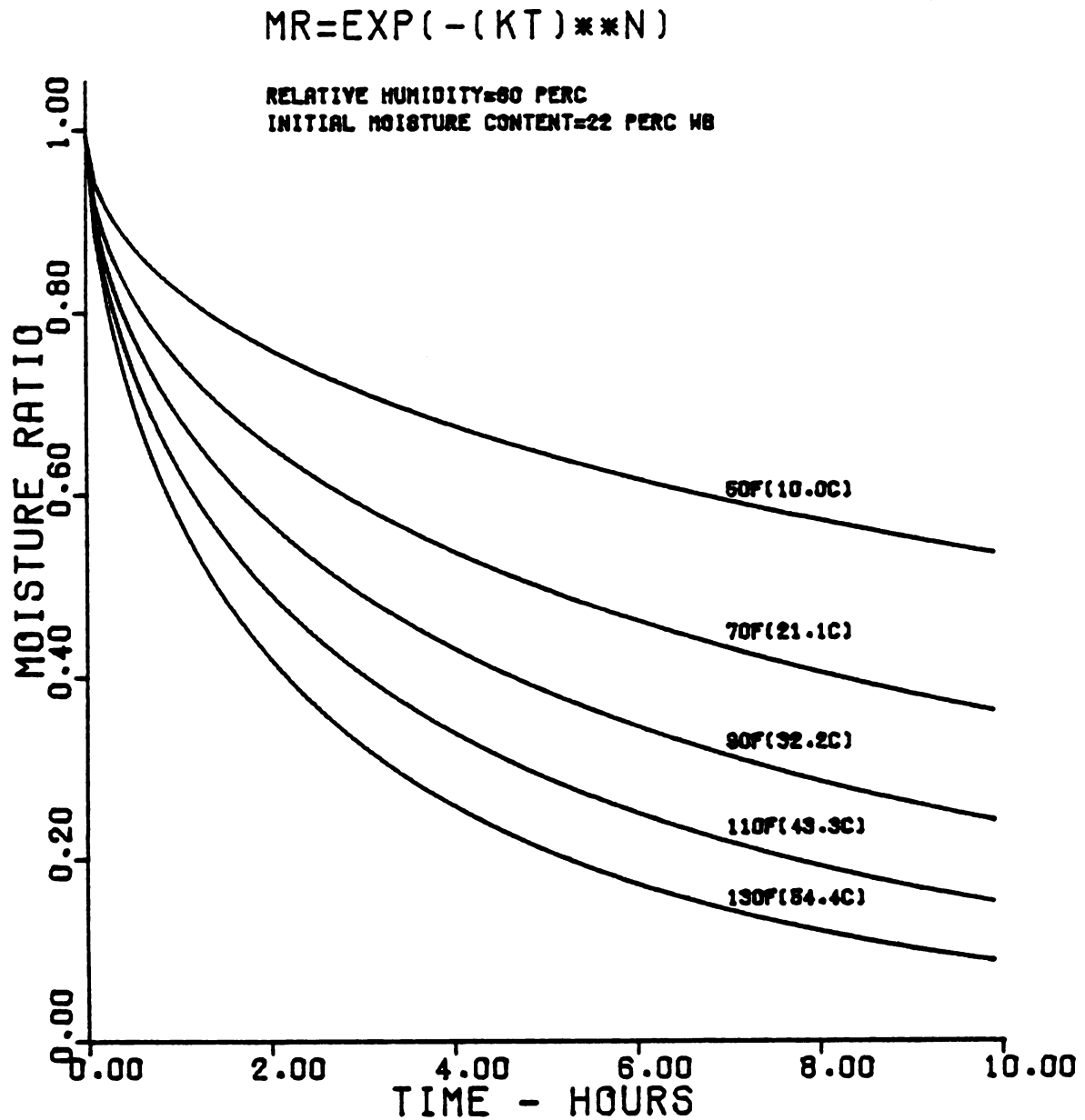


Figure 7: Response of the Overhults thin-layer drying equation for soybeans when the drying parameters are estimated by the White equations.

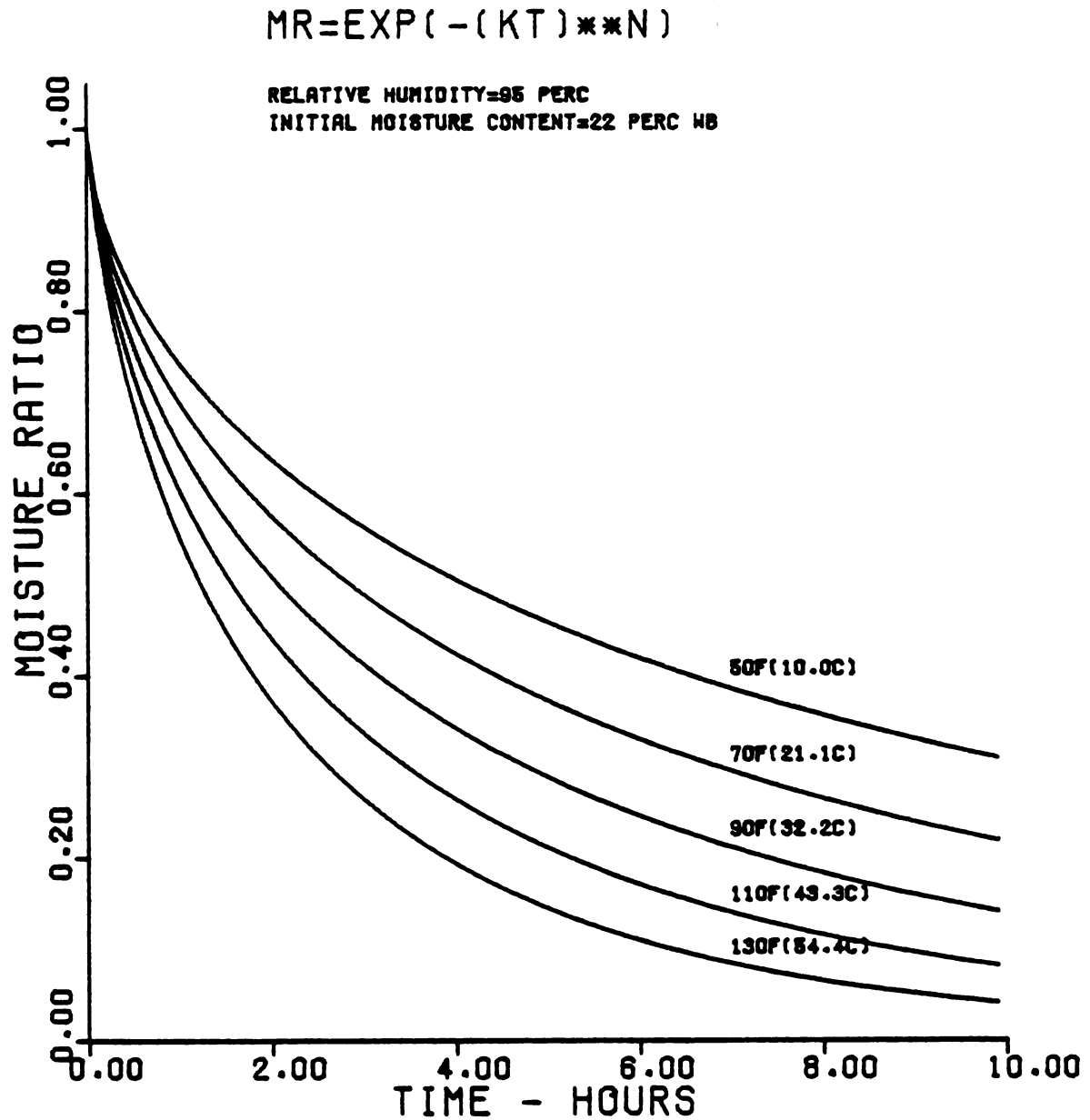


Figure 8: Response of the Overhults thin-layer drying equation for soybeans when the drying parameters are estimated by the White equations.

$$MR = \exp(-(KT) \times N)$$

INITIAL MOISTURE CONTENT=22 PERC HB
RELATIVE HUMIDITY=0 - 100 PERC

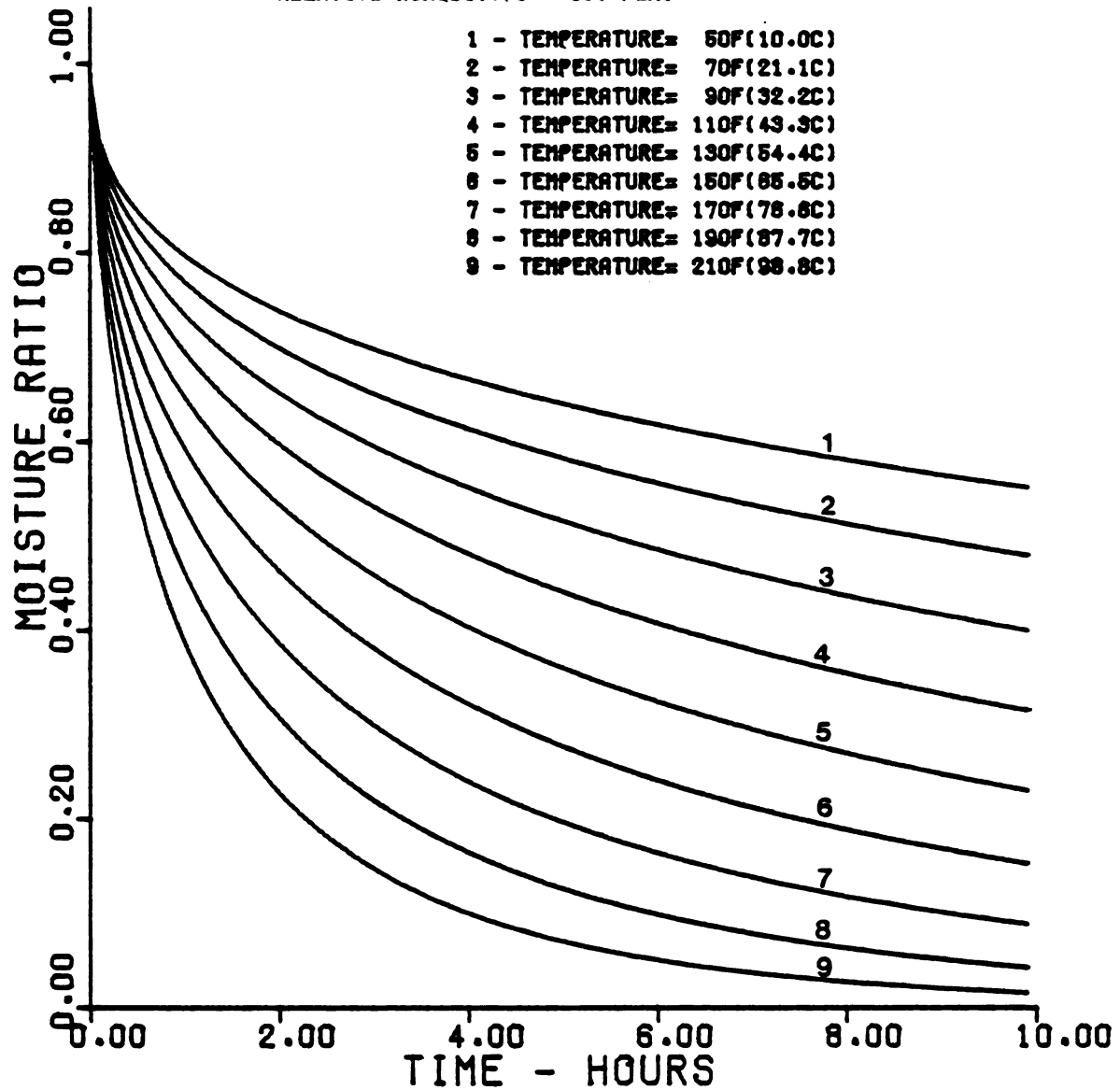


Figure 9: Response of the original Overhults thin-layer drying equation for soybeans.

ROA-MACEDO DRYING EQUATION

INITIAL MOISTURE CONTENT=22 PERC WB
RELATIVE HUMIDITY=0 - 100 PERC

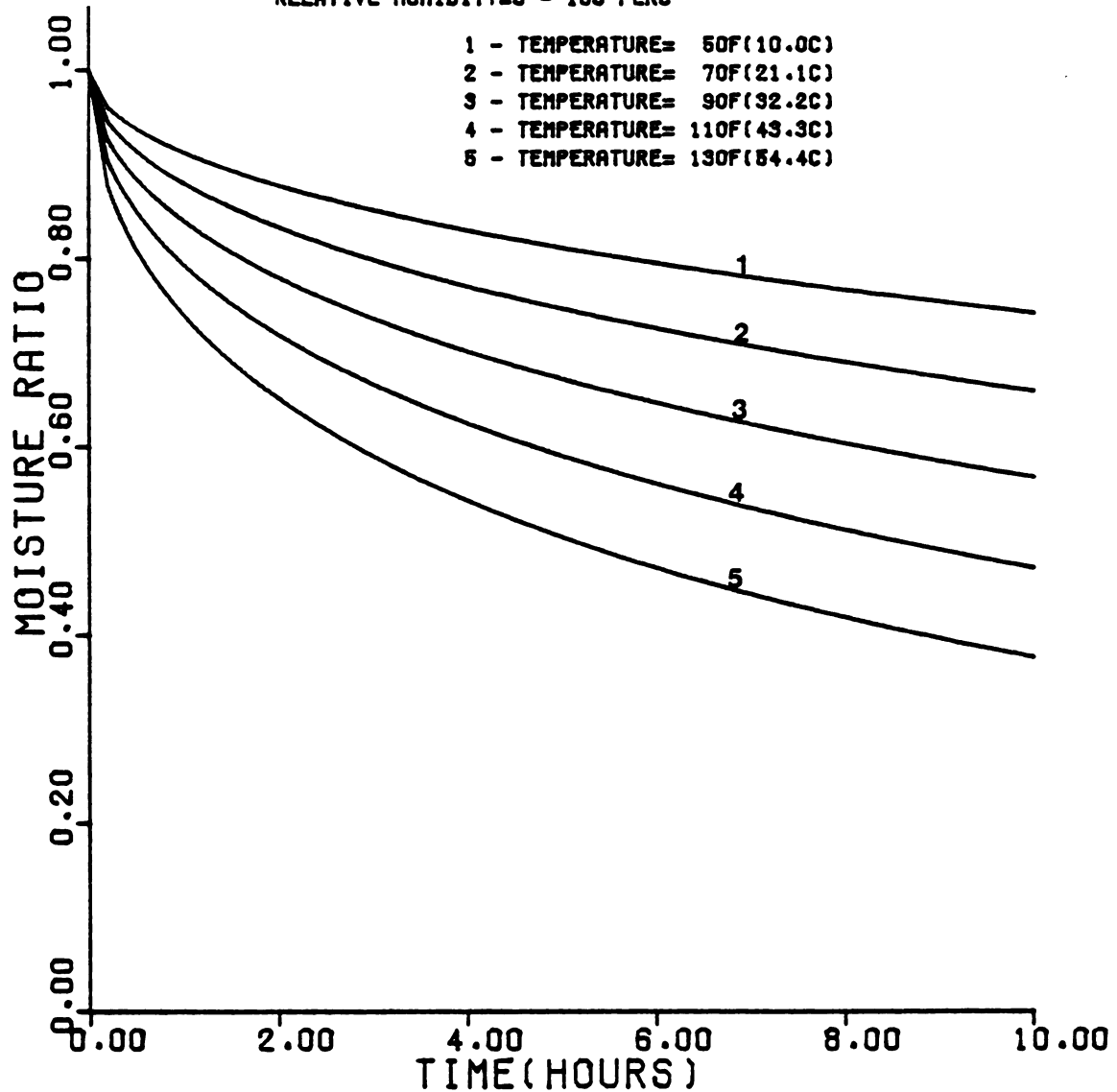


Figure 10: Response of the Roa-Macedo thin-layer drying equation for soybeans.

5.1.2 Equilibrium moisture content

There are several equilibrium moisture content equations available for soybeans. Some are specific for soybeans and others can predict moisture equilibrium for several agricultural products by varying one or more coefficients in the equations.

An equation which accurately describes equilibrium moisture content is important for computation of the drying and desorption rates because it determines the driving force for these processes. Nevertheless, variations in the M_e values reported for one product at the same relative humidity and temperature are common. Some of the causes which may be responsible for the variation are: 1) differences in moisture equilibrium determination methods; 2) experimental errors in moisture equilibrium determination, resulting from difficulties in maintaining and measuring relative humidities and temperatures while the samples equilibrate; 3) inadequate measurement of the moisture content and relative humidity; and 4) product from different varieties and with different histories.

Henderson (1952) proposed a semi-theoretical equation based on the thermodynamic relationships for adsorption to calculate the equilibrium moisture content:

$$1 - RH = \exp(-A T_{abs} M_e^B) \quad (28)$$

where

A and B are product constants

T_{abs} = ambient temperature ($^{\circ}R$)

RH = relative humidity (decimal)

M_e = moisture equilibrium (percent, dry basis)

Values for A and B were determined by Henderson for several products. For soybeans at 25°C, A and B are equal to $3.20 \cdot 10^{-5}$ and 1.52, respectively. These parameters were reevaluated by Alam (1972) and found to be $A = 4.667 \cdot 10^{-5}$ and $B = 1.48234$, at the same temperature. A restriction of the Henderson type equation is that it fails to give acceptable M_e predictions for relative humidities above 80 percent.

Alam (1972) also determined the values for the constants of soybeans in the Sabbah moisture equilibrium equation originally developed for corn:

$$M_e = a - RH^b / T^c \quad (29)$$

where, for soybeans:

$$a = 1.617 \cdot 10^{-4}$$

$$b = 2.85274$$

RH = relative humidity (percent)

T = temperature (°F)

Reasonable predictions for the equilibrium moisture content were obtained for relative humidities above 70 percent.

Alam (1972) also developed a third order polynomial equilibrium moisture content equation for soybeans:

$$\begin{aligned} M_e = & c_1 + c_2 RH + c_3 T + c_4 RH T + c_5 RH^2 + c_6 RH^2 T \\ & + c_7 T^2 + c_8 RH T^2 + c_9 RH^2 T^2 + c_{10} RH^3 + c_{11} RH^3 T \\ & + c_{12} RH^3 T^2 + c_{13} T^3 + c_{14} RH T^3 + c_{15} RH^2 T^3 \\ & + c_{16} RH^3 T^3 \end{aligned} \quad (30)$$

where	$c_1 = 2.98305$	$c_9 = 0.52060 \cdot 10^{-5}$
	$c_2 = 0.29107$	$c_{10} = 0.75358 \cdot 10^{-4}$
	$c_3 = 0.10662$	$c_{11} = 0.23991 \cdot 10^{-5}$
	$c_4 = 0.12514 \cdot 10^{-1}$	$c_{12} = -0.36882 \cdot 10^{-7}$
	$c_5 = -0.65510 \cdot 10^{-2}$	$c_{13} = -0.48010 \cdot 10^{-5}$
	$c_6 = -0.34487 \cdot 10^{-3}$	$c_{14} = 0.68246 \cdot 10^{-6}$
	$c_7 = 0.131125 \cdot 10^{-4}$	$c_{15} = -0.19123 \cdot 10^{-7}$
	$c_8 = -0.18787 \cdot 10^{-3}$	$c_{16} = 0.13494 \cdot 10^{-9}$

T = temperature ($^{\circ}\text{C}$)

RH = relative humidity (percent)

M_e = equilibrium moisture content (percent)

Alam reported that the equation was developed for the desorption isotherms over the entire range of relative humidities and for temperatures ranging from 5°C (41°F) to 55°C (131°F). However, the results could not be duplicated by the author who found negative moisture equilibrium values at low relative humidities for temperatures higher than 32.2°C (90°F). These results may be observed in Figures 12 through 14.

Pfost et al. presented an equilibrium moisture content equation which can be utilized for several products:

$$M_e = E - F \ln(-R(T + C) \ln(RH)) \quad (31)$$

where, for soybeans

$$E = 0.375314$$

$$F = 0.066816$$

$$C = 24.576$$

$$R = \text{universal gas constant (1.987 cal/kg } ^{\circ}\text{K)}$$

$$T = \text{temperature (} ^{\circ}\text{C)}$$

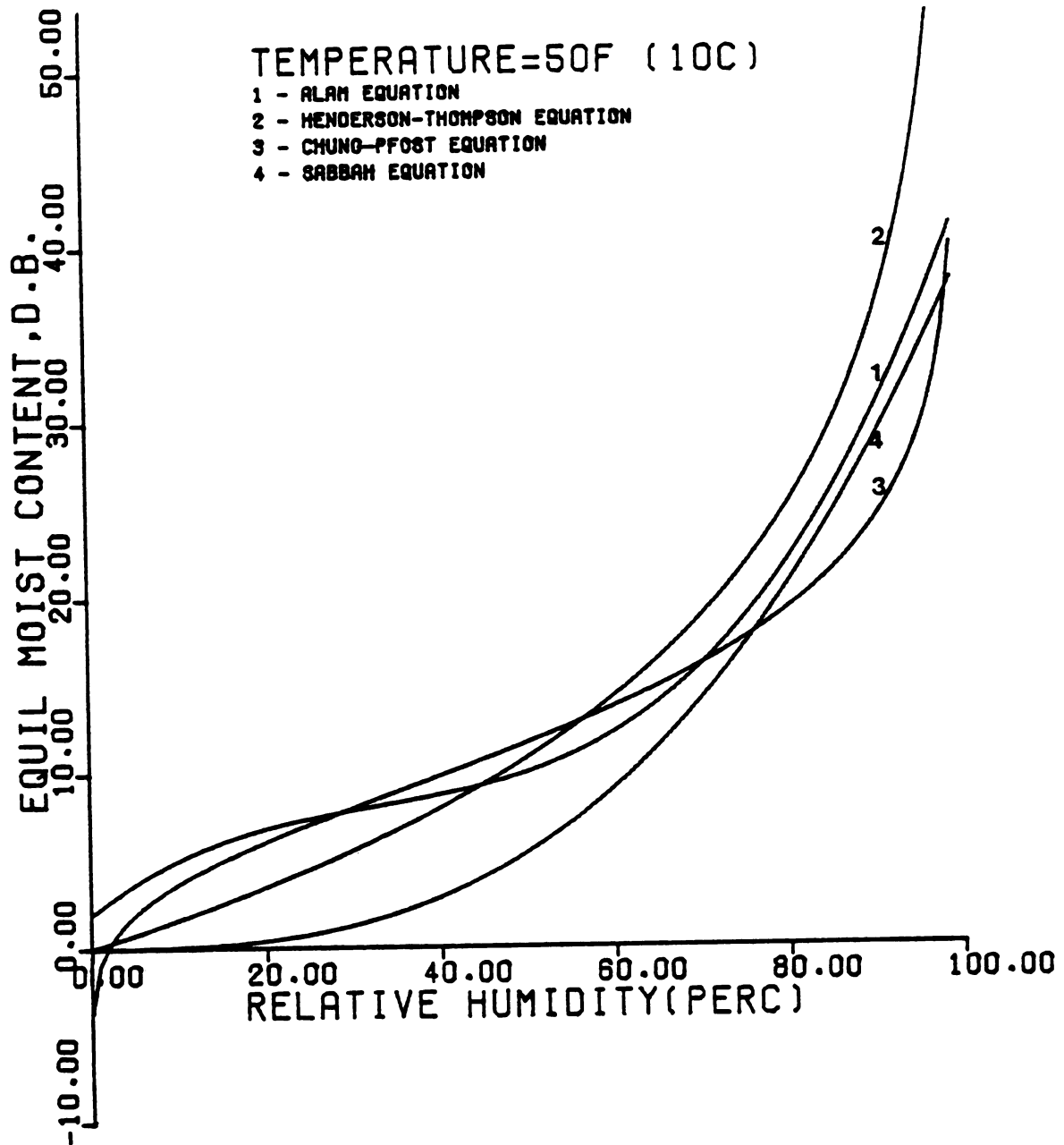


Figure 11: Soybean equilibrium moisture content prediction according to Alam, Henderson-Thompson, Chung-Pfost, and Sabbah equations, at 10°C.

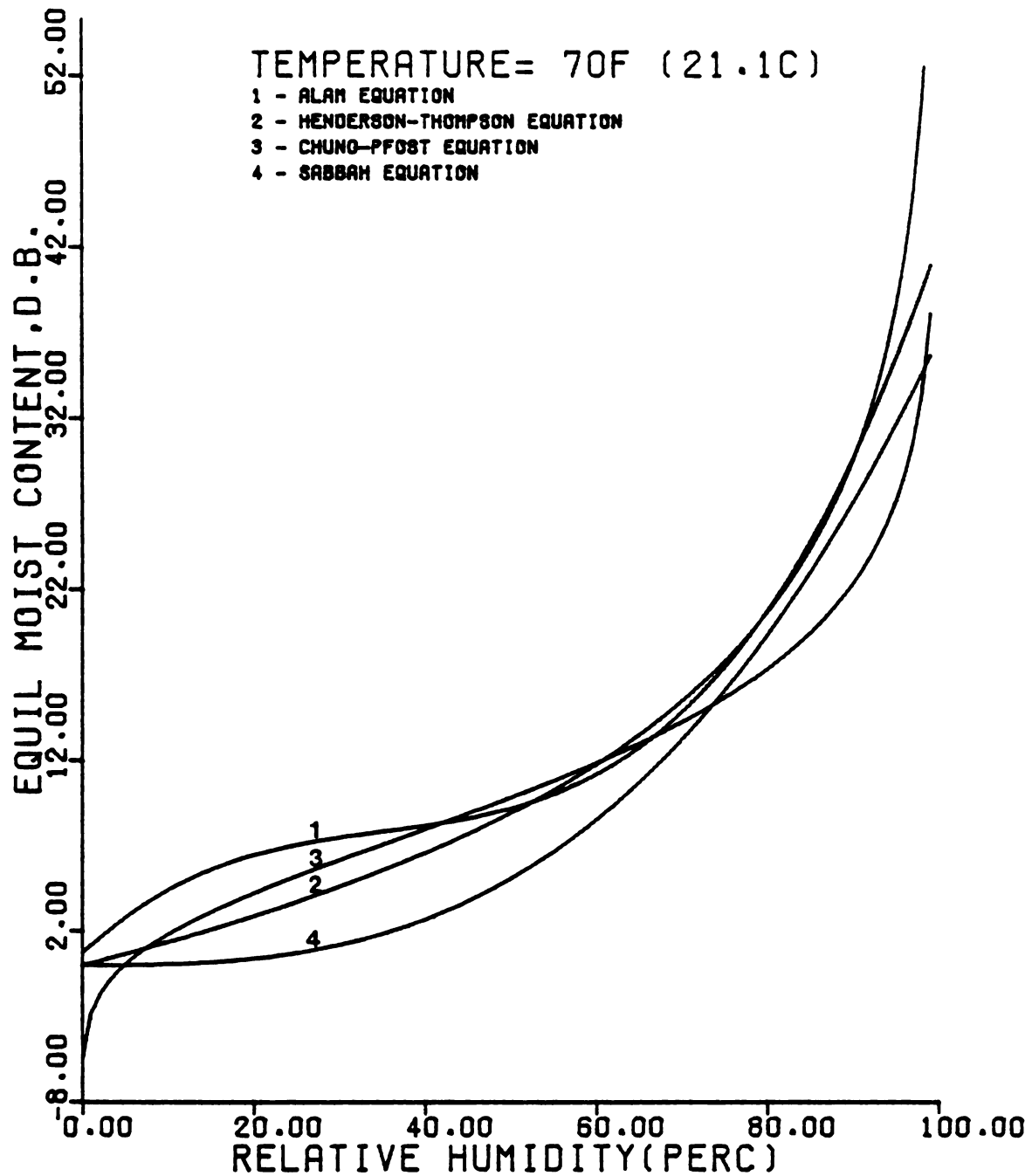


Figure 12: Soybean equilibrium moisture content prediction according to Alam, Henderson-Thompson, Chung-Pfost, and Sabbah equations, at 21.1°C.

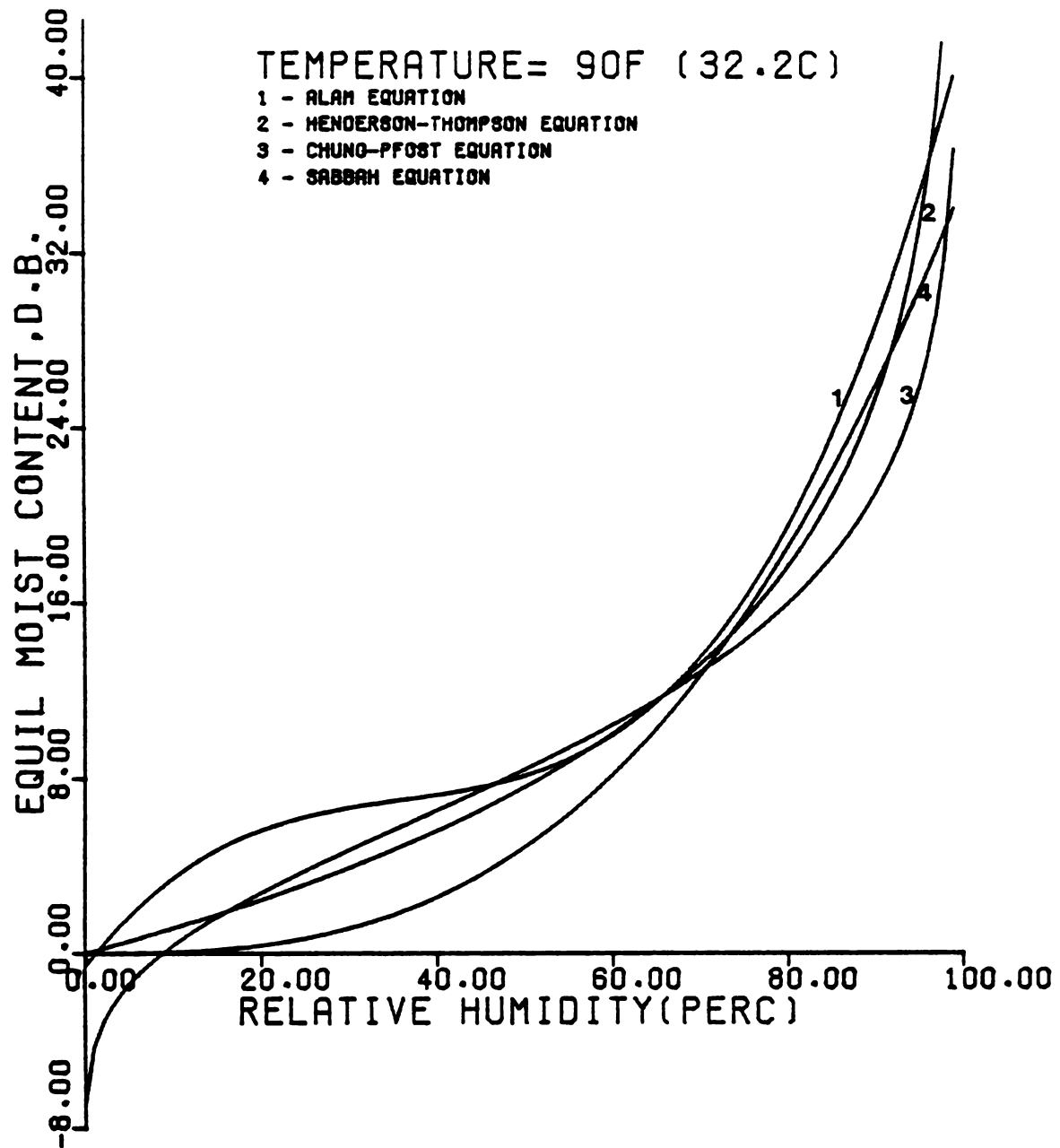


Figure 13: Soybean equilibrium moisture content prediction according to Alam, Henderson-Thompson, Chung-Pfost, and Sabbah equations, at 32.2°C.

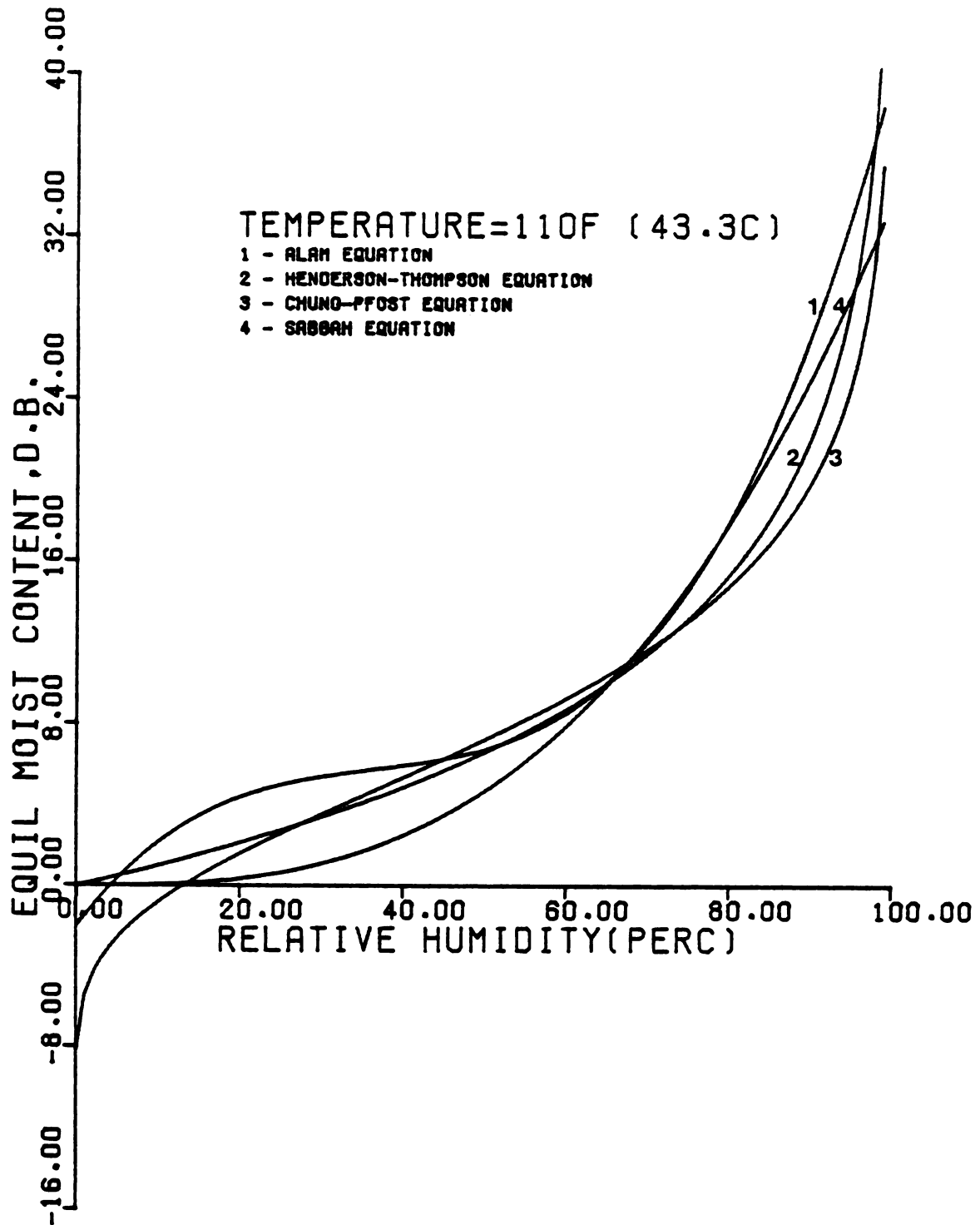


Figure 14: Soybean equilibrium moisture content prediction according to Alam, Henderson-Thompson, Chung-Pfost, and Sabbah equations, at 43.3°C.

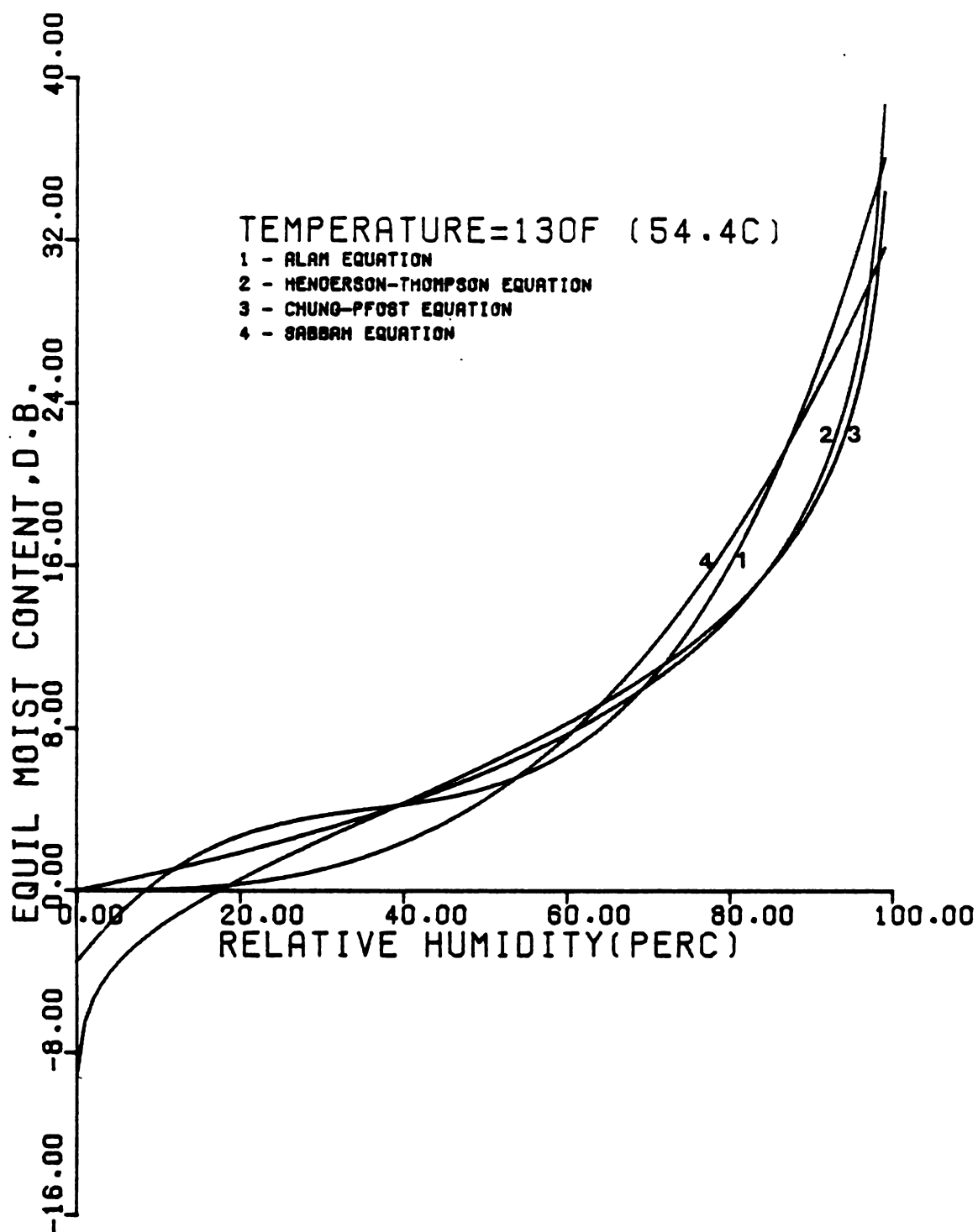


Figure 15: Soybean equilibrium moisture content prediction according to Alam, Henderson-Thompson, Chung-Pfost, and Sabbabh equations, at 54.4°C.

RH = relative humidity (decimal)

M_e = moisture equilibrium (decimal d.b.)

The Pfof equation has the same limitation as Equation (30) since it predicts negative M_e values at low relative humidities for temperatures between 10 and 54.44°C.

Pfof et al. (1976) also calculated the constants for the Henderson-Thompson type equilibrium moisture content equation for soybeans:

$$M_e = (\ln(1 - RH)/(-k(T+C)100)N)^{-1} \quad (32)$$

where

T = temperature (°C)

k = 0.000503633

C = 43.016

N = 1.3628

Although the Henderson-Thompson equation does not have a sigmoidal shape (which is characteristic of the equilibrium moisture content curve for biological products), it does not give negative values. This is an important characteristic when the M_e is part of a computer simulation program. At relative humidities higher than 95 percent, the M_e calculated with Equation (32) is overestimated, a behavior which requires a bound on the M_e values for simulation.

Most of the research conducted on soybean drying has been conducted at low temperatures. Thus, most of the equilibrium moisture content equations for soybeans were developed for low temperatures. As a result, all EMC equations presented here have restrictions in one way or another

when used in high drying temperature simulations. Equations (29) through (32) were plotted in the entire range of relative humidities and for five temperatures, from 10-54.44°C. The results are shown in Figures 11 through 15. By analyzing these plots, one can observe that the Sabbah and Henderson-Thompson equations do not give moisture equilibrium values lower than zero. It was attempted to combine the Sabbah and Henderson-Thompson equations. Equation (32) was used from zero to 70 percent relative humidity and Equation (29) above 70 percent. Figure 17 shows what happens at the transition region at 43.3°C. The transition from one region to another may be relatively smooth and acceptable for computer simulation (see Figure 16). However, when the combined equations are plotted at 21.1°C, a discontinuity occurs at the transition which leads to instability in the simulation results (see Figure 17).

To solve the instability problem at the transition point, the average equilibrium moisture content was calculated from Equations (29) and (32). Although the "average" equation does not show any discontinuity it under-estimates the equilibrium moisture content for relative humidities below 70 percent because of the limitations of Equation (29). The under-estimation of the equilibrium moisture content contributes to instability of the results when the average EMC is utilized in the computer program. Figure 18 presents the average equilibrium moisture content curves for temperatures from 10-54.44°C thus obtained.

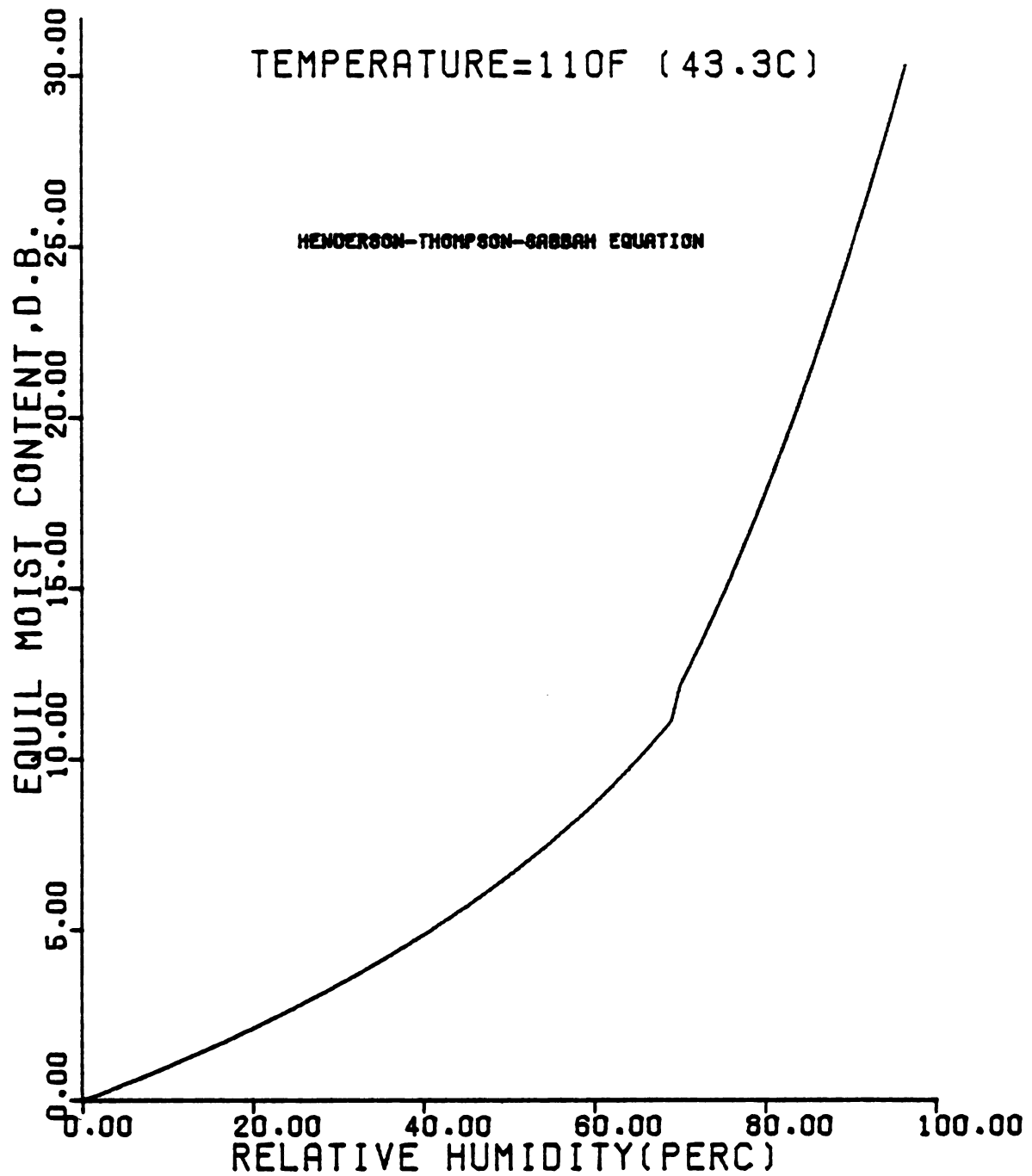


Figure 16: Soybean equilibrium moisture content prediction at 43.3°C using a combination of the Henderson-Thompson and Sabbah equations.

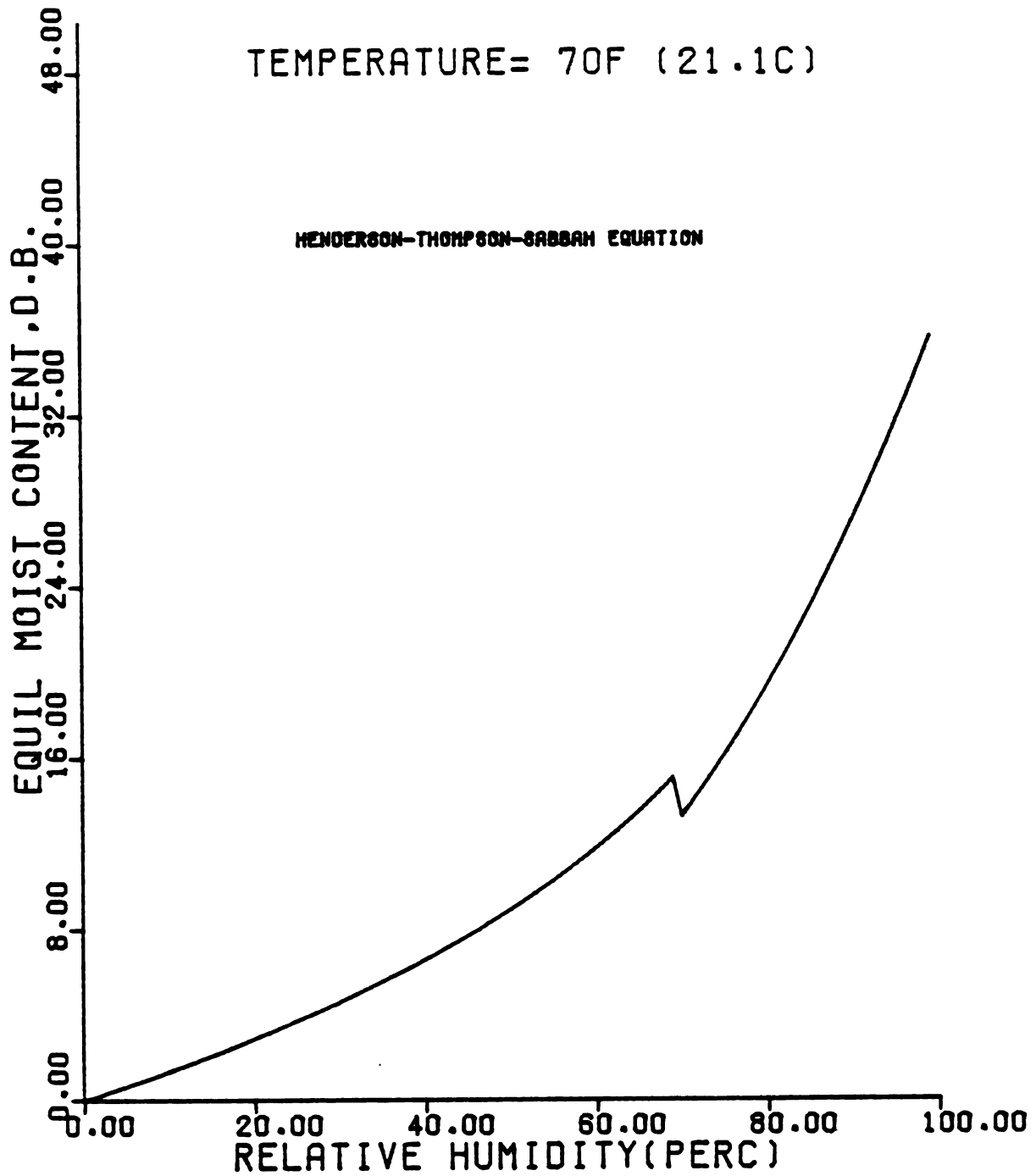


Figure 17: Soybean equilibrium moisture content prediction at 21.1°C using a combination of the Henderson-Thompson and Sabbah equations.

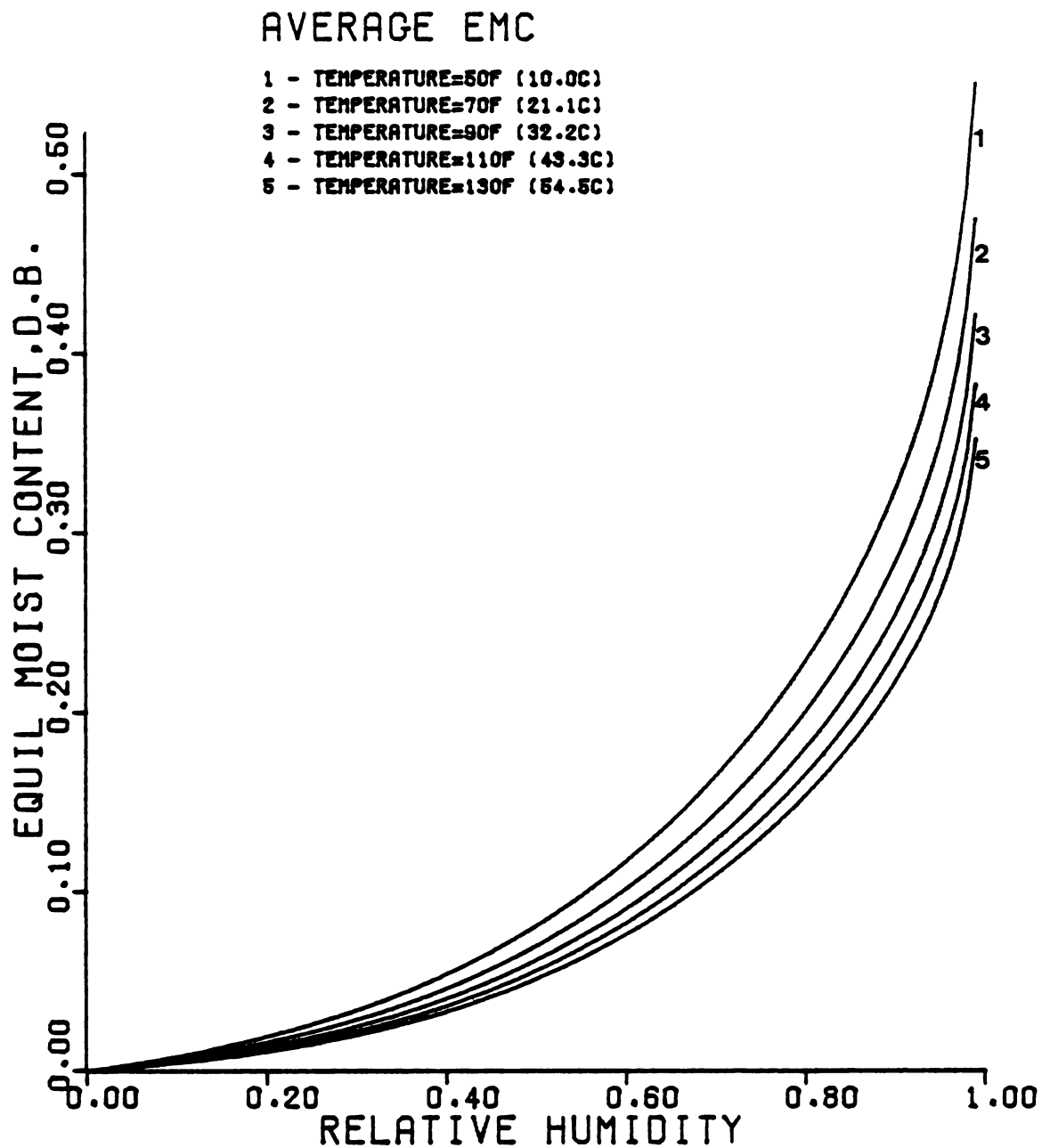


Figure 18: Soybean equilibrium moisture content prediction using the average between the Henderson-Thompson and Sabbah equations at five levels of temperature.

At late stage of this research, an additional equilibrium moisture content equation became available (Roa et al., 1977):

$$M_e = (p_1 RH + p_2 RH^2 + p_3 RH^3) \exp((q_0 + (q_1 RH + q_2 RH^2 + q_3 RH^3 + q_4 RH^4) (T + q_5))) \quad (33)$$

where

M_e = equilibrium moisture content (decimal, dry basis)

RH = relative humidity (decimal)

T = temperature ($^{\circ}$ C)

p_1 = 0.3167048

p_2 = -0.4084806

p_3 = 0.4687752

q_0 = -0.0106576

q_1 = -0.06349201

q_2 = 0.2160320

q_3 = -0.3108765

q_4 = 0.1684076

q_5 = -14.04595

Equation (33) was derived in the temperature range of 20–60 $^{\circ}$ C.

The equation is plotted in Figure 19 for five temperatures.

It can be observed that the curves have a common point at

87 percent relative humidity. Because the M_e values are over-estimated above that point, the results in that range are presented in Appendix C.

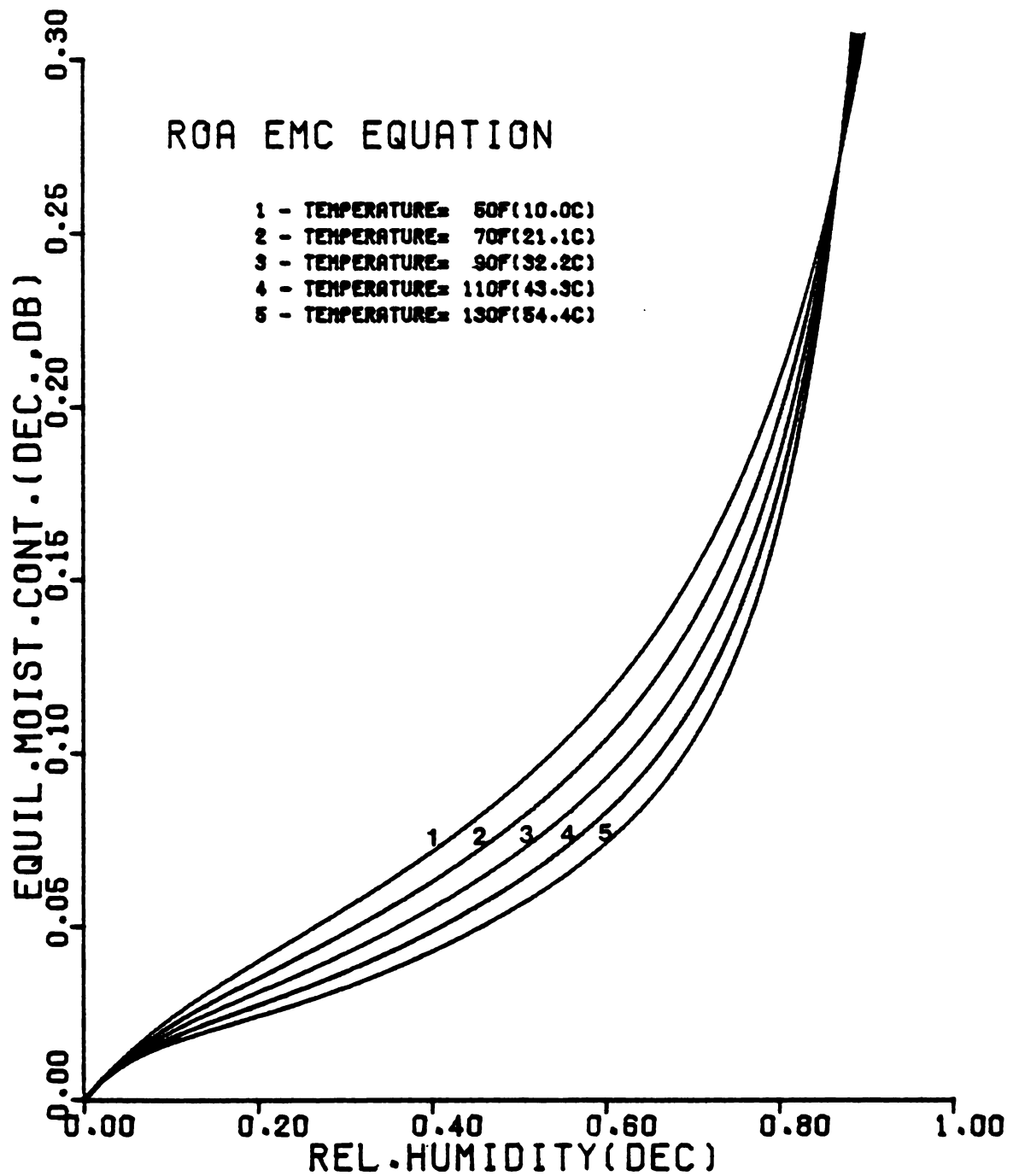


Figure 19: Soybean equilibrium moisture content prediction according to the Roa equation for five levels of temperature.

5.1.3 Specific heat

Alam (1972) carried out specific heat determinations by a calorimetric procedure. The specific heat values obtained at various moisture levels are linearly related, resulting in the following empirical equation:

$$c_p = 0.39123 + 0.0046057 M \quad (34)$$

where

c_p = specific heat (cal/g°C)

M = moisture content (percent, d.b.)

5.1.4 Latent heat of vaporization

The energy required to evaporate moisture from a product being dried is called the latent heat of vaporization.

Othmer (1940) proposed the following equation for the latent heat of vaporization:

$$h_{fg} = h_{fg}' (1 + A \exp(B)) \quad (35)$$

Alam and Shove (1973) determined the constants for the latent heat equation from equilibrium moisture content data for soybeans in the range of 5.66 to 27.51 percent dry basis and temperatures from 5-55°C:

$$h_{fg} = (2502.1 - 2.386 \theta) \cdot (1 + 0.216 \exp(-6.233 M)) \quad (36)$$

5.1.5 Air and other soybean properties

A psychrometric model developed by Brooker et al. (1974) permits the calculation of any property of moist air given any other two properties. The model, known as SYCHART, is stored on a permanent file on the CDC 6500 computer at Michigan State University.

The grain and air properties listed in Table 4 are treated as constants.

5.1.6 Energy and static pressure equations

The energy to heat the drying air can be calculated by an enthalpy balance on the air flowing through the heater apparatus:

$$E = (G_a(c_a + c_v H_{in}) \cdot (T - T_{amb}))/G_p \quad (37)$$

Pressure drop evaluation is based on the Shedd curves which are represented by the following pressure-flow relationship (Brook, 1977):

$$Q_a = A (SP/x_1)^B \quad (38)$$

where, for soybeans

$$A = 75.2$$

$$B = 1/1.431$$

$$Q_a = \text{airflow rate (cfm)}$$

$$x_1 = \text{column depth (ft)}$$

Rearranging Equation (38) leads to:

$$SP = x_1(Q_a/75.2)^{1.431} \quad (39)$$

A copy of the computer program partially developed for this thesis is presented in Appendix A.

Table 4: Air and soybean properties treated as constants
in the simulation program.

Dry bulk density, kg/m^3	929.000
Specific heat of soybeans, $\text{kJ/kg } ^\circ\text{C}$	1.675
Specific surface area, m^2/m^3	1522.300
Specific heat of dry air, $\text{kJ/kg } ^\circ\text{C}$	1.013
Specific heat of water vapor, $\text{kJ/kg } ^\circ\text{C}$	1.884

Source: Brook (1977).

CHAPTER VI

RESULTS AND DISCUSSION

6.1 Concurrent Flow Dryer

The analysis of the concurrent flow dryer is based on the data acquired during the test runs in the laboratory. The calculations assume LP gas to have 45,226.741 kJ/kg (19444 BTU/lb), air to have a specific heat of 0.000239 J/kg°K (0.25 BTU/lb°F), the air density to be the same for one entire test, and a test weight of 57 lb/bushel.

The set of tests consisted of three runs at different drying air temperatures at the same product flow rate. Samples were taken at the grain outlet at equally spaced time intervals and the moisture content, germination, cracks and splits were analyzed. The results are:

FIRST TEST: 12.13.78

inlet air temperature: TIN: 121.11°C (250°F)

inlet moisture content, wet basis, percentage - XMIN: 14.18

outlet moisture content, wet basis, percentage - XMOUT: 12.58

grain flow rate - GFR: 543.48 kg/hr (1200 lb/hr)

inlet grain temperature - TGIN: 11.67°C (53°F)

outlet grain temperature - TGOUT: 28.33°C (83°F)

ambient temperature, dry bulb - TAMB: 24.44°C (76°F)

ambient temperature, wet bulb - TAMBW: 15°C (59°F)

LP gas used - 2.26 kg (5 lb)

drying time - TIME: 2.58 hr

dry matter - DM

$$\begin{aligned} \text{DM} &= \text{GFR} (1 - \text{XMOUT}) \\ &= 543.48 (1 - 0.1258) \\ &= 475.11 \text{ kg/hr (1049.04 lb/hr)} \end{aligned}$$

water in grain (in) - WIN

$$\begin{aligned} \text{WIN} &= \text{DM} \cdot \text{XMIN} / (1 - \text{XMIN}) \\ &= 475.11 \cdot 0.1418 / (1 - 0.1418) \\ &= 78.50 \text{ kg/hr (173.33 lb/hr)} \end{aligned}$$

water in grain (out) - WOUT

$$\begin{aligned} \text{WOUT} &= \text{GFR} \cdot \text{XMOUT} \\ &= 543.38 \cdot 0.1258 \\ &= 68.37 \text{ kg/hr (150.96 lb/hr)} \end{aligned}$$

specific volume (air) - SV = 0.857 m³/kg (13.70 cu ft/lb)

water removed - WR

$$\begin{aligned} \text{WR} &= \text{WIN} - \text{WOUT} \\ &= 78.50 - 68.37 \\ &= 10.13 \text{ kg/hr (22.37 lb/hr)} \end{aligned}$$

LP gas consumption - LPG

$$\begin{aligned} \text{LPG} &= \text{LP} / \text{TIME} \\ &= 2.26 / 2.58 \\ &= 0.88 \text{ kg/hr (1.93 lb/hr)} \end{aligned}$$

energy used - EN

$$\begin{aligned} \text{EN} &= \text{LPG} \cdot 45,226.77 \\ &= 0.88 \cdot 45,226.77 \\ &= 39,799.54 \text{ kJ/hr (37,772.58 BTU/hr)} \end{aligned}$$

efficiency - EFF

$$\begin{aligned}
 \text{EFF} &= \text{EN}/\text{WR} \\
 &= 39,799.54/10.13 \\
 &= 3928.88 \text{ kJ/kg of water removed} \\
 &\quad (1688.77 \text{ BTU/lb})
 \end{aligned}$$

For the second test, as well as for the third one, two stage drying was simulated. For the first stage drying the cooler was turned off and the drying process was continued for 1.5 hr. A tempering time of two hours was established, after which the second stage drying was started. The results for the second test follow:

SECOND TEST: 12.22.78

First Stage: TIN = 121.11°C (250°F)

XMIN = 14.69

XMOUT = 13.24

GFR = 432.48 kg/hr (1200 lb/hr)

TGIN = 11.67°C (53°F)

TGOUT = 28.33°C (83°F)

TAMB = 23.33°C (74°F)

TAMBW = 13.89°C (57°F)

SV = 0.851 m³/kg (13.60 cu ft/lb)

LP = 1.47 kg (3.25 lb)

TIME = 2.0 hr

dry matter -

DM = 543.48 (1-0.1201)

= 478.21 kg/hr (1055.88 lb/hr)

water in grain (in) -

$$\begin{aligned} \text{WIN} &= 478.21 \cdot 0.1469 / (1 - 0.1469) \\ &= 82.35 \text{ kg/hr (181.82 lb/hr)} \end{aligned}$$

water in grain (out) -

$$\begin{aligned} \text{WOUT} &= 543.48 \cdot 0.1324 \\ &= 71.96 \text{ kg/hr (158.88 lb/hr)} \end{aligned}$$

water removed -

$$\begin{aligned} \text{WR} &= 82.35 - 71.96 \\ &= 10.39 \text{ kg/hr (22.94 lb/hr)} \end{aligned}$$

LP gas consumption -

$$\begin{aligned} \text{LPG} &= 1.47 / 2.0 \\ &= .74 \text{ kg/hr (1.62 lb/hr)} \end{aligned}$$

energy used -

$$\begin{aligned} \text{EN} &= 0.74 \cdot 45,226.74 \\ &= 33,467.79 \text{ kJ/hr (31,763.30 BTU/hr)} \end{aligned}$$

efficiency -

$$\begin{aligned} \text{EFF} &= 33,467.79 / 10.39 \\ &= 3221.15 \text{ kJ/kg of water removed} \\ &\quad (1384.56 \text{ BTU/lb}) \end{aligned}$$

Second Stage:

$$\begin{aligned} \text{TIN} &= 93.33^\circ\text{C (200}^\circ\text{F)} \\ \text{XMIN} &= 13.24 \\ \text{XMOUT} &= 12.01 \\ \text{TIME} &= 1.50 \text{ hr} \\ \text{LP} &= 0.91 \text{ kg/hr (2.0 lb/hr)} \end{aligned}$$

water in grain (out) -

$$\begin{aligned} \text{WIN} &= 543.48 \cdot 0.1201 \\ &= 65.27 \text{ kg/hr (144.12 lb/hr)} \end{aligned}$$

water removed -

$$\begin{aligned} \text{WR} &= 71.96 - 65.27 \\ &= 6.69 \text{ kg/hr (14.77 lb/hr)} \end{aligned}$$

LP gas consumption -

$$\begin{aligned} \text{LPG} &= 0.91/1.5 \\ &= 0.61 \text{ kg/hr (1.34 lb/hr)} \end{aligned}$$

energy used -

$$\begin{aligned} \text{EN} &= 0.61 \cdot 45,226.74 \\ &= 27,588.31 \text{ kJ/hr (26,133.26 BTU/hr)} \end{aligned}$$

efficiency -

$$\begin{aligned} \text{EFF} &= 27,588.31/6.69 \\ &= 4123.81 \text{ kJ/kg of water removed} \\ &\quad (1772.56 \text{ BTU/lb}) \end{aligned}$$

overall dryer efficiency -

$$\begin{aligned} \text{OEFF} &= (\text{EN}(\text{first stage}) + \text{EN}(\text{second stage})) / \\ &\quad (\text{WR}(\text{first stage}) + (\text{WR}(\text{second stage}))) \\ &= (33.467.79 + 27,588.31) / (10.39 + 6.69) \\ &= 3574.71 \text{ kJ/kg of water removed} \\ &\quad (1536.53 \text{ BTU/lb}) \end{aligned}$$

The third test produced the following results:

THIRD TEST:

First Stage: $T_{IN} = 148.89^{\circ}\text{C}$ (300°F)

$X_{MIN} = 13.52$

$X_{MOUT} = 12.73$

$$\text{GFR} = 543.38 \text{ kg/hr (1200 lb/hr)}$$

$$\text{TGIN} = 5.56^{\circ}\text{C (42}^{\circ}\text{F)}$$

$$\text{TGOUT} = 23.33^{\circ}\text{C (74}^{\circ}\text{F)}$$

$$\text{TAMB} = 24.44^{\circ}\text{C (76}^{\circ}\text{F)}$$

$$\text{TAMBW} = 15.00^{\circ}\text{C (59}^{\circ}\text{F)}$$

$$\text{SV} = 0.854 \text{ m}^3/\text{kg (13.65 cu ft/lb)}$$

$$\text{LP} = 1.13 \text{ kg (2.50 lb)}$$

$$\text{TIME} = 1.5 \text{ hr}$$

dry matter -

$$\text{DM} = 543.48 (1 - 0.1124)$$

$$= 482.39 \text{ kg/hr (1065.12 lb/hr)}$$

water in grain (in) -

$$\text{WIN} = 482.39 \cdot 0.1352 / (1 - 0.1352)$$

$$= 75.42 \text{ kg/hr (166.52 lb/hr)}$$

water in grain (out) -

$$\text{WOUT} = 543.48 \cdot 0.1273$$

$$69.19 \text{ kg/hr (152.76 lb/hr)}$$

water removed -

$$\text{WR} = 75.42 - 69.19$$

$$= 6.23 \text{ kg/hr (13.76 lb/hr)}$$

LP gas consumption -

$$\text{LPG} = 1.13 / 1.5$$

$$= 0.75 \text{ kg/hr (1.66 lb/hr)}$$

energy used -

$$\text{EN} = 0.75 \cdot 45,226.74$$

$$= 33,920.06 \text{ kJ/hr (32,192.54 BTU/hr)}$$

efficiency -

$$\begin{aligned} \text{EFF} &= 33,920.06/6.23 \\ &= 5444.63 \text{ kJ/kg of water removed} \\ &\quad (2340.29 \text{ BTU/lb}) \end{aligned}$$

Second Stage:

$$\text{TIN} = 121.11^{\circ}\text{C} \quad (250^{\circ}\text{F})$$

$$\text{SMIN} = 12.73$$

$$\text{XMOUT} = 11.24$$

$$\text{TIME} = 1.5 \text{ hr}$$

$$\text{LP} = 1.02 \text{ kg} \quad (2.25 \text{ lb})$$

water in grain (out) -

$$\begin{aligned} \text{WOUT} &= 543.48 \cdot 0.1124 \\ &= 61.09 \text{ kg/hr} \quad (134.88 \text{ lb/hr}) \end{aligned}$$

water removed -

$$\begin{aligned} \text{WR} &= 69.19 - 61.09 \\ &= 8.10 \text{ kg/hr} \quad (17.88 \text{ lb/hr}) \end{aligned}$$

LP gas consumption -

$$\begin{aligned} \text{LPG} &= 1.02/1.5 \\ &= 0.68 \text{ kg/hr} \quad (1.50 \text{ lb/hr}) \end{aligned}$$

energy used -

$$\begin{aligned} \text{EN} &= 0.68 \cdot 45,226.74 \\ &= 30,754.19 \text{ kJ/hr} \quad (29,187.90 \text{ BTU/hr}) \end{aligned}$$

efficiency -

$$\begin{aligned} \text{EFF} &= 30,754.19/8.10 \\ &= 3796.81 \text{ kJ/kg of water removed} \\ &\quad (1632 \text{ BTU/lb}) \end{aligned}$$

overall efficiency -

$$\begin{aligned} \text{OEFF} &= (33.920.06 + 30,754.19)/(6.23 + 8.10) \\ &= 4513.21 \text{ kJ/kg of water removed} \\ &\quad (1939.93 \text{ BTU/lb}) \end{aligned}$$

Excellent control was achieved for the inlet drying air temperatures in all three tests. Special consideration of the wet bulb temperature depression is necessary. The maximum wet bulb depression is obtained when the air velocity through the wet wick is above 4.57 m/s (15 ft/sec) (Brooker et al., 1974). Because the cross sectional area of the concurrent and counterflow exhaust ducts are both 0.0081 m^2 (0.0873 ft^2), the minimum airflow necessary to overcome the velocity requirements is $2.23 \text{ m}^3/\text{min}$ (78.54 cfm). As the airflow rate through the cooler is only $0.60 \text{ m}^3/\text{min}$ (21 cfm), the measured wet bulb temperature of the cooler exhaust is too high. In the concurrent exhaust, the wet bulb temperature is correctly measured because the airflow was at least $3.83 \text{ m}^3/\text{min}$ (135 cfm).

An average flow rate of 543.48 kg/hr (1200 lb/hr), $\pm 3.2 \text{ kg/hr}$ (7 lb/hr), was measured for the three tests.

The LP gas measurement presented a problem. The gas consumption was estimated by the tank weight variation before and after each test. A Toledo scale was utilized as the weighing device. Because the tank was installed outside the building, precise weight readings were difficult to obtain due to the wind effects. The author feels that this explains the discrepancy between the LP gas consumption

data for the first, second and third tests. In theory, all three values should have been equal for the stages in which the same inlet drying temperature was used. However, variations from 0.88 kg/hr to 0.68 kg/hr were recorded for the LP gas.

The soybean moisture content was evaluated according to Service and Regulatory Announcements No. 147 of the United States Department of Agriculture. Besides the error in the weight measurements due to the limited scale accuracy, a rounding-off error occurred in the calculations because the scale was accurate to only two decimal places. The author feels that a scale accurate to four decimal places should have been used because relatively small samples (about 5 grams) were involved. Another error present in the moisture content evaluations is due to sampling. Samples were taken as the dryer was being filled and accepted as representative of the dryer load. Nevertheless, analyzing the moisture content at several times during the drying tests, it was observed that the initial moisture content by as much as ± 2 percent.

A value of $3.83 \text{ m}^3/\text{min}$ (135 cfm) was obtained for the airflow through the drying section. However, as the airflow was checked from the energy calculations, the following results were attained:

1. first test

- air flow: $5.61 \text{ m}^3/\text{min}$ (197.96 cfm)

2. second test

2.1 first stage

- air flow: $4.64 \text{ m}^3/\text{min}$ (163.63 cfm)

2.2 second stage

- air flow: $5.40 \text{ m}^3/\text{min}$ (190.61 cfm)

3. third test

3.1 first stage

- air flow: $3.71 \text{ m}^3/\text{min}$ (130.78 cfm)

3.2 second stage

- air flow: $4.08 \text{ m}^3/\text{min}$ (144.06 cfm)

The discrepancy in these results is assumed to be caused by the incorrect values measured in weighing the LP gas consumption. The value of $3.83 \text{ m}^3/\text{min}$ was thus accepted as the airflow reference value.

Germination, cracks and splits results are presented in Table 5 for the extreme cases. The values for germination, cracks and splits at the beginning of the drying tests are expected to be similar for all three tests because they are the soybean characteristics before any drying was performed. Because the initial crack and split values are significantly different, the results in Table 5 indicate that the soybean sample was not originally homogeneous. An expected decrease in the percentage of germination and an increase in splits and cracks percentage was observed for all tests. The complete results are presented in Appendix D.

Table 5: Soybean germination, crack and split variations after drying in a concurrent flow dryer.

	121.11°C	121.11-93.33°C	148.89-121.11°C
Germination (%)			
initial	91.00	95.50	93.00
minimum	83.50	84.00	75.50
Cracks (%)			
initial	2.77	3.83	8.51
maximum	15.63	21.05	18.18
Splits (%)			
initial	1.20	3.57	3.87
maximum	4.48	5.68	6.60

The measured efficiency values fall in the interval expected for concurrent flow dryer, i.e., from 4185 kJ/kg of water removed (1800 BTU/lb) to 5120 kJ/kg of water removed (2200 BTU/lb). The high values encountered for the efficiency in the first stage of the third run is the result of the low inlet soybean temperature for that test. As a result, part of the heat available for removing water from the soybeans was used to warm up the product, diminishing the amount of water removed. The data show that the concurrent flow dryer is an efficient device for drying soybeans.

6.2 Crossflow Simulation

The crossflow dryer simulated in this thesis is commercially available. The air and product conditions represent typical conditions of the harvesting season. A schematic of the commercial unit is presented in Appendix B.

The computer simulation program permits a choice of the reversal of airflow, of a different number of stages of different lengths, and of variable inlet air temperatures and airflows. Recirculating airflow may be simulated after a quick hand evaluation of the new inlet conditions is made.

The results obtained from the simulation are presented in Tables 6 through 9. The inlet conditions for each stage are presented at the top of each table.

Besides the minimum, maximum and average moisture contents and temperatures, the outlet soybean moisture equilibrium, and the air relative humidity and humidity ratio

Table 6: Input and results for the crossflow dryer simulation, first stage.

EXEC BEGUN.08.20.33.
 TYPE OF PRODUCT(CORN=1 OR SOYBEAN=2):2. 2.0000

CROSSFLOW GRAIN DRYER SIMULATION
 USING THE OVERHULTZ THINLAYER EQUATION FOR SOYBEAN
 AND EMC BY ROA

[INPUT CONDITIONS FOR STAGE 1:
 INLET AIR TEMP, F :130. 130.0000
 INLET AMBIENT TEMP, F :60. 60.0000
 AMBIENT REL HUM, DEC :.6 .6000
 TYPE OF FUEL USED (1=NO.2 FUEL
 2=NAT.GAS, 3=L.P.GAS):1. 1.0000
 CALCULATED AMBIENT ABS HUM= .0068
 CALCULATED INLET ABS HUM= .0087
 AIRFLOW, CFM/BU (AT DRYING TEMP):110. 110.0000
 INLET GRAIN TEMP, F:60. 60.0000
 INLET MOISTURE, WET BASIS PERCENT:22. 22.0000
 COLUMN WIDTH, IN:12. 12.0000
 COLUMN LENGTH, FT:23.5 23.5000
 GRAINFLOW, BU/HR/SQ FT:20. 20.0000
 OUTPUT INTERVAL, FT:1. 1.0000
 HYBRID DRYING FACTOR,DEC:1. 1.0000
 NO.OF STAGES(DRYER+COOLER):4. 4.0000

PRELIMINARY CALCULATED VALUES

AIRFLOW, CFM/SQ FT 88.4244
 DRY AIRFLOW RATE, LB/HR-FT2 388.5833
 INLET MC(DRY BASIS DECIMAL) .2821
 GRAIN FLOW RATE, BUSHELS/HR-FT2 20.0000
 GRAIN FLOW RATE, FT/HR 24.8800

TIME DEPTH		MOISTURE-WB			TEMPERATURE					
HR	FT	MAV	MIN	MAX	TAUG	TMIN	TMAX	HOUT	RH	MEOUT
.02	.50	.2196	.2114	.2231	65.2	60.0	116.5	.0111	98.21	.2656
.06	1.49	.2195	.2049	.2226	70.7	60.9	125.8	.0116	99.20	.2715
.10	2.49	.2192	.2004	.2233	75.8	62.4	127.5	.0123	99.16	.2728
.14	3.48	.2188	.1967	.2238	80.4	65.0	128.0	.0135	99.04	.2748
.18	4.48	.2181	.1936	.2242	84.2	68.8	128.3	.0153	98.63	.2761
.22	5.47	.2173	.1908	.2246	87.1	72.8	128.5	.0175	98.02	.2759
.26	6.47	.2163	.1883	.2250	89.3	74.2	128.7	.0193	97.48	.2749
.30	7.46	.2151	.1860	.2253	91.1	74.5	128.8	.0204	97.13	.2739
.34	8.46	.2138	.1838	.2256	92.5	74.8	128.9	.0209	96.95	.2733
.38	9.45	.2125	.1818	.2259	93.8	75.1	129.0	.0211	96.87	.2729
.42	10.45	.2112	.1799	.2260	95.0	74.7	129.0	.0211	96.82	.2726
.46	11.44	.2098	.1781	.2262	96.1	75.2	129.1	.0211	96.79	.2724
.50	12.44	.2084	.1764	.2263	97.2	74.8	129.1	.0210	96.80	.2724
.54	13.44	.2070	.1747	.2265	98.3	75.3	129.2	.0210	96.76	.2721
.58	14.43	.2056	.1732	.2266	99.3	75.0	129.2	.0209	96.77	.2721
.62	15.43	.2042	.1717	.2268	100.3	75.6	129.2	.0208	96.74	.2718
.66	16.42	.2027	.1702	.2269	101.3	75.2	129.3	.0208	96.76	.2719
.70	17.42	.2012	.1688	.2270	102.3	75.1	129.3	.0207	96.72	.2716
.74	18.41	.1997	.1675	.2272	103.2	75.7	129.3	.0206	96.72	.2714
.78	19.41	.1982	.1662	.2273	104.2	75.4	129.4	.0206	96.73	.2714
.82	20.40	.1967	.1649	.2274	105.1	75.3	129.4	.0205	96.70	.2712
.86	21.40	.1951	.1637	.2275	106.0	75.9	129.4	.0204	96.69	.2711
.90	22.39	.1936	.1625	.2276	106.8	75.8	129.4	.0203	96.72	.2712
.94	23.39	.1920	.1613	.2277	107.7	75.6	129.4	.0203	96.73	.2712
.96	23.88	.1914	.1608	.2280	108.6	78.5	129.4	.0154	71.52	.1505

AVERAGE AIR EXHAUST TEMP, F 75.1951
 AVERAGE AIR EXHAUST HUM.RATIO .0187
 ENERGY SUPPLIED, BTU/SQ FT 157204.4265
 WATER REMOVED, LB/SQ FT-HR 65.3743
 EFFICIENCY, BTU/LB H2O 2404.6830
 TOTAL DRYER WATER REMOVED, LB/SQ FT-HR 65.3743
 TOTAL DRYER EFFICIENCY, BTU/LBH2O 2404.6830
 INLET MOISTURE EQUILIBRIUM-WB .0207
 DRY AIRFLOW RATE, LB/HR FT2 388.5833
 STATIC PRESSURE, IN H2O 1.2609
 TOTAL HORSE POWER, HP/FT2 OF WIDTH 1.6505

Table 7: Input and results for the crossflow dryer simulation, second stage.

CROSSFLOW GRAIN DRYER SIMULATION
USING THE OVERHULTZ THINLAYER EQUATION FOR SOYBEAN
AND EMC BY ROA

INPUT CONDITIONS FOR STAGE 2:

INLET AIR TEMP, F :130.	130.0000
INLET AMBIENT TEMP, F :60.	60.0000
AMBIENT REL HUM, DEC :.6	.6000
CALCULATED AMBIENT ABS HUM=	.0068
CALCULATED INLET ABS HUM=	.0087
AIRFLOW, CFM/BU (AT DRYING TEMP):110.	110.0000
COLUMN LENGTH, FT:23.5	23.5000
TYPE OF ARRAY CONVERSION (1=NO CHANGES, 2=REVERSE AIRFLOW):2.	2.0000

TIME DEPTH		MOISTURE-WB			TEMPERATURE					
HR	FT	MAV	MIN	MAX	TAUG	THIN	TMAX	HOUT	RH	MEOUT
.02	.50	.1895	.1602	.2252	105.9	73.4	127.1	.0269	28.81	.0498
.06	1.49	.1877	.1594	.2146	102.2	77.6	123.7	.0234	29.04	.0510
.10	2.49	.1864	.1587	.2119	100.2	81.1	126.9	.0168	24.34	.0454
.14	3.48	.1852	.1581	.2077	98.7	82.5	127.8	.0153	25.81	.0483
.18	4.48	.1841	.1576	.2042	97.9	83.3	128.2	.0148	29.24	.0542
.22	5.47	.1830	.1573	.2011	97.8	84.0	128.4	.0145	33.69	.0620
.26	6.47	.1819	.1570	.1984	98.4	84.5	128.6	.0143	39.00	.0715
.30	7.46	.1809	.1567	.1959	99.5	84.9	128.7	.0142	44.55	.0820
.34	8.46	.1799	.1566	.1937	101.0	85.3	128.8	.0141	49.16	.0914
.38	9.45	.1790	.1565	.1917	102.7	85.6	128.9	.0141	51.61	.0967
.42	10.45	.1780	.1564	.1898	104.5	86.0	129.0	.0141	51.42	.0963
.46	11.44	.1770	.1563	.1880	106.3	87.4	129.1	.0141	49.13	.0914
.50	12.44	.1760	.1561	.1863	107.8	89.6	129.1	.0140	45.80	.0846
.54	13.44	.1750	.1560	.1847	109.2	92.0	129.2	.0140	42.34	.0779
.58	14.43	.1741	.1558	.1831	110.3	94.4	129.2	.0140	39.26	.0721
.62	15.43	.1731	.1556	.1816	111.3	96.4	129.2	.0139	36.72	.0676
.66	16.42	.1722	.1553	.1802	112.1	98.1	129.3	.0138	34.69	.0640
.70	17.42	.1712	.1550	.1789	112.8	99.5	129.3	.0138	33.07	.0613
.74	18.41	.1703	.1547	.1776	113.4	100.7	129.3	.0137	31.74	.0590
.78	19.41	.1694	.1544	.1763	114.0	101.7	129.3	.0136	30.64	.0572
.82	20.40	.1685	.1541	.1751	114.5	102.6	129.4	.0135	29.69	.0556
.86	21.40	.1676	.1538	.1739	115.0	103.4	129.4	.0135	28.86	.0542
.90	22.39	.1667	.1534	.1728	115.4	104.1	129.4	.0134	28.12	.0530
.94	23.39	.1659	.1530	.1717	115.8	104.7	129.4	.0133	27.45	.0519
.96	23.88	.1654	.1529	.1711	116.0	105.0	129.4	.0133	27.13	.0514

AVERAGE AIR EXHAUST TEMP, F	99.9437
AVERAGE AIR EXHAUST HUM.RATIO	.0150
ENERGY SUPPLIED, BTU/SQ FT	157204.4265
WATER REMOVED, LB/SQ FT-HR	55.5476
EFFICIENCY, BTU/LB H2O	2830.0865
TOTAL DRYER WATER REMOVED, LB/SQ FT-HR	120.9219
TOTAL DRYER EFFICIENCY, BTU/LBH2O	2600.0995
INLET MOISTURE EQUILIBRIUM-WB	.0207
DRY AIRFLOW RATE, LB/HR FT2	388.5833
STATIC PRESSURE, IN H2O	1.2609
TOTAL HORSE POWER, HP/FT2 OF WIDTH	3.3009

Table 8: Input and results for the crossflow dryer simulation, third stage.

CROSSFLOW GRAIN DRYER SIMULATION
USING THE OVERHULTZ THINLAYER EQUATION FOR SOYBEAN
AND EMC BY ROA

INPUT CONDITIONS FOR STAGE 3:

INLET AIR TEMP, F :60.	60.0000
INLET AMBIENT TEMP, F :60.	60.0000
AMBIENT REL HUM, DEC :.6	.6000
CALCULATED AMBIENT ABS HUM=	.0068
CALCULATED INLET ABS HUM=	.0068
AIRFLOW, CFM/BU (AT DRYING TEMP):110.	110.0000
COLUMN LENGTH, FT:7.85	7.8500
TYPE OF ARRAY CONVERSION	
(1=NO CHANGES, 2=REVERSE AIRFLOW):1.	1.0000

TIME DEPTH		MOISTURE-WB			TEMPERATURE							
HR	FT	MAV	MIN	MAX	TAUG	TMIN	TMAX	HOUT	RH	MEOUT		
.02	.50	.1650	.1527	.1706	111.5	79.8	121.8	.0113	22.87	.0450		
.06	1.49	.1643	.1523	.1695	105.3	61.6	116.7	.0107	21.43	.0428		
.10	2.49	.1636	.1519	.1686	99.5	60.1	113.0	.0100	19.94	.0405		
.14	3.48	.1631	.1514	.1680	93.8	60.0	110.1	.0095	18.64	.0385		
.18	4.48	.1627	.1510	.1677	88.4	60.0	107.8	.0089	17.61	.0369		
.22	5.47	.1624	.1505	.1675	83.2	60.0	106.0	.0085	16.98	.0360		
.26	6.47	.1621	.1501	.1675	78.2	59.9	104.2	.0081	17.04	.0363		
.30	7.46	.1619	.1497	.1674	73.7	59.9	100.7	.0077	18.09	.0384		
.32	7.96	.1618	.1495	.1674	71.7	59.9	98.3	.0076	19.10	.0403		

AVERAGE AIR EXHAUST TEMP, F	104.8688
AVERAGE AIR EXHAUST HUM.RATIO	.0091
ENERGY SUPPLIED, BTU/SQ FT	0.0000
WATER REMOVED, LB/SQ FT-HR	7.4742
EFFICIENCY, BTU/LB H2O	0.0000
TOTAL DRYER WATER REMOVED, LB/SQ FT-HR	128.3960
TOTAL DRYER EFFICIENCY, BTU/LBH2O	2448.7431
INLET MOISTURE EQUILIBRIUM-WB	.1239
DRY AIRFLOW RATE, LB/HR FT2	389.8055
STATIC PRESSURE, IN H2O	1.2609
TOTAL HORSE POWER, HP/FT2 OF WIDTH	3.8522

Table 9: Input and results for the crossflow dryer simulation, fourth stage.

CROSSFLOW GRAIN DRYER SIMULATION
USING THE OVERHULTZ THINLAYER EQUATION FOR SOYBEAN
AND EMC BY ROA

INPUT CONDITIONS FOR STAGE 4:

INLET AIR TEMP, F :60.	60.0000
INLET AMBIENT TEMP, F :60.	60.0000
AMBIENT REL HUM, DEC :.6	.6000
CALCULATED AMBIENT ABS HUM=	.0068
CALCULATED INLET ABS HUM=	.0068
AIRFLOW, CFM/BU (AT DRYING TEMP):110.	110.0000
COLUMN LENGTH, FT:7.85	7.8500
TYPE OF ARRAY CONVERSION	
(1=NO CHANGES, 2=REVERSE AIRFLOW):2.	2.0000

TIME	DEPTH	MOISTURE-WB			TEMPERATURE						
HR	FT	MAV	MIN	MAX	TAUG	TMIN	TMAX	HOUT	RH	MEOUT	
.02	.50	.1618	.1495	.1674	70.7	59.9	89.7	.0074	65.89	.1397	
.06	1.49	.1616	.1495	.1674	70.4	60.0	85.0	.0074	65.36	.1382	
.10	2.49	.1615	.1495	.1673	70.0	60.1	81.9	.0074	64.25	.1349	
.14	3.48	.1614	.1495	.1673	69.5	60.0	79.6	.0074	61.15	.1262	
.18	4.48	.1613	.1495	.1671	68.9	60.0	77.6	.0074	56.08	.1131	
.22	5.47	.1612	.1494	.1669	67.9	60.0	76.0	.0073	50.21	.0994	
.26	6.47	.1611	.1494	.1667	66.8	60.0	74.7	.0073	45.13	.0886	
.30	7.46	.1610	.1494	.1666	65.5	59.9	73.5	.0072	41.94	.0823	
.32	7.96	.1610	.1494	.1665	64.8	59.9	73.0	.0072	41.20	.0809	

AVERAGE AIR EXHAUST TEMP, F	64.9376
AVERAGE AIR EXHAUST HUM.RATIO	.0073
ENERGY SUPPLIED, BTU/SQ FT	0.0000
WATER REMOVED, LB/SQ FT-HR	1.7237
EFFICIENCY, BTU/LB H2O	0.0000
TOTAL DRYER WATER REMOVED, LB/SQ FT-HR	130.1197
TOTAL DRYER EFFICIENCY, BTU/LBH2O	2416.3039
INLET MOISTURE EQUILIBRIUM-WB	.1239
DRY AIRFLOW RATE, LB/HR FT2	389.8055
STATIC PRESSURE, IN H2O	1.2609
TOTAL HORSE POWER, HP/FT2 OF WIDTH	4.4036
THIS IS THE END OF CROSSFLOW	
STOP	

at the outlet conditions, some additional quantities are evaluated after each stage. Some values refer to the stage just simulated and others are cumulative results. Belonging to the first group are: (1) the average air exhaust temperature, (2) the average air exhaust humidity ratio, (3) the energy supplied, (4) the water removed, (5) the energy efficiency of the stage, (6) the dry airflow rate, and (7) the static pressure. In the second group fall: (1) the total dryer water removed, (2) the total dryer efficiency, and (3) the total horsepower. These figures permit the reader to observe how the soybeans and the air behave inside the dryer.

At the bottom of Figure 9, the total dryer efficiency is tabulated. In the simulated case, the overall efficiency is 5620.31 kJ/kg of water removed (2416.3 BTU/lb), a typical value for a crossflow dryer. The overall efficiency can be improved if some changes are made in the cooler dimensions (in the present dryer only a small amount of water is removed by the cooling air). It should be noted that the efficiency only includes the energy used to increase the drying air temperature. The electricity required to run the fans is not included in the efficiency calculations.

The results in Tables 6 through 9 are a sample of the features of the crossflow model. They are characteristics of the input conditions. The output will be different if one or more input parameters change.

English units are used in the simulation of this dryer

because the American grain dryer industry is not yet using the SI units. The appropriate unit conversion factors can be found in Appendix E.

CHAPTER VII

CONCLUSIONS

1. Drying air temperatures up to 148.89°C (300°F) may be used to dry soybeans in a concurrent flow dryer without a significant reduction in the product quality (germination, cracks and splits), provided the mass flow rate is at least 540 kg/hr.

2. The increase in cracks and splits is due to the combined effect of drying and handling (two augers moved the beans through and out of the dryer). However, it was not possible to determine which of these effects was the most important. Previous studies showing a decrease in the crack percentage in favor of an increase in splits was not confirmed on this research. The results here reported show an increase in both figures, a more logical behavior.

3. An efficient crossflow dryer model resulted from the soybean drying simulation.

4. Continuous flow drying of soybeans at high temperatures is a feasible practice. The adoption of such a practice will stimulate early harvest of soybeans which results in less field and harvesting losses. Besides, early harvested soybeans reach the market when the price is higher. In Brazil, anticipation of the harvesting

season will have one additional advantage, i.e., there will be more time for planting the next crop, thus making the practice of double cropping more attractive.

CHAPTER VIII

SUGGESTIONS FOR FURTHER STUDIES

1. Future experimental work with the concurrent flow drying of soybeans should include variations in the air and mass flow rates.

2. Initial moisture content on the order of 16-22 percent should be tested because the feasibility of continuous soybean drying will be greatly increased if the drying process can start at those levels of moisture content.

3. Special care must be taken in the moisture evaluation of the product. A scale accurate to four decimal places should be used because small variations in the weight readings may cause significant error in the moisture content calculations.

4. A statistical sampling method should be used.

5. An equilibrium moisture content equation should be developed to assist in the dryer simulation that uses high air temperatures. The available equilibrium moisture content equations are acceptable for low temperature drying simulations but may not describe the drying behavior adequately at higher temperatures than for which they were developed.

6. A thin-layer equation which accounts for the moisture diffusion inside the soybeans should be developed because it describes the drying process in a more realistic way.

7. An equation which predicts the germination loss of the soybeans would be valuable in drying simulations.

APPENDICES

APPENDIX A
LISTING OF THE COMPUTER PROGRAM

APPENDIX A

LISTING OF THE COMPUTER PROGRAM

```

PROGRAM XFLQ(INPUT,OUTPUT)
C***** C C O S S F L C W G R A I N D R Y E R M O D E L
C***** F.W. BAKKER-ARKEVA, PROJECT LEADER
C***** R.C. ERGCK, PROGRAMMER
C***** MODIFIED BY V.A. DALPASQUALE
C*****
C***** DESCRIPTION
C***** MAIN PROGRAM FOR SIMULATION OF A CROSSFLOW DRYER
C*****
COMMON/MAIN/XMT,THT,RHT,DELT,CFM,XMO,KAB,TOTEN,TOTH20,XMS,TOTSP,
+YLENGTH,IPROD,FH,HDF,NSTG
COMMON/INPT/BPH,GP,GVEL,IND1,DELX,YLENG,DBTPR,XWIDE
COMMON/PRPRT/SA,CA,CV,CW,RHOP,CP
COMMON/LATENT/HA,H8
COMMON/TENT/K1,K2,XMR
COMMON/NAMES/SNAME,SPROD,SEMC
COMMON/PRESS/PATM
COMMON/NAME/INAME,IPRODU,IEMC
REAL K1,K2
DIMENSION XM(300),RH(300),T(300),H(300)
F(T)=T+459.69
C***** INPUT CONDITIONS OF DRYER TO BE SIMULATED
YADD=0.
NSTG=1
TOTEN=0. STOTH20=0. STOTSP=0.
PRINT 170
READ 200,PRODUCT
PRINT 199,PRODUCT
IPROD=IFIX(PRODUCT)
CALL DATE(IPROD)
IF(IPROD.EQ.2) GO TO 2
PRINT 201,INAME,IPRODU,IEMC,NSTG
GO TO 3
PRINT 201,SNAME,SPROD,SEMC,NSTG
2 READ 200,TIN
3 PRINT 199,TIN
PRINT 199
READ 200,TAMB
PRINT 199,TAMB
PRINT 202
READ 200,RHAMB
PRINT 199,RHAMB
PRINT 230
READ 200,FUEL
PRINT 199,FUEL
HI=HADBPH(F(TAMB),RHAMB)
PRINT 240,HI
CALL ABSH(HIN,TAMB,TIN,HI,FUEL,IPROD)
PRINT 250,HIN
PRINT 203
READ 200,CFMBU
PRINT 199,CFMBU
PRINT 204
READ 200,THIN
PRINT 199,THIN
PRINT 205
READ 200,XMOW
PRINT 199,XMOW
XMO=XMOW/(100.-XMOW)
ITME=0
PRINT 207
READ 200,XWIDE
PRINT 199,XWIDE
PRINT 208
READ 200,YLENG
PRINT 199,YLENG
PRINT 206
READ 200,BPH
PRINT 199,BPH
IF(BPH.GT.0.0) GOTO 9
ITME=1
PRINT 210
READ 200,TIME
PRINT 199,TIME
TIME=TIME/60.
BPH=YLENG/TIME/1.244
9 GVEL=BPH*1.244

```


APPENDIX A, continued:

```

XWIDE=XWIDE/12.
CFM=CFMBU*XWIDE/1.244
PRINT 200
READ 200,DSTPR
PRINT 199,DSTPR
IF(IPROD.EQ.2) GO TO 48
PRINT 211
READ 200,FM
PRINT 199,FM
PRINT 212
READ 200,HDF
PRINT 199,HDF
PRINT 210
READ 200,STAGES
PRINT 199,STAGES
48 C***** COMPUTE STEP AND ARRAY SIZES
DELX=0.05
IF(IPROD.EQ.2) DELX=0.02
IND=INT(XWIDE/DELX)+1
IND1=IND+1
DELX=XWIDE/FLOAT(IND)
DELT=0.02
IF(IPROD.EQ.2) DELT=0.02
C***** COMPUTE INLET RH AND INITIALIZE ALL ARRAY POSITIONS NECESSARY
RHIN=RHDBHA(F(TIN),HIN)
RMT=RHIN
DO 1 I=1,IND1
XM(I)=XMO=XMO
H(I)=HIN
T(I)=THIN
RH(I)=RHIN
1 CONTINUE
T(1)=TIN
YLENGTH=YLENG
C***** CONVERT AIRFLOW TO LB/HR
GA=60.*CFM/VSDDBHA(F(TAMB),HIN)
C***** PRINT HEADER PAGE OF CONDITIONS AND PROPERTIES
PRINT 215,CFM,GA,XMO,BPH,GVEL
C***** CALL CRFLW FOR SIMULATING A SINGLE CROSSFLOW STAGE
10 CALL CRFLW(XM,RH,T,H,TIN,THIN,HIN,YADD,TAMB,GA,RHAMB)
IF(NSTG.EQ.STAGES) GO TO 25
NSTG=NSTG+1
IF(IPROD.EQ.2) GO TO 30
PRINT 201,INAME,IPRODU,IEMC,NSTG
GO TO 40
30 PRINT 201,SNAME,SPROD,SEMC,NSTG
40 READ 200,FIN
IF(TIN.LT.0.) GOTO 20
PRINT 199,TIN
PRINT 190
READ 200,TAMB
PRINT 199,TAMB
PRINT 202
READ 200,RHAMB
PRINT 199,RHAMB
HI=HADBHRH(F(TAMB),RHAMB)
PRINT 240,HI
IF(TIN.EQ.TAMB) GO TO 12
CALL ABSH(HIN,TAMB,TIN,HI,FUEL,IPROD)
GO TO 13
12 HIN=HI
13 PRINT 250,HIN
PRINT 203
READ 200,CFMBU
PRINT 199,CFMBU
CFM=CFMBU*XWIDE/1.244
GA=60.*CFM/VSDDBHA(F(TAMB),HIN)
YADD=YADD+YLENG/GVEL
IF(ITIME.GT.0) GOTO 15
PRINT 208
READ 200,YLENG
PRINT 199,YLENG
GOTO 16
15 PRINT 218
READ 200,TIME
PRINT 199,TIME
TIME=TIME/60.

```

APPENDIX A, continued:

```

16      YLENG=1.244*TIME*8PH
      PRINT 221
      READ 198 ITYPE
      PRINT 199 F10.4(ITYPE)
      IF(ITYPE.EQ.2) CALL CONVERT(XM,RH,T,H)
      T(1)=TIN
      H(1)=HIN
      RH(1)=RHDBWA(F(TIN),HIN)
      YLENGTH=YLENGTH+YLENG
      GOTO 10
20      YLENG=YADD+YLENG/GVEL
25      PRINT 260
      STOP
170     FORMAT(1X*TYPE OF PRODUCT(CORN=1 OR SOYBEAN=2):*)
190     FORMAT(5X*INLET AMBIENT TEMP, F:*)
198     FORMAT(I1)
199     FORMAT(1H+,40X,F10.4)
200     FORMAT(F10.2)
201     FORMAT(*CROSSFLOW GRAIN DRYER SIMULATION*/
      ** USING THE *A10* THINLAYER EQUATION FOR *A10 /
      ** AND EMC BY *A10//
      ** INPUT CONDITIONS FOR STAGE*I2*:*/
      5X*INLET AIR TEMP, F:*)
202     FORMAT(5X*AMBIENT REL HUM, DEC:*)
203     FORMAT(5X*AIRFLOW, CFM/BU (AT DRYING TEMP):*)
204     FORMAT(5X*INLET GRAIN TEMP, F:*)
205     FORMAT(5X*INLET MOISTURE, WET BASIS PERCENT:*)
206     FORMAT(5X*GRAINFLOW, BU/HR/SQ FT:*)
207     FORMAT(5X*COLUMN WIDTH, IN:*)
208     FORMAT(5X*COLUMN LENGTH, FT:*)
209     FORMAT(5X*OUTPUT INTERVAL, FT:*)
210     FORMAT(5X*NO. OF STAGES(DRYER+COOLER):*)
211     FORMAT(5X*FINE MATERIALS DECIMAL:*)
212     FORMAT(5X*HYBRID DRYING FACTOR, DEC:*)
215     FORMAT(/* PRELIMINARY CALCULATED VALUES*/
      ** AIRFLOW, CFM/SQ FT *F8.4/
      ** DRY AIRFLOW RATE, LB/HR-FT2 *F8.4/
      ** INLET MC(DRY BASIS DECIMAL) *F8.4/
      ** GRAIN FLOW RATE, BUSHELS/HR-FT2 *F8.4/
      ** GRAIN FLOW RATE, FT/HR *F8.4)
218     FORMAT(5X*DRYING TIME, MIN:*)
221     FORMAT(5X*TYPE OF ARRAY CONVERSION*/
      5X*(1=NO CHANGES, 2=REVERSE AIRFLOW):*)
230     FORMAT(5X*TYPE OF FUEL USED (1=NO.2 FUEL*/
      5X*2=NAT.GAS, 3=L.P.GAS):*)
240     FORMAT(5X*CALCULATED AMBIENT ABS HUM=*9X,F10.4)
250     FORMAT(5X*CALCULATED INLET ABS HUM=*11X,F10.4)
260     FORMAT(5X,*THIS IS THE END OF CROSSFLOW*)
      END

```

APPENDIX A, continued:

```

SUBROUTINE CRSFLW(XM,RH,T,H,TIN,THIN,HIN,YADD,TAMP,SA,RHAMB)
C***** SUBROUTINES USED
C***** BLOCKDATA
C***** LAYEQ
C***** READYTH
C*****
C***** FUNCTION SUBPROGRAMS USED
C***** EMC
C***** SYCHART PACKAGE
C*****
      DIMENSION XM(300),RH(300),T(300),H(300),RHK(300)
      COMMON/MAIN/XMT,THT,RHT,DELT,CFM,XMO,KAB,TOTEN,TOTH20,XMS,TOTSP,
      +YLENGTH,IPROD,FH,HDF,NSTG
      COMMON/INPT/BPH,GP,GVEL,IND1,DELT,YLENG,DBTPR,XWIDE
      COMMON/PPRTY/SA,CA,CV,CW,RHOP,CP
      COMMON/LATENT/HA,HB
      COMMON/PRESS/PATM
      DATA PATM/14.3/
      F(T)=T+.45969
      RHC=0.999999999
      PRL=0.0 $ YL=0.0
      SUMZT=0
      ITERCT=0 $ IEXIT=0 $ KAB=0
      TOTBTUW=0
      XMAVE=0.0
      HAVER=0.0
      KCGUNT=0
      RHIN=RHDBHA(F(TIN),HIN)
C***** BEGIN TIME LOOP
      DELT=GVEL*DELT
      IF(NSTG.NE.1) GO TO 4
      T(2)=(2.*TIN+THIN)/3.
      T(3)=(T(2)+THIN)/2.
4      YL=YL+DELT
C***** COMPUTE MC FOR DEPTH = 0.
      THT=TIN
      XMT=XM(1)
      RHT=RHIN
      IF(IPROD.EQ.2) GO TO 5
      CALL LAYEQ
      GO TO 6
5      CALL LAYEQSQ(J)
6      XM(1)=XMT
C***** BEGIN DEPTH LOOP
      DO 102 J=2,IND1
      JM=J-1
      THT=T(J)
      XMT=XM(J)
      HFG=HEATLAT(XMT,THT)
      RHT=RH(J)
C***** CALL SUBROUTINE CONTAINING M EQUATION
      IF(IPROD.EQ.2) GO TO 7
      CALL LAYEQ
      GO TO 8
7      CALL LAYEQSQ(J)
      CP=0.39123+0.46057*XMT
      CONTINUE
C***** COMPUTE CONSTANTS USED BY EQUATIONS WITHIN LOOP
      CON1=SA*DELT
      CON2=CW-CV
      CON12=CON1*CON2
      CON3=HFG+212.*(CW-CV)
      CON13=CON1*CON3
      CON4=RHOP*DELT
      CON5=CON4/CON1
      CON6=CON1/CON4
C***** H EQUATION
80      H(J)=H(JM)-CON5*(XMT-XM(J))
C***** T EQUATION
      T1=CON1*(H(J)-H(JM))
      T2=CON1*(CA+CV*H(JM))
      T3=CON4*(CP+CV*XM(J))
      T(J)=(-T1+CON3+T2*T(JM)+T3*THT)/(-T1+CON2+T2+T3)
      TABS=F(T(J))
C***** COMPUTE RH AND CHECK FOR CONDENSATION
      RH(J)=RHDBHA(TABS,H(J))
      RHK(J)=100.*RH(J)

```

APPENDIX A, continued:

```

C***** IF(RH(J).LT.RHC) GO TO 9
C***** CONDENSATION SIMULATOR
TS=T(J)
TABS=F(TS)
HS=HADERH(TABS,RHC)
DHDT=HS-HADERH(TABS-1,RHC)
C***** RE-EVALUATE M AND THETA USING MASS AND ENERGY BALANCES
T1=HS-H(JM)-DHDT*TS
A=CON12*DHDT
B=CON12*T1-T2-T3-CON13*DHDT
C=T2*T(JM)+T3*TH-CON13*T1
T(J)=(-B-SQRT(B*B-4.*A*C))/(2.*A)
H(J)=HS+DHDT*(T(J)-TS)
RH(J)=RHOBHA(F(T(J)),H(J))
RHK(J)=100.*RH(J)
XPT=XM(J)-CON6*(H(J)-H(JM))
9 XM(J)=XMT
C***** END WIDTH LOOP
GP=GVEL*RHOP
102 CONTINUE
ITERCT=ITERCT+1
SUMZT=SUMZT+T(IND1)
C***** CHECK IF LONG ENOUGH OR DRY ENOUGH OR TIME TO SAVE VALUES FOR
C***** PRINTING--IF NONE OF THESE GO TO BEGINNING OF LENGTH LOOP
IF(YL-GE.YLENG) GO TO 12
IF(YL-PRL) 4,13,13
C***** SET FLAG IF EXIT CONDITION MET
12 IEXIT=1
C***** MAKE FINAL CALCULATIONS AND STORE APPROPRIATE VALUES
13 PRL=PRL+CBTPR
CALL CRSPR(XM,RH,T,H,YL,XMAVE,RHK,XMEINW,HAVER)
KCOUNT=KCOUNT+1
IF(IEEXIT.NE.1) GO TO 4
ENERGY=GA*(CA+CV*HIN)*(TIN-TAMB)*YLENG
WATER=(XMS-XMAVE)*RHOP*GVEL
XMS=XMAVE
BTUH2O=ENERGY/WATER
SUMZT=SUMZT/FLOAT(ITERCT)
HAVER=HAVER/FLOAT(KCOUNT)
TOTEN=TOTEN+ENERGY
TOTH2O=TOTH2O+WATER
TOTBTUW=TOTEN/TOTH2O
YLENGTH=YLENGTH+YLENG
IF(IPROD.EQ.2) GO TO 40
QA=CFM*0.005075
IF(CFM-40.) 60,70,70
60 SP=1.2239183E-3*(20529.535*QA**2/ALOG(1.+30.597*QA)+(14.5566-26.41
+8*QA)*FM)
GO TO 50
70 SP=1.2239183E-3*(436.667*QA+7363.038*QA**2+22525.819*QA*FM)
GO TO 50
40 SP=XWIDE*(CFM/75.2)**1.431
50 POWER=SP*CFM/(6350.*0.5)*YLENGTH
PRINT 212,SUMZT,HAVER,ENERGY,WATER,BTUH2O,TOTH2O,TOTBTUW
PRINT 220,XMEINW,GA,SP,POWER
RETURN
212 FORMAT(// * AVERAGE AIR EXHAUST TEMP, F *F12.4/ *F12.4/
+* AVERAGE AIR EXHAUST HUM.RATIO *F12.4/
+* ENERGY SUPPLIED, BTU/SQ FT *F12.4/
+* WATER REMOVED, LB/SQ FT-HR *F12.4/
+* EFFICIENCY, BTU/LB H2O *F12.4/
+* TOTAL DRYER WATER REMOVED, LB/SQ FT-HR *F12.4/
+* TOTAL DRYER EFFICIENCY, BTU/LB H2O *F12.4)
220 FORMAT(* INLET MOISTURE EQUILIBRIUM-WB *F12.4/
+* DRY AIRFLOW RATE, LB/HR FT2 *F12.4/
+* STATIC PRESSURE, IN H2O *F12.4/
+* TOTAL HORSE POWER, HP/FT2 OF WIDTH *F12.4)
END

```

APPENDIX A, continued:

```

SUBROUTINE CRSPR(XM,RH,T,H,YL,XMAVE,RHK,XMEINW,HAVER)
C*****
  DIMENSION XM(300),RH(300),T(300),H(300),RHK(300)
  COMMON/MAIN/DUM(5),XMO,KAB,SKIP(5),IPROD
  COMMON/INPT/BPH,GP,GVEL,IND1,DELX,YLENG,DBTPR
C*****
  IF(XMAVE.GT.0.0) GOTO 5
  PRINT 50
  5 CONTINUE
  HAVER=HAVER+H(IND1)
  TIME=YL/GVEL
  XMAX=XMIN=SUM=XM(1)
  TMAX=TMIN=T(2)
  SUMT=T(1)
  DO 10 J=2,IND1
    IF(XM(J).GT.XMAX) XMAX=XM(J)
    IF(XM(J).LT.XMIN) XMIN=XM(J)
    IF(T(J).GE.TMAX) TMAX=T(J)
    IF(T(J).LE.TMIN) TMIN=T(J)
    SUMT=SUMT+T(J)
  10 SUM=SUM+XM(J)
  XMAVE=SUM/FLOAT(IND1)
  TAVE=SUMT/FLOAT(IND1)
  XMWB=XMAVE/(1.+XMAVE)
  XMAXWB=XMAX/(1.+XMAX)
  XMINWB=XMIN/(1.+XMIN)
  IF(IPROD.EQ.2) GO TO 20
  XMEIN=EMC(RH(1),T(1)) $ XMEOUT=EMC(RH(IND1),T(IND1))
  GO TO 30
20 XMEIN=SOYEMC(RH(1),T(1)) $ XMEOUT=SOYEMC(RH(IND1),T(IND1))
30 XMEINW=XMEIN/(1.+XMEIN)
  XMEOUTW=XMEOUT/(1.+XMEOUT)
  PRINT 55,TIME,YL,XMWB,XMINWB,XMAXWB,TAVE,TMIN,TMAX,H(IND1),
    +RHK(IND1),XMEOUTW
  RETURN
50 FORMAT(///' * TIME DEPTH*4X*MOISTURE-WB*6X*TEMPERATURE*/
  +3X*HR FT MAV MIN MAX TAVG TMIN TMAX HOUT RH MEOUT
  +')
55 FORMAT(2X,F4.2,F6.2,3F6.4,3F6.1,F6.4,F6.2,F6.4)
  END

```

```

SUBROUTINE CONVERT(XM,RH,T,H)
C*****
  DIMENSION XM(300),RH(300),T(300),H(300)
  COMMON/INPT/BPH,GP,GVEL,IND1,DELX,YLENG,DBTPR
C*****
  ITYPE=2 - SIMULATES REVERSED AIRFLOW
C*****
  IT=IND1+1
  INDOS=IND1/2
  DO 10 I=1,INDOS
    IT=IT-1
    TEMP=XM(IT)
    XM(IT)=XM(I)
    XM(I)=TEMP
    TEMP=RH(IT)
    RH(IT)=RH(I)
    RH(I)=TEMP
    TEMP=T(IT)
    T(IT)=T(I)
    T(I)=TEMP
    TEMP=H(IT)
    H(IT)=H(I)
    H(I)=TEMP
  10 CONTINUE
  RETURN
  END

```

APPENDIX A, continued:

```

SUBROUTINE LAYEQ
C***** DESCRIPTION
C***** SUBROUTINE TO FIND THE MOISTURE CONTENT BASED ON EQUA-
C***** TIONS BY J.M. TROEGER AND F.M. DEL GIUDICE
C***** USAGE
C***** USED IN THE FIXED BED AND CROSSFLOW MODELS WITH GRAIN
C***** TEMPERATURES BETWEEN 20 F AND 160 F
C*****
COMMON /MAIN/XMC,TH,RH,DELT,CFM,XMO,KAB,AVOID(7),HDF
COMMON /NAME/INAME,IPRODU,IEMC
DATA INAME,IPRODU,IEMC/10HTROETHOM,10H CORN,10H DEBOER /
C*****
C***** S T A T E M E N T F U N C T I O N S
C*****
P1(XM,R,T)=EXP(-2.45+6.42*XM**1.25-3.15*P+9.62*XM+SQRT(R)+.03*T-.04
102*CFM)
P2(R,T)=EXP(2.82+7.49*(R+.01)**.67-.0179*T)
P3(P,Q)=(-.12*(XMO-XME)**(Q+1.))*P*Q
Q1(XM,R,T)=-3.98+2.87*XM-(.019/(R+.015))+.016*T
Q2(R)=-EXP(.81-3.11*R)
TF(P,Q,XO,XF,TO)=P*(XF-XME)**Q-P*(XO-XME)**Q+TO
XMN(P,Q,XO,TI,TO)=((TI-TO)/P+(XO-XME)**Q)**(1./Q)+XME
C*****
C***** P R O G R A M
C*****
CALL READYTH FOR PRELIMINARY CHECKS AND CALCULATIONS
CALL CALL_READYTH(TXMO,DELM,XME,IPOPS,XPR)
C***** CHECK ABSORPTION FLAG...IF SET GO TO ABSORPTION SIMULATION
C***** IF(IPOPS-1)1,6,1
1 IF(TH.GT.140.) GOTO 100
C***** COMPUTE TRANSITION M,P1,Q1, AND FIRST TRANSITION TIME
X1M=.4*DELM+XME
X2M=.12*DELM+XME
TINC=DELT*60.
P=P1(TXMO,RH,TH)
Q=Q1(TXMO,RH,TH)
TX=TF(P,Q,TXMO,X1M,0.0)
C***** CHECK IF PRESENT M IS IN FIRST REGION...IF IS IS COMPUTE
C***** EQUIVALENT TIME AND ADD TINC
IF(XMC.LT.X1M) GO TO 3
TI=TF(P,Q,TXMO,XMC,0.0)+TINC
C***** CHECK IF EQUIVALENT TIME+TINC IS LESS THAN TRANSITION TIME..
C***** IF IT IS COMPUTE NEW M AND RETURN
IF(TI.GT.TX) GO TO 2
XMC=HDF*XMN(P,Q,TXMO,TI,0.0)
RETURN
C***** EQUIVALENT TIME+TINC IS IN SECOND REGION--COMPUTE P2, Q2 AND
C***** NEW M THEN RETURN
2 P=P2(RH,TH)
Q=Q2(RH)
XMC=HDF*XMN(P,Q,X1M,TI,TX)
RETURN
C***** * IS NOT IN FIRST REGION--COMPUTE P2, Q2 AND SECOND
C***** TRANSITION TIME
3 P=P2(RH,TH)
Q=Q2(RH)
TX1=TX
TX=TF(P,Q,X1M,X2M,TX1)
C***** CHECK IF PRESENT M IS IN SECOND REGION...IF IT IS COMPUTE
C***** EQUIVALENT TIME AND ADD TINC
IF(XMC.LT.X2M) GO TO 5
TI=TF(P,Q,X1M,XMC,TX1)+TINC
C***** CHECK IF EQUIVALENT TIME+TINC IS LESS THAN TRANSITION TIME..
C***** IF IT IS COMPUTE M AND RETURN
IF(TI.GT.TX) GO TO 4
XMC=HDF*XMN(P,Q,X1M,TI,TX1)
RETURN
C***** EQUIVALENT TIME+TINC IS IN THIRD REGION--COMPUTE P3, Q3 AND
C***** NEW M THEN RETURN
4 P=P3(P,Q)
Q=-1.0
XMC=HDF*XMN(P,Q,X2M,TI,TX)
RETURN
C***** * IS NOT IN SECND REGION--COMPUTE P3, Q3, EQUIVALENT TIME+
C***** TINC AND NEW M THEN RETURN
5 P=P3(P,Q)

```

APPENDIX A, continued:

```

      Q=-1.0
      TI=TF(P,Q,X2M,XMC,TX)+TINC
      XMC= HDF*XMN(P,Q,X2M,TI,TX)
      RETURN
C*****
C*****      ABSORPTION SIMULATION
C*****      FIND NEW M AND INCREMENT COUNTER
C*****      6 DIV=-.625*PSDB(TH+459.69)**(.466*RH)*RH*RH*RH
      XMC= HDF*((XMC-XME)*EXP(DIV*DELT)+XME)
      KAB=KAB+1
      RETURN
100      ALMR=ALOG(XMR)
      A=-1.86178+.0048843*TH
      B=427.364*EXP(-0.03301*TH)
C*****      FIND EQUIVALENT TIME BASED ON CURRENT TEMP AND MC
C*****      ADD DELT AND SOLVE FOR NEW MC
      TI=ALMR*(A+B*ALMR)+DELT
      ALMR=(-A-SQRT(A*A+4.0*B*TI))/(2.0*B)
      XMC= HDF*(DELT*EXP(ALMR)+XME)
      RETURN
      END
C*****
SUBROUTINE ABSH(HIN,TAMB,TIN,HI,FUEL,IPROD)
C*****
C*****      FUEL=1 STANDS FOR NO.2 FUEL
C*****      FUEL=2 STANDS FOR NATURAL GAS
C*****      FUEL=3 STANDS FOR LIQUID PROPANE GAS
C*****
      IFUEL=IFIX(FUEL)
      IF(IFUEL.EQ.1) A=7.0143E-5
      IF(IFUEL.EQ.2) A=8.175E-5
      IF(IFUEL.EQ.3) A=7.593E-5
      IF(IPROD.EQ.2) CP=0.400
      IF(IPROD.EQ.1) CP=0.268
      HFUEL=A*(1+HI)*CP*(TIN-TAMB)
      HIN=HI+HFUEL
      FUEL=FLCAT(IFUEL)
      RETURN
      END
C*****
FUNCTION HEATLAT(XMC,TH)
C*****
C*****      FUNCTION USED FOR COMPUTING THE LATENT HEAT OF VAPORIZATION
C*****      OF WATER IN THE GRAIN.
C*****
      COMMON/LATENT/HA,HB
      HEATLAT=(1094.-0.57*TH)*(1.+HA*EXP(HB*XMC))
      RETURN
      END

```

APPENDIX A, continued:

```

FUNCTION SOYEMC(RH,T)
C*****
C*****      FUNCTION SUBROUTINE TO COMPUTE EQUILIBRIUM MOISTURE CONTENT
C*****OF SOYBEANS FROM A RELATIVE HUMIDITY AND TEMPERATURE,USING
C*****EQUATION BY ROA
C*****
      T=5./9.*(T-32.)
      SOYEMC=(.0.3167048*RH-.0.4024806*RH*RH+.0.4687752*RH*RH*RH)*
      +EXP(-0.0106576+(-0.06349201*RH+.0.2160320*RH*RH-.0.3108765*RH*RH*RH
      +0.1684076*RH*RH*RH*RH)*(T-14.04595))
      T=9.*T/5.+32.
      RETURN
      END

```

```

SUBROUTINE DATE(IPROD)
C***** SUBROUTINE USED FOR INITIALIZING CONSTANTS FOR PRODUCTS
COMMON/PPRPTY/ SA,CA,CV,CW,RHOP,CP
COMMON/LATENT/HA,HB
IF(IPROD.EQ.2) GO TO 50
C***** INITIALIZE CONSTANTS FOR CORN
SA=23.9
CA=0.242
CV=0.45
CW=1.0
RHOP=38.71
HA=4.349
HB=-28.25
CP=0.268
RETURN
C***** INITIALIZE CONSTANTS FOR SOYBEANS
SA=46.43
CA=0.242
CV=0.45
CW=1.0
RHOP=57.99
HA=0.21484
HB=-6.233
RETURN
END

```

	SUBROUTINE SOYREAD(TXMO,DELM,XME,IOOPS,XMR)	5690
C*****		5700
C*****		5710
C*****	DESCRIPTION	5720
C*****	SUBROUTINE TO MAKE PRELIMINARY CHECKS AND CALCULATIONS FOR	5730
C*****	SOYBEAN THINLAYER EQUATIONS AND TO CALCULATE EQUILIBRIUM MOISTURE	5740
C*****	CONTENT FOR SOYBEANS USING ALAMS EQUATION	5750
C*****		5760
	COMMON/MAIN/XMC,TH,RH,DELT,CFM,XMO,KAB	5770
	IOOPS=0	5780
C*****	COMPUTE EQUILIBRIUM MOISTURE CONTENT, COMPARE TO PRESENT MOISTURE	5790
C*****	CONTENT...IF GREATER SET IOOPS=1	5800
	XME=SOYEMC(RH,TH)	5810
	IF(XME-XMC)20,10,10	5820
10	IOOPS=1	5830
C*****	COMPARE PRESENT MOISTURE CONTENT TO INITIAL MOISTURE CONTENT. SET	5840
C*****	TXMO EQUAL TO THE LARGER VALUE	5850
20	IF(XMO-XMC)30,40,40	5860
30	TXMO=XMC	5870
	GO TO 50	5880
40	TXMO=XMO	5890
C*****	COMPUTE MOISTURE RATIO	5900
50	DELM=TXMO-XME	5910
	XMR=(XMC-XME)/DELM	5920
	RETURN	5930
	END	5940

APPENDIX A, continued:

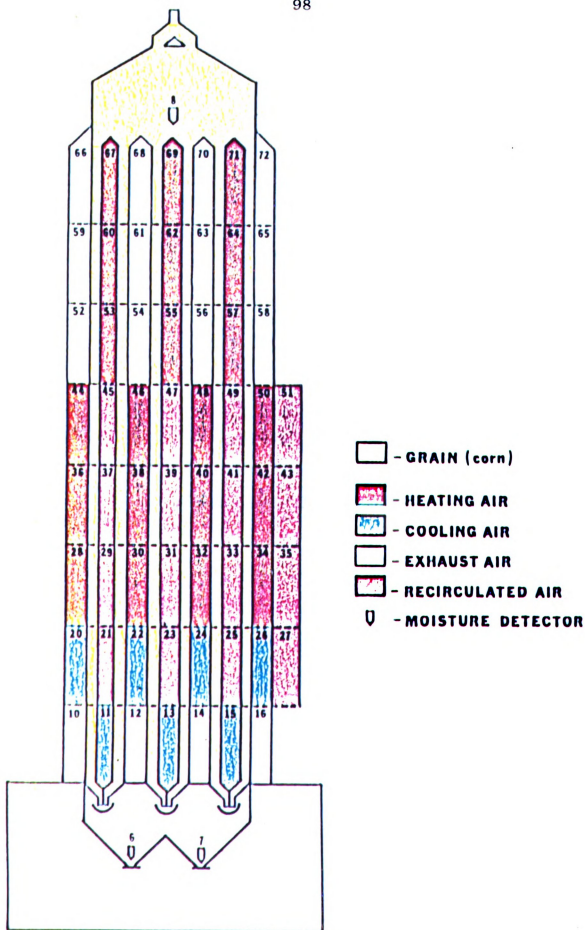
```

SUBROUTINE LAYEREQ(J)
C*****
C*****          V.A.DALPASQUALE
C*****
C*****DESCRIPTION
C*****SUBROUTINE USED TO FIND THE MOISTURE CONTENT BASED ON
C*****EQUATION BY OVERHULTZ AND EQUILIBRIUM MOISTURE CONTENT BY ROA
C*****
COMMON /MAIN/XMC,TH,RH,DELT,CFM,XMO,KAB,AVOID(7),HDF
COMMON /NAMES/SNAME,SPROD,SEMC
DATA SNAME,SPROD,SEMC/10H0VERHULTZ,10H0SOYBEAN,10H0ROA
+
F(T)=TH+459.69
C*****
C*****
C*****          CALL SOYREAD FOR PRELIMINARY CHECKS AND CALCULATIONS
CALL SOYREAD(TXMO,DELM,XME,IOOPS,XMR)
IF(ICOPS.EQ.1) GO TO 200
XMO=XMO/(1.+XMO)
IF(XMO.LE.0.20) GO TO 10
IF(XMO.GT.0.20) GO TO 20
10  CK=EXP(11.752 - 7912.7/F(TH))
GO TO 50
20  IF(XMO.GT.0.25) GO TO 30
CK=EXP(10.906 - 7357.0/F(TH))
GO TO 50
30  CK=EXP(10.375 - 6779.3/F(TH))
50  CN=0.3529 + 0.00136*TH
IF(CK.LE.0.0) CK=0.0001
IF(TXMO.EQ.XMC) GO TO 100
TI=(-ALOG(XMR))*((1./CN)/CK+DELT
XMC=HDF*((XMC-XME)*EXP(-((CK*TI)**CN))+XME)
RETURN
100 XMC=HDF*((XMO-XME)*EXP(-((CK*DELT)**CN))+XME)
RETURN
200 DIV=-.625*PSDB(TH+459.69)**(.466*RH)*RH*RH*RH
XMC=HDF*((XMC-XME)*EXP(DIV*DELT)+XME)
KAB=KAB+1
RETURN
END

```

APPENDIX B

SCHEMATIC OF THE COMMERCIAL UNIT SIMULATED IN THIS THESIS



APPENDIX C

EQUILIBRIUM MOISTURE CONTENT RESULTS FROM ROA EQUATION

FOR RELATIVE HUMIDITY HIGHER THAN 90 PERCENT

FOR SEVERAL TEMPERATURES

APPENDIX C

EQUILIBRIUM MOISTURE CONTENT RESULTS FROM ROA EQUATION
FOR RELATIVE HUMIDITY HIGHER THAN 90 PERCENT
FOR SEVERAL TEMPERATURES

Relative Humidity (%)	Temperature (°F)				
	50	70	90	110	130
M_e (percent, dry basis)					
90	31.13	32.21	33.33	34.48	35.68
91	32.63	34.19	35.82	37.54	39.33
92	34.25	36.37	38.82	41.02	43.56
93	36.00	38.78	41.78	45.00	48.48
94	37.90	41.46	45.34	49.59	54.24
95	39.97	44.43	49.38	54.88	61.00
96	42.23	47.74	53.98	61.02	68.99
97	44.69	51.45	59.22	68.18	78.48
98	47.38	55.60	65.24	76.55	89.82
99	50.33	60.27	72.16	86.40	103.44
100	53.58	65.53	80.15	98.04	119.92

APPENDIX D
GERMINATION, CRACK AND SPLIT RESULTS
AND TEMPERATURE RESULTS

APPENDIX D

Table D.1: Germination, crack and split results for
Test No. 1 (121.11°C).

Sample No.	Germination (%)	Cracks (%)	Splits (%)
1	85.0	2.77	1.20
2	90.0	5.85	2.73
3	90.0	6.82	3.17
4	91.0	6.70	2.58
5	88.5	7.54	3.55
6	83.0	6.38	3.03
7	83.0	4.86	3.65
8	86.0	6.40	2.53
9	84.5	6.54	3.18
10	84.0	5.97	3.47
11	85.0	5.79	2.50
12	87.0	10.02	2.16
13	89.0	8.64	3.39
14	84.0	6.34	3.21
15	85.5	11.41	3.94
16	86.5	14.84	3.63
17	83.5	15.63	4.48

APPENDIX D

Table D.2: Germination, crack and split results for Test No. 2 (121.11-93.33°C).

Sample No.	Germination (%)	Cracks (%)	Splits (%)
1	95.5	3.83	3.57
2	95.0	5.34	3.44
3	91.5	6.74	3.87
4	85.0	6.83	4.13
5	81.0	5.49	4.38
6	90.5	4.84	3.90
7	87.0	5.65	4.38
8	88.0	9.01	3.61
9	84.0	9.65	4.25
10	87.0	6.51	2.25
11	87.0	8.48	5.68
12	85.0	8.15	2.92
13	89.5	8.99	5.47
14	86.0	10.49	3.39
15	88.0	11.98	4.11
16	87.0	9.56	3.41
17	86.0	10.10	5.41
18	85.5	11.29	3.38
19	85.0	12.33	5.28
20	89.0	21.05	4.87

APPENDIX D

Table D.3: Germination, crack and split results for Test No. 3 (148.89-121.11°C).

Sample No.	Germination (%)	Cracks (%)	Splits (%)
1	87.5	8.51	3.87
2	90.5	6.31	2.23
3	92.0	5.12	4.66
4	86.5	10.38	3.34
5	93.0	10.06	5.12
6	80.5	9.62	2.41
7	82.0	9.71	3.42
8	81.0	10.05	4.23
9	81.5	14.46	3.87
10	84.5	12.80	5.36
11	88.0	10.29	3.26
12	83.5	10.69	3.59
13	81.0	11.65	5.01
14	83.0	16.20	4.76
15	75.5	12.29	6.18
16	79.5	18.18	5.04
17	82.0	16.06	6.60

APPENDIX D

Table D.4: Temperature results (°F) for the concurrent flow dryer.

	Test No. 1	Test No. 2	Test No. 3
Inlet drying air	250	250-200	300-250
Drying section:			
1 ft depth	104	104	112
2 ft depth	103	103	110
3 ft depth	101	101	106
Outlet air, dry bulb	112	107	124
Outlet air, wet bulb	95	98	101
Cooling section:			
inlet air, dry bulb	78	74	74
inlet air, wet bulb	61	61	55
outlet air, dry bulb	93	92	87
outlet air, wet bulb	84	81	75

APPENDIX E
CONVERSION FACTORS

APPENDIX E

CONVERSION FACTORS

Unit Conversions	English or Metric	SI
Area	1 ft ²	9.290x10 ⁻² m ²
Convective Heat-Transfer Coefficient	1 BTU/h ft ² °F	5.678 W/m ² °C
Density	1 lb/ft ³	1.602x10 kg/m ³
Energy	1 kcal	4.187x10 ³ J
	1 BTU	1.055x10 ³ J
Enthalpy, specific	1 BTU/lb	2.326x10 ³ J/kg
Force	1 lbf	4.448 N
Heat Flux	1 kcal/h m ²	1.163 W/m ²
	1 BTU/h ft ²	3.155 W/m ²
Heat Release Rate (mass)	1 BTU/h lb	6.461x10 ⁻¹ W/kg
Length	1 ft	3.048x10 ⁻¹ m
Mass	1 lb	4.536x10 ⁻¹ kg
	1 tonne	1.000x10 ³ kg
	1 ton	1.016x10 ³ kg
Power	1 BTU/h	2.931x10 ⁻¹ W
	1 hp	7.457x10 ² W
Pressure	1 standard atmosphere	1.013x10 ⁵ N/m ²
	1 bar	1.000x10 ⁵ N/m ²
	1 lbf/in ²	6.895x10 ³ N/m ²
	1 in water	2.491x10 ² N/m ²
	1 mm Hg	1.333x10 ² N/m ²
Surface per Unit Volume	1 ft ² /ft ³	3.280 m ² /m ³
Specific Heat	1 BTU/lb F	4.187x10 ³ J/kgK
Temperature Difference	1 deg F (deg R)	5/9 deg C (deg K)
Thermal Conductivity	1 BTU/h ft ² (°F/ft)	1.731 W/m ² (°C/m)

APPENDIX E, continued:

Unit Conversions	English or Metric	SI
Velocity	1 ft/h	$8.467 \times 10^{-5} \text{ m/s}$
Viscosity, absolute (or dynamic)	1 lb/ft h	$4.134 \times 10^{-4} \text{ kg/m s}$
Viscosity, kinematic	1 ft ² /h	$2.581 \times 10^{-5} \text{ m}^2/\text{s}$
Volume	1 bu (volume)	$3.523 \times 10^{-2} \text{ m}^3$
	1 ft ³	$2.832 \times 10^{-2} \text{ m}^3$
	1 U.S. gal	$3.785 \times 10^{-3} \text{ m}^3$
Airflow	1 cfm	$2.832 \times 10^{-2} \text{ m}^3/\text{min}$
	1 cfm	$4.719 \times 10^{-4} \text{ m}^3/\text{sec}$
	1 cfm/ft ²	$3.048 \times 10^{-1} \text{ m/min}$
	1 cfm/ft ²	$5.080 \times 10^{-3} \text{ m/sec}$

REFERENCES

REFERENCES

- Alam, A. 1972 Drying simulation of soybeans. Unpublished Ph.D. thesis. University of Illinois: Urbana, IL.
- Alam, A. and Shove, G. 1973. Simulation of soybean drying. Trans. ASAE 16:134-136.
- Bakker-Arkema, F. W., Lerew, L. E., DeBoer, S. F., and Roth, M. G. 1974. Grain Dryer Simulation. Research Report 224. Agr. Exp. Sta., Michigan State University: East Lansing, MI.
- Bakker-Arkema, F. W., Lerew, L. E., Brook, R. C., and Brooker, D. B. 1978. Energy and capacity performance evaluation of grain dryers. ASAE Paper No. 78-3523. Am. Soc. Agr. Eng.: St. Joseph, MI.
- Bakker-Arkema, F. W., Brook, R. C., and Lerew, L. E. 1978. Cereal grain drying. In: Advances in Cereal Science and Technology, ed. by Y. Pomeranz, pp. 1-90. American Association of Cereal Chemists, Inc: St. Paul, MN.
- Bakker-Arkema, F. W., Brooker, D. B., and Roth, M. G. 1976. Feasibility study of in-bin corn drying in Missouri using solar energy. USDA Special Report.
- Bakker-Arkema, F. W., and Green, R. 1977. High temperature wheat drying. ASAE Paper No. 77-3527. Am. Soc. Agr. Eng.: St. Joseph, MI.
- Bakshi, A. S., Singh, R. P., Wang, C. Y., and Steffe, J. F. 1978. Energy costs of a conventional and air recycling crossflow rice dryer. ASAE Paper No. 78-3011. Am. Soc. Agr. Eng.: St. Joseph, MI.
- Brook, R. G. 1977. Design of multistage grain dryers. Unpublished Ph.D. thesis. Michigan State University: East Lansing, MI.
- Brook, R. G., and Bakker-Arkema, F. W. 1977. Design of multistage grain dryers using computer simulation. ASAE Paper No. 77-3529. Am. Soc. Agr. Eng.: St. Joseph, MI.

- Brooker, D. B., Bakker-Arkema, F. W., and Hall, C. W. 1974. Drying Cereal Grains. AVI: Westport, CT.
- Chanchai, R., White, G. M., Loewer, O. J., and Engli, D. B. 1976. Influence of heated air drying on soybean impact damage. Trans. ASAE 19:372-377.
- Farmer, D. M., Bakker-Arkema, F. W., DeBoer, S. F., and Roth, M. G. 1972. Simulation and optimal design of a commercial concurrent-counterflow grain dryer - the Anderson model. ASAE Paper No. 72-847. Am. Soc. Agr. Eng.: St. Joseph, MI.
- Hall, G. E. 1974. Damage during handling of shelled corn and soybeans. Trans. ASAE 17:335-338.
- Henderson, S. M. 1952. A basic concept of equilibrium moisture. Agr. Eng. 33(1).
- Kalchik, S. V. 1977. Drying of soybeans in a pilot scale concurrent flow dryer. Unpublished M.S. thesis. Michigan State University: East Lansing, MI.
- Keener, H. M., and Glenn, T. L. 1978. Measuring performance of grain drying systems. ASAE Paper No. 78-3521. Am. Soc. Agr. Eng.: St. Joseph, MI.
- Lerew, L. E., Bakker-Arkema, F. W., and Brook, R. C. 1972. Simulation of a commercial crossflow dryer: The Hart-Carter model. ASAE Paper No. 72-829. Am. Soc. Agr. Eng.: St. Joseph, MI.
- Matthes, R. K., and Welch, G. B. 1974. Heated air drying of soybean seed. ASAE Paper No. 74-3001. Am. Soc. Agr. Eng.: St. Joseph, MI.
- Othmer, D. F. 1940. Correlation vapor pressure and latent heat data. Ind. Eng. Chem. 32:841-846.
- Overhults, D. G., White, G. M., Hamilton, H. E., and Ross, I. J. 1973. Drying soybeans with heated air. Trans. ASAE 16:112-113.
- Pfost, D. L. 1975. Environmental and varietal factors affecting damage to seed soybeans during drying. Unpublished Ph.D. thesis. The Ohio State University: Columbus, OH.
- Pfost, H. B., Maurer, S. G., Chung, D. S., and Milliken, G. A. 1976. Summarizing and reporting equilibrium moisture data for grains. ASAE Paper No. 76-3520. Am. Soc. Agr. Eng.: St. Joseph, MI.

- Pinheiro-Filho, J. B. 1976. An experimental study of the effect of intermittent drying of soybeans on quality and rate of drying. Unpublished Ph.D. thesis. Purdue University: West Lafayette, IN.
- Roa, G. and Macedo, I. C. 1976. Drying of carioca dry beans with solar energy in a stationary bin. ASAE Paper No. 76-3021. Am. Soc. Agr. Eng.: St. Joseph, MI.
- Roa, G., Fioreze, R., Rossi, S. J., and Villa, L. G. 1977. Dynamic estimation of thin-layer drying parameters. ASAE Paper No. 77-3530. Am. Soc. Agr. Eng.: St. Joseph, MI.
- Rodda, E. D., and Ravalo, E. J. 1978. Soybean seed storage under constant and ambient tropical conditions. ASAE Paper No. 78-7002. Am. Soc. Agr. Eng.: St. Joseph, MI.
- Sabbah, M. A., Meyer, G. E., Keener, H. M., and Roller, W. L. 1976. Reversed-air drying for fixed bed of soybean seed. ASAE Paper No. 76-3023. Am. Soc. Agr. Eng.: St. Joseph, MI.
- Thompson, T. L., Foster, G. H., and Peart, R. M. 1969. Comparison of concurrent-flow, crossflow and counterflow grain drying methods. USDA, Mkt. Res. Rep. 841.
- Ting, K. C., White, G. M., and Loewer, O. J. 1978. Seed coat damage in deep-bed drying of soybeans. ASAE Paper No. 78-3006. Am. Soc. Agr. Eng.: St. Joseph, MI.
- USDA. 1978. Agricultural Statistics. USDA: Washington, DC.
- Walker, L. P. 1978. Process analysis of a multistage concurrent rice dryer. Unpublished Ph.D. thesis. Michigan State University: East Lansing, MI.
- White, G. M., Loewer, O. J., Ross, I. J., and Egli, D. B. 1976. Storage characteristics of soybeans dried with heated air. Trans. ASAE 19:306-310.
- White, G. M., Bridges, T. C., Loewer, O. J., and Ross, I. J. 1978. Seed coat damage in thin-layer drying of soybeans as affected by drying conditions. ASAE Paper No. 78-3052. Am. Soc. Agr. Eng.: St. Joseph, MI.

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