Investigation of a Simulation Model for Peanut Drying Incorporating Air Recirculation

by

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(ABSTRACT)

Virginia type peanuts were dried in three laboratory dryers to verify a simulation model based on Troeger and Butler's drying equations. The energy saving potential of air recirculation was also investigated. Four tests consisting of eleven drying experiments were conducted in Fall, 1986. Two air recirculation schedules were employed and three average air flow rates were used. An experimental procedure was developed to measure input and output parameters of the drying system. The weight loss of the top layer of the peanut bed was recorded with a data acquisition system. The electrical energy input to the heaters was also recorded. Based on the analysis of the data, the following conclusions were made: (1) The Troeger model predicted a lower moisture release rate than the actual rate for Virginia type peanuts. (2) If the break points in the Troeger model were changed to 0.20 and 0.70 from 0.12 and 0.40, respectively, the model predicted the final moisture content more accurately. (3) Energy savings as high as 50 percent were achieved using the recirculation schedules.

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Table of Contents.

List of Figures.

Figure

List of Tables.

Table

Chapter 1. Introduction

Energy has become a very important driving force in developed countries as well as in developing countries. In order to be more competitive in the market, farmers and food industrialists seek more productive technologies which demand high quality energy. This increasing reliance on high quality energy in agriculture and the food industry makes food production more vulnerable to price fluctuations in petroleum products. Even though we are currently experiencing an oil glut in the world market from oil producing countries, the cold fact remains the same; our non-renewable energy resources are being rapidly depleted.

Energy conservation in existing agricultural production systems is one avenue available for investigation to make food production less dependent on petroleum based fuels. The United States Energy Research and Development Administration (ERDA) listed the following benefits of energy conservation in its report to Congress (Friedrich,1978).

- A barrel of oil saved can result in reduced imports.
- It typically costs less to save a barrel of oil than to produce one through the development of new technology.
- Energy conservation generally has a beneficial effect on the environment in comparison to energy produced and used.
- Capital requirements to increase energy use efficiency are generally lower than capital needs to produce an equivalent amount of energy from new sources since most new supply technologies are highly capital intensive.
- Conservation technologies can generally be implemented at a faster rate and with less government involvement in the near term than new technologies.
- Energy efficiency actions can reduce the pressure for accelerated introduction of new supply technologies. Since the actions persist over time, the benefits are continuing.

American farmers use 3 to 4 percent of all energy consumed in the United States. The total food system consumes 12 to 17 percent of energy consumption in this country (Friedrich,1978). These figures are small compared to the energy consumed by industrial processes which is 37% of total energy use, or transportation which is 26%. But actual energy values in American agriculture are not small. American farmers use 5.0 billion liters (120 trillion BTU) of liquified petroleum gas (LPG) annually in crop drying alone (Friedrich,1978). Corn drying consumes 60 TJ each year in the United States. Therefore, conservation strategies can be expected to affect farmers' budgets significantly. The Federal Energy Administration estimated that 525 TJ could be saved in Agriculture annually by 1985 which is a significant 20 percent reduction of the 1975 agricultural energy consumption of 2.64 PJ. ERDA predicted a realistic saving of 740 TJ in food production using available conservation strategies (Friedrich,1978).

Crop drying is an important component of a food production system which uses direct energy. Most commercial crop dryers use LP gas or natural gas as their heat source. To reduce the risk of loss from bad weather, farmers harvest crops early and artificially dry their crops to safe moisture levels.

Energy usage in peanut drying is only a small part of total energy use. But the efforts to conserve energy in peanut drying should not be underestimated because conservation technologies developed in peanut drying can be adapted to dry other crops. Apart from that, potential energy savings in peanut drying can lead to substantial reductions in peanut production costs.

World annual peanut production is 17 million Mt. The United States produces 10% of the total (Woodroof,1983). It is estimated that 1.2 MJ/kg of heat energy is required to dry peanuts. If 20% of this energy could be conserved, the United States alone can save 14 ML of LPG per year. Farmers in Virginia would save around 2 ML of LPG per year.

Chapter 2. Objectives

The specific objectives of this research work are:

1. To investigate the validity of the peanut drying simulation model based on Troeger and Butler's (1979) drying equations, using the data collected during eleven drying experiments in Fall, 1986.

2. To investigate the energy saving potential of two air recirculation schedules employed in peanut drying tests.

Chapter 3. Literature Review

3.1 Introduction

Peanuts have more than 40% moisture content (wet basis) just after digging under normal weather conditions. Since high moisture content increases water activity in biological materials which leads to mold growth and general deterioration of quality, the moisture level of peanuts must be reduced to less than 10% wet basis for safe storage. The process of removing moisture without lowering the quality of peanuts is called 'curing'. Dickens and Pattee (1972) stated that the meaning of the term 'curing' includes " physical and biochemical changes in addition to the moisture loss that occurs during preservation by drying." Usually peanuts are cured in the field to reduce the moisture content to about 20% and then mechanical curing processes are used to reduce the moisture content to 10%.

Mechanical curing processes are conducted by using specially designed commercial wagons or trailers which have a perforated floor over a plenum. The trailer dryers are widely used in the United States because of advantages they have in material handling. Normally, air is heated using liquified petroleum gas burners.

The quality of peanuts is not a quantifiable factor. According to Dickens and Pattee (1972), peanuts are said to have good quality if kernels do not skin or split excessively during shelling, and possess an acceptable flavor. The factors that affect the quality of peanuts are numerous. Some of them are (a) physiological maturity of peanuts at the time of digging, (b) rate of drying, (c) drying temperature, (d) the relative humidity of drying air, (e) duration of exposure to heated air, (f) final moisture content of dried peanuts, (g) air flow rate, and (h) amount of foreign materials present in peanuts. These factors are interrelated with the exception of factor (a). An understanding of these factors helps in designing and operating curing equipment.

3.2 *Theoretical Considerations in Drying*

The drying of agricultural products with shells is a complex phenomenon involving heat and mass transfer. Although the drying of farm crops differs in many ways from drying of industrial products such as ceramics, paper etc, theoretical concepts prevalent in those areas can be modified to create a conceptual framework for farm crop drying.

Hall (1980) summarized the vapor pressure theory of drying used to explain drying of agricultural products. When a peanut is surrounded by heated air, heat is transferred into the solid initially raising the shell temperature. Then, the vapor pressure at the inner and outer surface of the shell is increased creating vapor pressure gradients in both directions. As the temperature of the kernel increases with time, the vapor pressure at the surface of the kernel increases establishing a vapor pressure gradient within the shell so that vapor moves from the kernel to the shell and then to the air stream. The vapor pressure gradient between the kernel and the shell and the gradient between the shell and air are dominant factors which drive the moisture transfer at higher moisture contents. When the moisture content is low, other factors such as capillary action, shrinkage and intermolecular water diffusion, in addition to the vapor pressure gradients, affect the rate of moisture transfer. Because of this changing nature of drying mechanisms, two major periods of drying are identified for farm crops. They are (a) the constant rate period and (b) the falling rate period.

When moisture content of a crop is high, the rate of drying is constant and the mechanism involved is similar to evaporation of moisture from a free water surface. The factors determining the rate of drying during this period are (a) area exposed, (b) vapor pressure difference, (c) mass transfer coefficient and (d) the heat transfer coefficient. Henderson and Perry (1976) discussed the general form of an equation which relates the above mentioned parameters to the drying rate.

The falling rate period of drying follows the constant rate period. During this period, moisture diffusion within the solid material becomes the dominant factor in drying. Therefore, the drying rate is more dependent upon the nature of the material. Because the constant rate period is relatively short, most drying of peanuts in trailers or wagons is in the falling rate period.

Hall (1980) discussed the falling rate period using a thin layer of grain fully exposed to the air stream. Modeling a thin layer of grain is less complicated than modeling individual grains. Thickness of a layer should be small enough to neglect variations in moisture content within the layer. The falling rate period can be divided into several segments for modeling.

3.3 *Thin Layer Drying Models for Peanuts*

Since updraft batch drying is the most common mode of drying grain, almost all the mathematical simulation models found in the literature are developed for simple batch drying. Thin layer drying models are based on an analysis of a thin layer of the material as an open system. Analysis involves application of mass and energy conservation laws to the system constituents, air, water and products as drying air is passing through the layer. For the mass balance of water, the moisture removal rate from the material should be available. Accurate modeling of the drying rate is very important and accuracy of the drying rate equation can be expected to have a significant contribution to the total accuracy of a mathematical simulation model.

Thompson et al.(1968) and Troeger and Hukill (1968) used two different approaches to model thin layer drying of corn. Troeger and Hukill used three falling rate periods to model the drying rate while Thompson et al. expressed it in one continuous equation. Both of these teams employed single layer laboratory dryers to collect data for model verification.

Concepts used in thin layer corn drying models were extended to peanut drying models by several investigators. Woodward et al.(1971) modeled the drying rate of freshly harvested Starr Spanish, Early Runner and Florigiant Virginia peanut pods, kernels, bald kernels, split kernels and hulls, using the following equation.

$$\frac{dM}{dt} = -a(M - M_e) \qquad [3.1]$$

where,

$\frac{dM}{dt}$ = rate of change of moisture with time

M = moisture content at time t, dry basis

M_e = equilibrium moisture content at the condition of drying air

a = falling rate drying index

They conducted single layer drying in wire baskets with air at 95 F and about 37% relative humidity. Air velocity was 6.1 meter per minute. Integration of equation 3.1 yields

$$\frac{M - M_e}{M_0 - M_e} = e^{-at} \qquad [3.2]$$

where,

M_0 = moisture content at time t=0, dry basis.

The data obtained fit equation 3.2 perfectly if a slightly inflated value of M_e was used. Equation 3.2 was modified to incorporate this feature and the modified equation is given below.

$$\frac{M - M_f}{M_A - M_f} = e^{-a(t-A)} \qquad [3.3]$$

where,

M_f = pseudo-equilibrium moisture which replaces the true equilibrium value

A = time when drying rate becomes proportional to excess moisture

M_A = moisture content at time A

Since the initial portion of the drying rate curves were not linear, "A" is the transition time from the constant rate period to the falling rate period. The term on the left side of equation 3.3 is called the moisture ratio. The pseudo-equilibrium moisture content was determined from linear regression of MR versus time for a range of M_f values. The value of M_f having the lowest standard error of estimate was chosen for that particular entering air condition. This model was in excellent agreement with data collected but unfortunately, authors reported falling rate index, a, and M_f only for a drying air temperature of 95 F and 37% relative humidity.

Young and Whitaker (1971) investigated the solutions of the diffusion equation for mass transfer in a plane sheet, an infinite cylinder and a sphere in order to express thin layer drying conditions of peanut pods mathematically. They performed single layer tests for green peanuts (NC 5 variety) at three dew point and four dry bulb temperatures. The experimental data were compared with the diffusion equations. They made the following observations and conclusions:

(a) There is no constant rate drying period for peanuts even with an initial moisture content as high as 106 percent dry basis.

(b) Dry bulb temperature of air has a significant effect on drying rate.

(c) Initial curvature of drying curves can be explained by diffusion equations, and exponential drying equations are not satisfactory for this purpose.

(d) The diffusion equation for the finite cylinder gives the best fit for the experimental data.

Troeger and Butler (1979) used the following model to simulate rate of peanut drying using solar energy.

$$\frac{dM}{dt} = -a\,(M_o - M_e)M_r^b \qquad [3.4]$$

where,

M = moisture content, dry basis (decimal)

t = time (h)

M_o = initial moisture content, dry basis (decimal)

M_e = equilibrium moisture content, dry basis,(decimal)

M_r = moisture ratio (dimensionless) which is defined by,

$$M_r = \frac{(M - M_e)}{(M_o - M_e)} \qquad [3.5]$$

a and b are functions of drying conditions defined by the following equations.

For $M_r \geq 0.40$,

$$a_1 = 0.02320 + 0.00045T + 0.00063T_{dp} + 0.00045T_{dp}M_o + 0.0080M_o \quad [3.6]$$

$$b_1 = 3.264 - 0.0252T - 0.0162T_{dp} - 0.0342T_{dp}M_o - 0.6080M_o \quad [3.7]$$

For $0.12 < M_r < 0.40$,

$$a_2 = a_1(2.40 - M_o) \quad [3.8]$$

$$b_2 = b_1(0.88 - 0.20M_o) \quad [3.9]$$

For $M_r \leq 0.12$,

$$a_3 = a_2(2.40 - M_o) \quad [3.10]$$

$$b_3 = b_2(0.88 - 0.20M_o) \quad [3.11]$$

where,

T = dry bulb temperature of air, C

T_{dp} = dew point temperature of the air, C

The values of above coefficients were determined statistically using experimental data obtained from a multilayer peanut dryer with a depth of 0.3 m. They suggested that the presence of foreign material had a significant effect on drying characteristics. Cundiff et al. (1983) suggested that if the transition moisture ratios (M_r) were changed at 0.7 and 0.2 instead of 0.40 and 0.12, a better drying rate model for Virginia type peanuts could be obtained.

From the above discussion, it is apparent that there are several ways to model the drying rate of peanuts. Except for the Troeger model, other models have been verified by using single layer dryers. These equations should be tested for multilayer dryers, where shrinkage of peanuts during drying is significant. The equation proposed by Woodward et al. (1971) provides a simple function which simulates the whole drying curve quite accurately. Further research should be done to determine psuedo-equilibrium moisture contents and drying indices for various drying air conditions. Young and Whitakers' (1971) equation, based on fundamentals of diffusion, provides an area for future study to incorporate the equation into mathematical simulation models.

3.4 *Equilibrium Moisture Content of Peanuts*

The adsorbed moisture within a peanut exerts a moisture vapor pressure in the immediate surroundings in propotion to the moisture content of the peanut. The equilibrium relative humidity is defined as the ratio of the moisture vapor pressure at the equilibrium state to the saturated vapor pressure of pure water at the temperature of the peanut. The moisture content at equilibrium is known as the equilibrium moisture content.

Beasley and Dickens (1963) studied the relationship between equilibrium relative humidity (ERH) and equilibrium moisture content of NC-2 Virginia bunch peanuts. They experimentally determined the equilibrium moisture curves for hulls, whole pods and kernels at three different temperatures, 50 F, 70 F and 90 F. Within the relative humidity range of 20% to 100%, the following observations and remarks can be made.

(a) Because hulls are more hygroscopic by nature than kernels, hulls had a higher equilibrium moisture content than kernels and whole pods below 95% ERH and at all temperatures tested.

(b) Kernel moisture and whole pod moisture show exponential response at high ERH values (above 90%) while hulls show less rapid increase in equilibrium moisture content at high ERHs.

(c) The behavior of whole pods is closer to kernels than hulls.

The experimental values were fitted to the following equation developed by Henderson (1952). Constants thus found are given in Table 3.1.

$$1 - rh = e^{-kTM^n} \qquad [3.12]$$

where,

rh = relative humidity, decimal

T = absolute temperature, degrees Rankine

Table 3.1. Variation of k and n with temperature and material.

Temp (°F)		n			$k \times 10^5$	
	Hulls	Kernels	Pods	Hulls	Kernels	Pods
90	1.88	1.87	1.85	1.61	5.06	3.81
70	1.99	2.05	1.94	1.11	3.46	2.81
50	2.19	2.43	1.89	0.56	1.48	2.86

M = moisture content (decimal), percent dry basis

k & n = characteristic constants of the material.

Henderson and Perry (1976) stated that equation 3.12 can be thermodynamically proved, but the variation in ERH with temperature has never been justified. Beasley and Dickens (1963) did not validate the accuracy of equation 3.12 with other data.

Troeger and Butler (1970) gave equilibrium moisture vs relative humidity plots for three varieties of peanuts (Starr Spanish, Early Runner and Florigiant) in three forms (whole pods, kernels only and hulls only). They used dry peanuts as well as green peanuts for their tests and made the following conclusions:

(a) The equilibrium moisture contents of green peanuts and dry peanuts were not significantly different at low relative humidities.

(b) When the temperature was increased, the equilibrium moisture content decreased for a given relative humidity within the low and medium relative humidity range and increased at high relative humidities.

(c) The mold growth experienced during the tests at high relative humidities affected the weight of the samples and lowered the moisture contents.

They give the following relationships for equilibrium moisture contents of hulls, whole pods, and kernels:

Dry basis moisture content of hulls = 1.4 x Dry basis MC of whole pods.

Dry basis moisture content of kernels = 0.87 x Dry basis MC of whole pods.

These relationships were valid for the range of relative humidities investigated.

Young (1976) determined experimentally the sorption and desorption equilibrium moisture content curves of Virginia type peanuts, NC-5 variety, at four different temperatures (15, 25, 35, and 45 C). He accommodated the hysteresis between the wetting and drying processes when modeling the data. Five equations widely used in modeling the equilibrium moisture content curves for biological materials were investigated. The equilibrium moisture content isotherms for whole pods were not included in the investigation.

Troeger and Butler (1979) used data given by Beasley and Dickens (1963) to derive the following equation for Virginia type peanuts.

$$M_e = (-\log(1-rh))^{0.7}\left[\frac{111}{(T_a+273)}\right]^{2.4} \qquad [3.13]$$

where,

T_a = dry bulb temperature of drying air, C

rh = relative humidity of drying air,decimal

Cook (1983) also used equation 3.13 in her computer model to simulate peanut drying with recirculation.

Analyses of data given by Beasley and Dickens (1963), Troeger and Butler (1970), and Young (1976) revealed that the equilibrium moisture contents reported under similar conditions and for the same material are within 5% to 30% if relative humidity is less than 80%. Generally, the equations do not fit well with experimental desorption data at low relative humidities (below 40%), while experimental sorption data agrees well with the equations. At low relative humidities, deviation between a value given by an equation and corresponding experimental equilibrium moisture content (desorption) can be as high as 50 percent.

3.5 Standard Peanut Curing Practices

Cured peanuts must have good quality to be competitive in the market. The factors that affect quality have already been listed. When these factors are controlled, quality of peanuts can be improved.

Singleton et al. (1969) analyzed volatiles produced by peanuts cured at 22, 35, 45, and 50 C and compared volatile profiles with respect to flavor and aroma. Content of acetaldehyde increased as curing temperature was increased. Ethyl acetate was not detected at 22 C, but traces were found beyond 35 C, which were directly related to deterioration in flavor. Beasley and Dickens (1963) concluded that a curing temperature exceeding 95 F (35 C) should not be employed because of resulting off-flavor in peanuts. If higher temperatures are to be used, the duration of exposure should be minimized to avoid less off-flavored peanuts. More off-flavor was produced when peanuts having 20% to 30% (w.b.) moisture content were exposed to high temperatures. In practice, air temperature of 95 F is considered to be the maximum allowable drying temperature.

The relative humidity of air at a given temperature is a measure of the moisture absorbing capacity. If the relative humidity is low, absorbing capacity is high. By reducing the relative humidity of air, drying rate can be increased but, as Beasley and Dickens (1963) reported, milling damage also increases. Their tests showed that high rates of drying produced low quality peanuts. They found that reducing final moisture contents from 9.5% to 6%, increased shelling damage 500% to 700%. Therefore, slower drying rates terminating near 9% moisture content (w.b.) are preferred.

As air velocity through a fixed bed of peanuts increases, the drying zone in the dryer moves more rapidly upwards. Air velocity should be high enough to avoid spoilage in the top layers. Beasley and Dickens (1963) investigated the effects of air flow rates on peanut drying rate. At moisture contents below 20%, air flow rate did not influence the drying rate significantly. They used three different flow rates (120 cfm/sq.ft of dryer cross sectional area, 72 cfm/sq.ft and 24 cfm/sq.ft) and found the maximum difference in drying time was four hours. But Blankenship and Pearson (1976) reported that by increasing air flow rate, drying rates can be increased with little effect on quality. Glover (1977) recommended an air flow rate of 10 m^3 per min per m^3 for peanuts in North Carolina and Mayfield and Donald (1979) recommended an air flow of 19 m^3 per min per m^3 for peanuts in Alabama.

Resistance of peanuts to air flow is important in the design process especially to select a suitable fan. Shedd (1953), Coates and Beasley (1961) and Steele (1974) studied the resistance of peanuts to air flow. Steele (1974) gave the following relationship relating the pressure drop and the apparent velocity of air through a bed of peanuts.

$$v = 0.0184 \left[\frac{\Delta p}{RL} \right]^{0.618} \qquad [3.14]$$

where,

v = apparent air velocity through bed of peanuts

Δp = pressure drop through bed of peanuts, Pa

L = thickness of peanut bed, m

R = moisture content correction factor, dimensionless

and $R = 0.962 + 0.00392M$

where, M = peanut moisture content, % dry basis

According to the above equation, moisture content affects the pressure drop.

3.6 Energy Conservation in Peanut Drying

Energy inputs for a peanut dryer include electrical energy to operate fans and control devices, and heat energy to raise the temperature of the drying air. Blankenship and Chew (1979) determined energy consumption during peanut drying with 3.73 kW, single trailer, and 7.46 kW, double trailer propane gas fired dryers. They studied the total cost versus initial moisture content of peanuts and presented linearly regressed relationships between the two variables for two types of dryers. For peanuts with 20% initial moisture content, the total energy cost to dry in trailers was estimated to be $ 5 per ton. Sixty percent increase in total energy costs can be expected if the initial moisture content is 30% (wet basis). There are three main approaches found in the literature to conserve energy in peanut drying. They are (a) using an alternate energy source such as solar heat, (b) employing an intermittent air supply and (c) partial recirculation of drying air.

Troeger (1980a) compared performance of prototypes of three peanut drying systems. They were (a) solar collector-water storage- supplementary LPG burner system, (b) solar collector-air rock storage- supplementary LPG burner system and (c) conventional LPG burner system. Types (a) and (b) are shown in Figure 3.1. He dried four metric tonnes of peanuts with average initial moisture content of 17.5%(w.b.). System a had a 82 m^2 collector and system b had a 140 m^2 collector. The average solar energy contribution of the water system was 41% of the total heat energy used, and that for the air-rock-storage system was 74%. Milling quality and drying time did not significantly differ from that obtained from the conventional drying system.

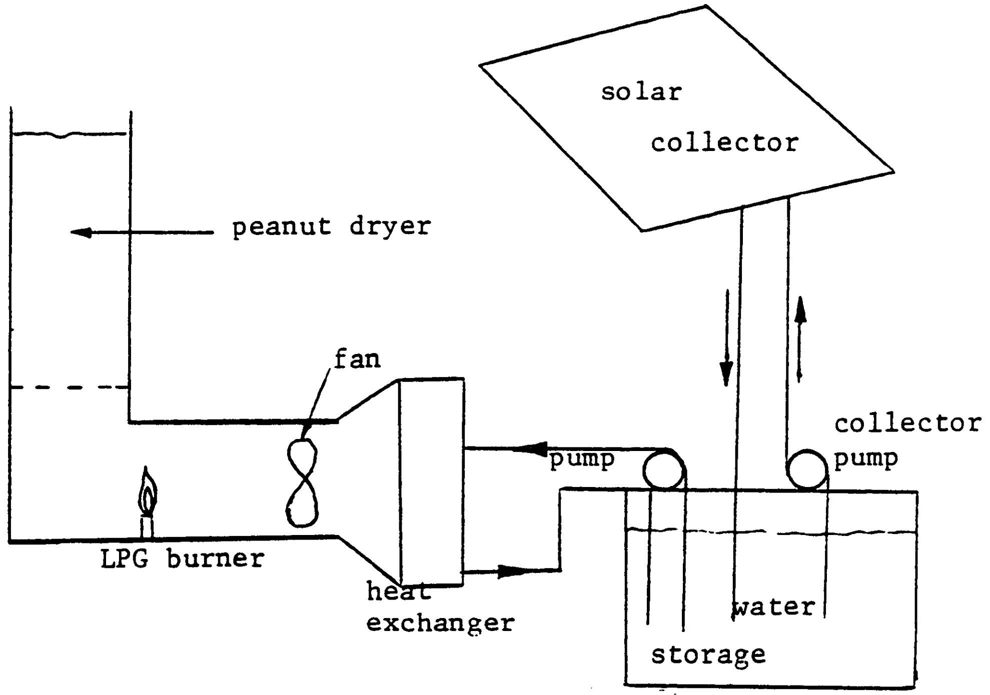

FIGURE 3.1a. Solar collector with water storage and supplementary LPG burner system.

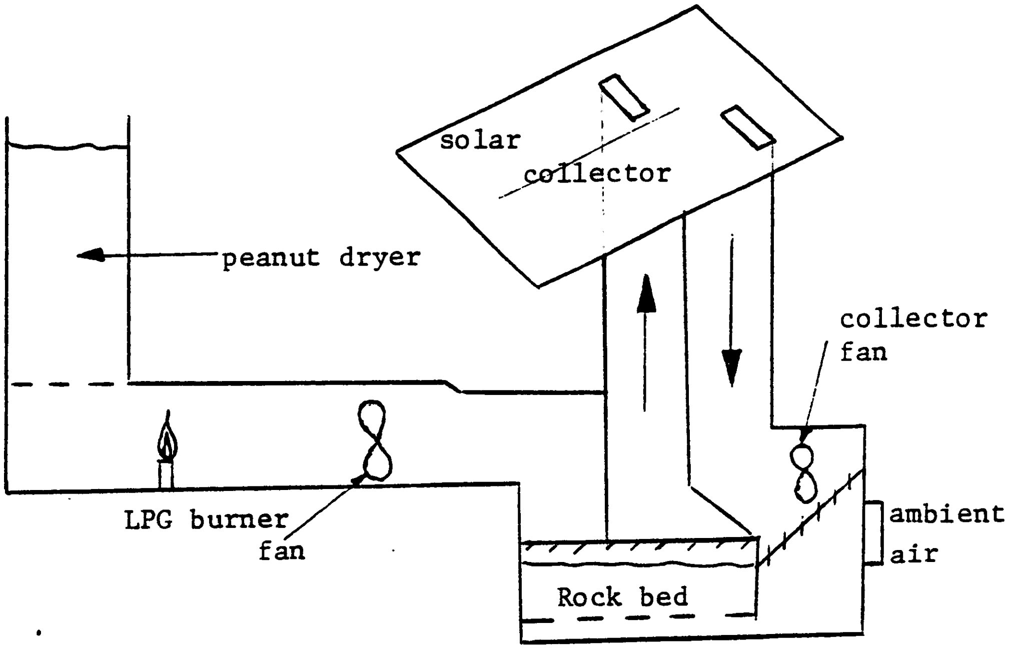

FIGURE 3.1b. Solar collector with rock storage and supplementary LPG burner system.

Troeger and Butler (1979) presented a mathematical simulation model for a solar drying system employing a transient simulation program (TRANSYS) developed by the Solar Energy Lab at the University of Wisconsin. Troeger (1983) discussed the design parameters involved in designing a peanut drying system using solar heated water.

Cundiff and Troeger (1981) studied the feasibility of using a solar energy system (flat plate collector- rock storage) in tobacco curing and peanut drying. Since tobacco is cured in July and August and peanuts are dried in September and October in Georgia, this arrangement is a practical way of sharing capital investment. Based on the analysis, if the solar system is designed to provide 20% of the heat energy required for five tobacco curing barns, it can supply 50% of the energy required for drying two wagons (8.4 Mg dry weight of peanuts).

Vaughan and Lambert (1980) reported design, construction, and testing of an integrated shed solar collector drying facility. The configuration is shown in Figure 3.2. This facility can handle six trailers and could be used for 40-50 days per year to dry peanuts. Recirculating air is solar heated while passing through the flat plate collector roof and gets mixed with outdoor air in the plenum. It was estimated that 2230 L of LPG were saved (36%) using this facility during season while 3975 L of LPG were used.

Troeger and Butler (1980b) reported a series of tests to reduce heat and electrical energy erquirement for peanut drying by shutting off dryers periodically. Peanuts were dried in 12 model bins (0.6mx0.6mx 1.2m deep) at two different air flow rates (12.5 m^3 air per min per m^3 of peanuts and 25 m^3 of air per min per m^3 of peanuts). The four shutting off schedules they used were 15 minutes interruption per hour, 30 minutes per hour, 45 minutes per hour and 1 hour in 4 hours. They were able to save 10% of total energy consumption using 15 minutes per hour schedule and air flow rate of 12.5 m^3 per min per m^3 of peanuts. However, heat energy consumption increased when operating at 25 m^3 per min per m^3 of peanuts. No differences in milling quality were detected among these treatments. Blankenship and Chew (1978) found a reduction in electrical energy use of 32% and a reduction in LPG consumption of 21% by shutting off the dryers for one third of the operational time. The strategy of interrupting air flow can also be employed to avoid peak hours in electricity demand thereby reducing running costs.

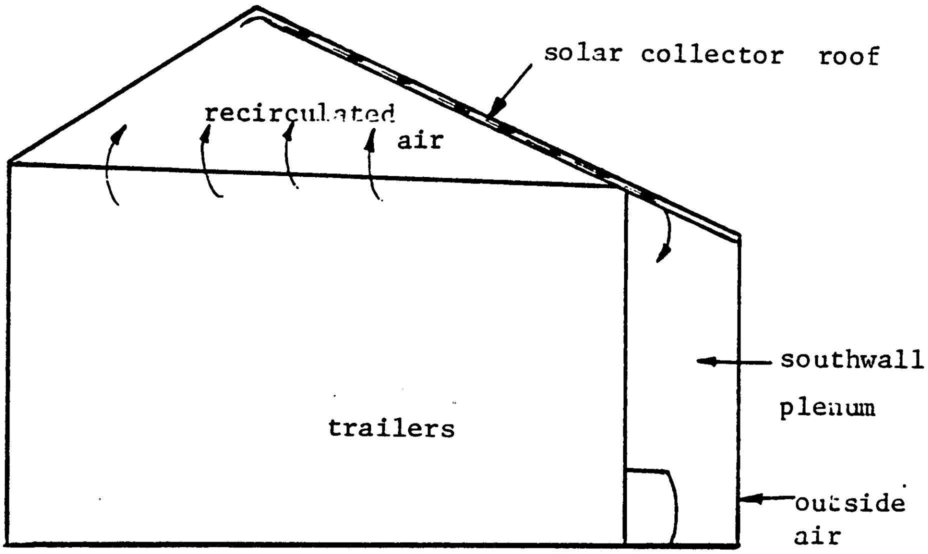

FIGURE 3.2. End veiw of the solar dryer facility (Vaughan and Lambert, 1980).

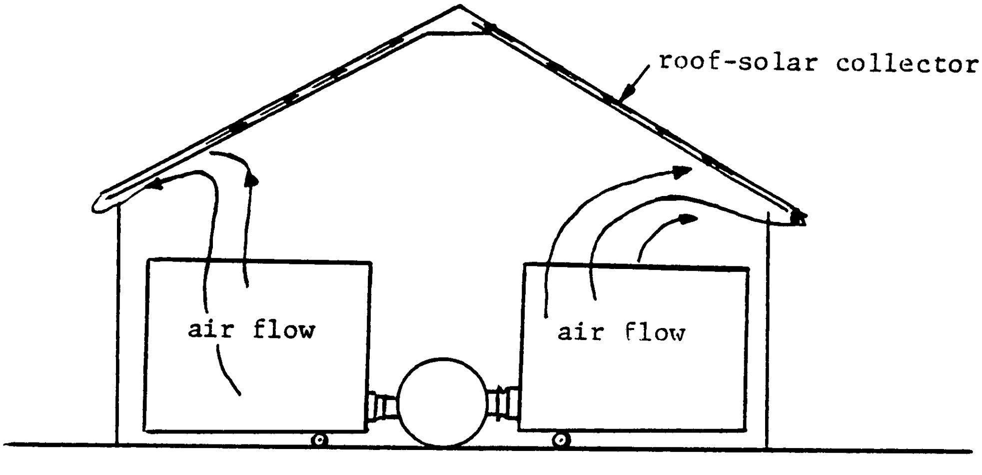

FIGURE 3.3. Recirculation of exhaust air with solar heating.

Vaughan and Cundiff (1984) investigated the cost effectiveness of replacing the conventional LPG burner with a heat pump for a six trailer peanut drying shed in which an average of six batches of peanuts are dried annually. They visualized a system having the heat pump evaporator installed in the exhaust air stream and the condenser located in the inlet air. The refrigerant is evaporated in the evaporator absorbing heat from the exhaust and pumped into the condensor giving off heat to the inlet air. They concluded that the drying system with a heat pump would not be cost effective because of high capital investment for the the heat pump. However, if a heat pump with a high COP is used throughout the year for other purposes besides drying peanuts, this method could be cost competitive.

Recirculation of exhaust air and mixing with ambient air in peanut curing facilities has two distinct advantages: (1) it allows one to exploit remaining drying potential of exhaust air and (2) it maintains a sufficiently high humidity in incoming air to prevent splitting damage associated with high drying rates. Harner et al. (1981) investigated energy savings from recirculation of exhaust air during peanut curing. They cured ten different batches of peanuts in a six trailer solar peanut drying system given in Figure 3.3. The recirculated exhaust air absorbed heat while passing through the bare plate collector fitted to the roof. The recirculated air constituted two thirds of the total air flow required by the fans. The rest was drawn through the portable collector. They reported an average fuel saving of 8.71 L LPG per hour from recirculation of exhaust air and solar energy during 1980 and 1981. The percentage energy saving from solar and recirculation ranged from 31.0% to 34.95% during 1980.

Cook et al. (1982) presented the energy savings from different recirculation strategies along with a simulation model adapted to incoporate recirculation. Continuation of their work is presented in this thesis. They used three laboratory test dryers later described in the thesis. The simulation model modified by Cook et al. was used to compare the three recirculation strategies given in Table 3.2. They reported energy saving up to 20% using these strategies, without increasing drying time.

Young (1985) compared energy consumption in dryers using partial air recirculation with conventional single pass dryers, and with dryers utilizing intermittent operation of fans and heaters. He studied five peanut drying units for three years. He concluded that the recirculation dryers showed significant advantages over conventional and intermittent air flow dryers. Energy savings averaged around 26% in the recirculation dryers; drying time was decreased by 15%; and the peanuts had slightly higher market value. He suggested that the upper limit temperature for recirculation dryers has to be reduced from 35C. This suggestion was based on the mold growth experienced during some trials using 35 C as the upper temperature limit.

Table 3.2. Recirculation strategies used by Cook et al. (1982).

hour	Recirculation (%)		
0-24	0	25	50
25-48	0	50	75
49-72	10	33	66

Chapter 4. Simulation Model for Peanut Drying

4.1 Model Development

Cook (1983) used the thin layer drying model developed by Troeger and Butler (1979) to simulate peanut drying in a laboratory dryer. In the model, the depth of a bed of peanuts is divided into finite layers and laws of conservation of mass and energy are applied to each layer during a finite time interval. It is assumed that properties of air entering each layer remain constant during each time interval. The equilibrium moisture content of whole pods of Virginia bunch peanuts (variety NC-2) is modeled using the equation given by Beasley and Dickens (1962). Appendix A contains a complete listing of the Fortran program written for the model and explanations of the Fortran variables associated with the program. In this chapter, a brief description of the model is presented along with modifications made to the model for use in this research work.

4.2 Assumptions and Physical Parameters Involved in the Model

The basic assumptions made in developing this model are given below.

1. Entering air properties to a layer are constant during the time interval chosen. This assumption makes the time interval employed in the model an important factor. Effects of this time interval on predicted values from the model must be investigated before using a particular time interval.

2. The moisture transfer from peanuts to air in a layer is given by the Troeger model.

3. The temperature of the peanuts is given by equation 4.17.

The model requires values of ambient dry and wet bulb temperatures, dry and wet bulb temperatures of air entering the first layer, initial moisture content of the peanuts, and the air flow rate. Air flow is calculated from experimentally determined fan curves. The model predicts the condition of air exiting each layer at a given time, and the moisture content of each layer at a given time.

4.3 Governing Equations of the Model

4.3.1 The Troeger Model

The rate of moisture removal from a thin layer of peanuts is given by,

$$\dot{M} = \ -a(M_o - M_e)M_r^b \qquad [4.1]$$

where,

$\dot{M}$ = time rate of change of moisture content, dry basis (d.b.), decimal,

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

M_e= equilibrium moisture content (d.b.), decimal, and

M_r= dimensionless ratio defined by,

$$M_r = \frac{(M - M_e)}{(M_o - M_e)}. \qquad [4.2]$$

The a and b parameters are functions of the drying conditions and they are defined as follows:

For $M_r \geq 0.40$,

$$a_1 = 0.02320 + 0.00045T + 0.00063T_{dp} + 0.00045T_{dp}M_o + 0.00800M_o \qquad [4.3]$$

$$b_1 = 3.264 - 0.0252T - 0.0162T_{dp} - 0.0342T_{dp}M_o - 0.6080M_o \qquad [4.4]$$

For $0.12 < M_r < 0.40$,

$$a_2 = a_1(2.40 \ - M_o) \qquad [4.5]$$

$$b_2 = b_1(0.88 \ - \ 0.20M_o) \qquad [4.6]$$

For $M_r \leq 0.12$,

$$a_3 = a_1(2.40 - M_o)^2 \qquad [4.7]$$

$$b_3 = b_1(0.88 - 0.20M_o)^2 \qquad [4.8]$$

Here,

T = dry bulb temperature of air, C

T_{dp} = dew point temperature of the air, C

For some ith interval equation 4.1 becomes

$$\dot{M}_i = -a_i(M_o - M_{ei})M_{ri}^{b_i} \qquad [4.9]$$

where,

$\dot{M}_i$ = time rate of change of moisture content (d.b) during ith interval,

M_o = moisture content (d.b.) at time = 0,

M_{ei} = equilibrium moisture content (d.b.) for drying air conditions which exist during ith interval,

M_{ri} = dimensionless ratio for ith interval defined by,

$$M_{ri} = \frac{(M_{i-1} - M_{ei})}{(M_o - M_{ei})} \qquad [4.10]$$

The parameters a_i and b_i are defined for the entering air dry bulb and dew point temperatures during the ith interval, T_{ei} and T_{dpei}, respectively.

The equilibrium moisture content (decimal) of entering air at temperature T_{ei} and relative humidity rh_{ei} is given by the Henderson equation (1952).

$$(1 - rh) = e^{-kTm_e^n} \qquad [4.10]$$

where,

rh = relative humidity, decimal

T = dry bulb temperature of air, entering a layer, Rankine,

k,n = constants for the material

m_e = equilibrium moisture content (w.b.), percent.

The constants k,n are functions of air temperature (F), and given by the following set of equations:

For $T < 70F$,

$$n = 1.94 + 0.0025(T - 70) \tag{4.11}$$

$$k = (2.81 - 0.0025\,(T - 70))\,10^{-5} \tag{4.12}$$

For $T > 70F$,

$$n = 1.94 - 0.0045(T - 70) \tag{4.13}$$

$$k = (2.81 + 0.05\,(T - 70))\,10^{-5} \tag{4.14}$$

The Henderson equation can be rearranged as follows:

$$m_e^n = \frac{-ln\,(1 - rh)}{k(T + 459.67)} \tag{4.15}$$

This value is converted to moisture content dry basis and used in the rest of the model.

The new moisture content for the layer in consideration is calculated by using the finite difference approach with respect to time.

$$M_i = \dot{M}_i \Delta T + M_{i-1} \tag{4.16}$$

4.3.2. Psychrometric Properties of Air

In the computer program, the psychrometric properties of air are calculated by calling the PSYC subroutine. These calculations are based on the ASAE data sheet D271.2 (ASAE,1982). The input for the subroutine is either dry bulb and wet bulb temperature of air or dry bulb temperature and humidity ratio, and it returns relative humidity (decimal), dew point temperature (C), wet bulb temperature (C), humidity ratio (dec.), saturation pressure (Pa), partial vapor press (Pa), enthalpy (J/kg), and specific volume ($\frac{m^3}{kg}$).

4.3.3. Peanut Temperature

Peanut temperature, required in the model to calculate the thermal energy stored in peanuts, is accomplished by using the following equation as given in the Troeger model:

$$\frac{(T_p - T)}{(T_{po} - T)} = P(Z_1)C(Z_2) \qquad [4.17]$$

where,

T_p = temperature of peanuts, C

T_{po} = temperature of peanuts at t=0, C

$$P(Z_1) = 1.267 \exp(-2.461Z_1) \qquad [4.18]$$

with $0.20 \leq Z_1 \leq 4.0$. Function P will be less than or equal to unity.

For $0.10 \leq Z_2 \leq 1.50$,

$$C(Z_2) = 1.557\, exp(-5.733Z_2) \qquad [4.19]$$

This function should also be less than or equal to unity. The parameters Z_1 and Z_2 are given by

$$Z_1 = 4a_o\frac{t}{L^2} \qquad [4.20]$$

$$Z_2 = 4a_o\frac{t}{D^2} \qquad [4.21]$$

where,

a_o = thermal diffusivity of peanuts, $\frac{m^2}{h}$

L = length of peanut, m,

D = diameter of peanut, m,

t = drying time, h.

For some ith interval with entering air dry bulb temperature T_{ei},

$$T_p = T_{ei} + P(Z_1)C(Z_2)(T_{po} - T_{ei}). \quad [4.22]$$

The drying time at the ith interval can be calculated from

$$t_i = (i-1)\Delta t. \quad [4.23]$$

4.4. Moisture Balance for a Layer of Peanuts

The air passing through the peanuts consists of moisture and dry air. Mass balance for moisture can be applied to a layer during any interval of time assuming that moisture transfer is negligible across the dryer walls. The moisture balance equation can be written for a layer for some ith interval as follows:

$$H_{exi} - H_{ei} = m_p \frac{(M_i - M_{(i-1)})}{\Delta m_{dai}\,\Delta t} \quad [4.24]$$

where,

H_{ei} = humidity ratio of entering air, kg water/kg dry air

H_{exi} = humidity ratio of exiting air, kg water/kg dry air

M_i = moisture content of peanuts (d.b.), kg water/kg dry solids

m_p = mass of peanuts solids in layer, kg

Δm_{dai} = mass flow of dry air during the ith interval, kg/h

Δt = time interval, h

Δm_{dai} can be calculated from the volume flow rate of drying air.

$$\Delta m_{dai} = 60\frac{\dot{V}_i}{V_{sai}} \quad [4.25]$$

where,

$\dot{V}_i$ = time average volume flow rate during the ith interval, m^3 per min

V_{sai} = specific volume during the ith interval, m_3 per kg dry air

The exiting air conditions of the ith layer are the entering air conditions of the i+1st layer.

4.5. *Energy Balance for a Layer*

For a given layer, the difference between sensible heat stored in peanuts at the beginning of a time interval and at the end of it should be equal to the difference between total heat input to the layer and total heat output from the layer during the time interval considered, provided that there is negligible heat transfer across the wall of the dryer. Therefore, the heat balance can be written as

$$m_p(C_p + M_i C_w)T_{p,i} - m_p(C_p + M_{i-1}C_w)T_{p,i-1} = (h_{ei} - h_{exi})\Delta m_{dai}\Delta t \qquad [4.26]$$

where,

C_p = specific heat of peanuts solids (kJ/kg-K)

C_w = specific heat of water in peanuts (kJ/kg-K)

h_{ei} = enthalpy of air entering the layer(kJ/kg-K)

h_{exi} = enthalpy of air exiting the layer (kJ/kg-K)

The structural heat loss component for the ith layer can be added to the left hand side of equation 4.26 to obtain a more accurate value for exiting air temperature.

4.6 Energy Model

An energy model was developed to calculate energy flows through the dryer. A complete listing of this computer program is given Appendix A. For any time interval, the energy contained in air entering the peanut bed minus the energy contained in air entering the heater section plus the heat loss in that section of the dryer should be equal to the heat energy added by the heater. Therefore, for any ith interval,

$$Q_{ci} = Q_{si} + Q_{gi}, \qquad [4.27]$$

where,

Q_{ci} = calculated heat energy input by the heater during ith interval, MJ per hour,

Q_{si} = structural heat loss from the ambient air door to the bottom of the peanut bed, MJ per hour,

Q_{gi} = heat gained by air passing through the heaters based on dry bulb temperature measurement of ambient and entering air and the air flow rate, MJ per hour.

If the time interval is an hour, the total heat energy for each term is,

$$Q_{tk} = \sum_{i=1}^{n} Q_{ki} \qquad [4.28]$$

where,

n = number of hours in the drying test,

k = c,s or g.

The structural heat is the energy required to elevate and maintain the temperature of a given dryer section. The main component of the heat loss is the conductive heat loss through the walls. The stored energy in the components is neglected except for the fan. The air temperature exiting the heater section is assumed equal to the temperature of air entering the peanut bed. The air temperature inside the section from the heater to the bottom of the peanut bed is also assumed equal to the entering air temperature. The structural heat loss is calculated using the following equation:

$$Q_{jsi} = A_j \frac{(T_{ji} - T_{ai})}{R} \qquad [4.29]$$

where,

Q_{jsi} = heat loss in jth section during ith interval, MJ/h

A_j = area of the wall in jth section, m^2

R = thermal resistance of the wall,

T_{ji} = air temperature in the jth section, C

T_{ai} = ambient air temperature, C

The heat gained by air is calculated from the following relationship:

$$Q_{gi} = 60V_i \frac{(h_{ei} - h_{ai})}{1000V_{sai}} \qquad [4.30]$$

where,

h_{ei} = enthalpy of entering air during ith interval, kJ/kg

h_{ai} = enthalpy of air entering the heater section, kJ/kg

V_i = volume flow rate of air during the ith interval, m^3/h

V_{sai} = specific volume of air, m^3/ kg.

Chapter 5. Experimental Methods

5.1. Laboratory Dryers

The three laboratory dryers used in these experiments were built in 1981 by the Department of Agricultural Engineering. The configuration of each dryer is shown in Figure 5.1. A dryer consists of four ducts having an inner uniform cross section of 0.5 m x 0.5 m. The vertical section above the fan can be removed and a crop to be dried can be stored in it. The height of the drying bed is 1.2 m. The top horizontal duct and the other vertical duct serve as a passage for recirculating air. The amount of recirculated air can be controlled by a hinged door located just above the ambient air entrance.

A cross section of the ducts is shown in Figure 5.2. The innermost layer consists of 0.95 cm thick plywood and the outer layer is made out of 0.64 cm thick plywood. A layer of polystryrene insulation of 3.81 cm thickness provides high resistance to heat flow through the walls.

Each dryer has a centrifugal fan driven by a 0.56 kW electric motor, which is mounted outside the dryer. The fan speed is varied using a variable speed drive. A 60 tooth gear is mounted on the fan shaft and each tooth generates a pulse as it passes near a magnetic sensor. These pulses are counted by a frequency counter and displayed as rpm.

Air is heated using finned strip heaters (Chromalox OTF-19 128258) which can be controlled to maintain air temperature at 35 C. During the tests, three 1500 W, 240 V heaters were used in each dryer. The temperature of air below the material bed is controlled by digital temperature controllers (Eurotherm Model 918) with a rated accuracy of ± 1 *C*. This temperature controller varies the current to the heaters according to the set point, and the temperature reading below the material bed. The temperature sensor for the controller is an iron constantan (ANSI type J) thermocouple junction. Maximum temperature in the lab dryer is 35 C.

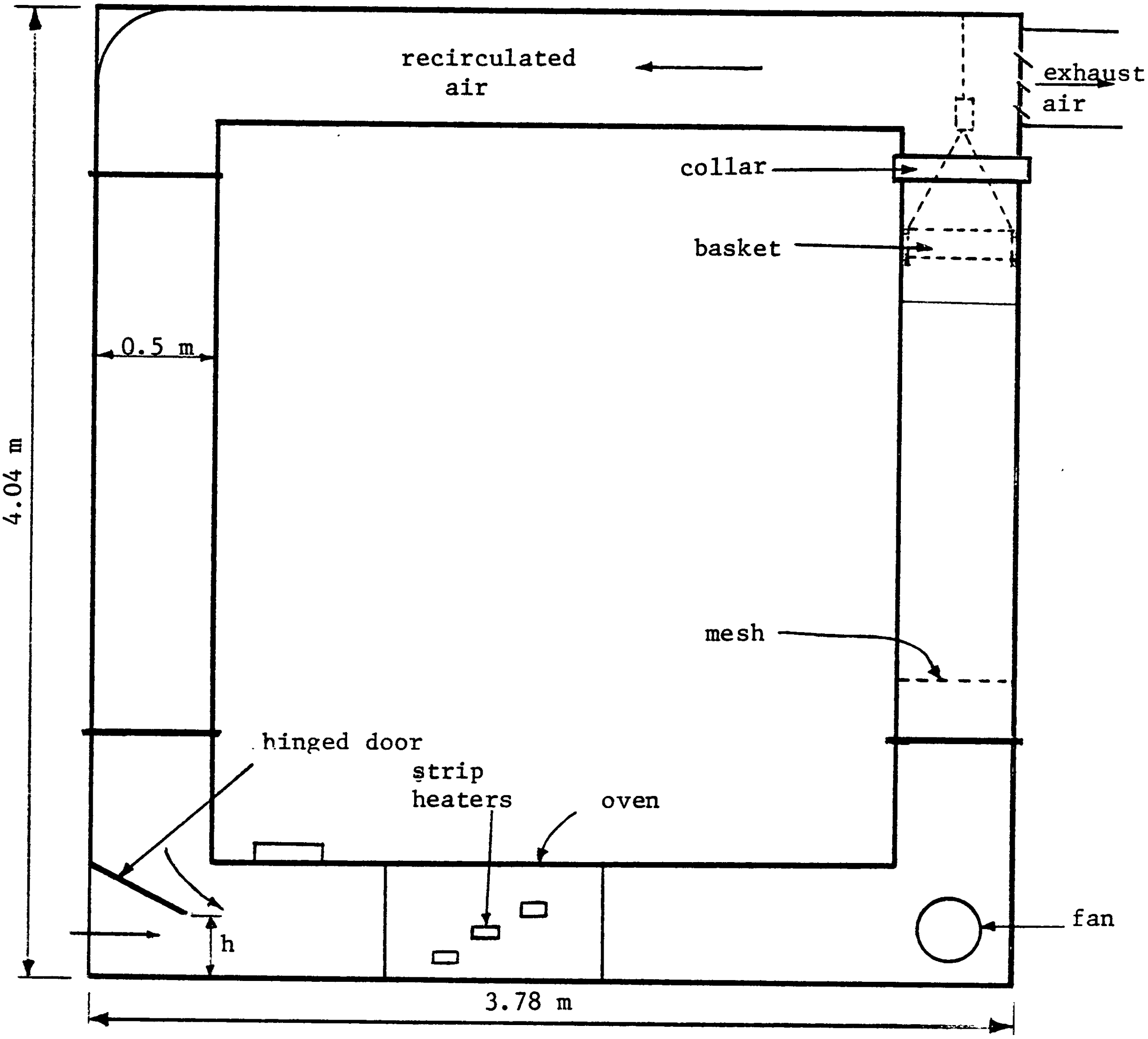

FIGURE 5.1. Laboratory dryer.

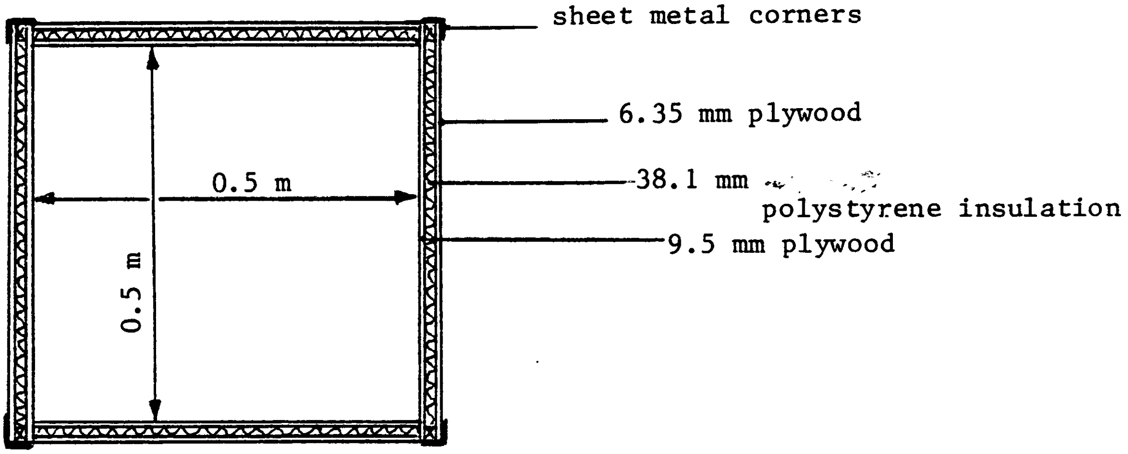

FIGURE 5.2. Cross section of a duct.

Air is exhausted through a metal vent at the top of the crop drying column into a sheet metal duct which channels the exhaust to the outside of the building. The vent opens under positive pressure inside the ducts.

The three dryers are installed side by side in the Energy Lab of the Agricultural Engineering Department. There is enough space to operate a forklift during the loading and unloading operations.

5.2.0. *Drying Tests*

Four tests were conducted during the Fall, 1986. These tests consisted of eleven drying experiments. Peanuts used for these tests were grown at the Tidewater Agricultural Experiment Station, Holland, Virginia. Remaining portion of peanuts brought for the first test was stored in a controlled environment chamber to prevent moisture loss. The controlled environment chamber was set at 90% relative humidity and 35 F dry bulb temperature. These peanuts were used for the second test.

5.2.1. Test 1

The first drying test began on October 06, 1986. Peanuts arrived at the laboratory about 1800 hours and were loaded into the dryers. Six samples of peanuts were selected for initial moisture content determination. First, the dryer column of the third dryer was removed and weighed. Then the column was filled with peanuts to the marked level and weighed again. The top-layer basket (tare weight was known) was filled with peanuts, weighed, and placed in the top of the drying column. Then the column was placed in the dryer and bolted at the bottom. The top layer basket was hooked to the load cell and then, the gap between the dryer column and the top section of the dryer was covered with the wooden collar. The PVC pipes which were used to sample air above the peanut bed were connected to the dryer. This procedure was repeated for dryers 1 and 2. The fan speed was set for 650 rpm in each dryer and heater controllers were set at 35 C. This test was conducted without recirculation. The experiments were started at 2000 hours on October, 06 , 1986. Duration of this test run was 60 hours. During this time interval, the following observations were made every four hours except at 0400 hours:

1. Static pressure readings below the peanut beds.
2. Dry bulb temperature of the air entering the peanut bed.
3. Dry and wet bulb temperatures of air leaving the top layers.
4. Ambient air dry bulb and wet bulb temperatures.

The following observations were recorded using a data acquisition system every 15 minutes.

1. Heat energy input.
2. Weight of the top layer baskets.

Due to malfunctioning of the data aquisition system, heat energy input for the first 12 hours could not be obtained. Weighing of the top layer baskets could not be carried out because of unexpected problems in the circuit.

At the end of the 60 hour period, dryer columns were weighed separately without baskets. Six peanut samples from each column were taken for final moisture content determinations. The top layer baskets were also weighed and three peanut samples were taken to determine the moisture content.

5.2.2. Test 2

Peanuts were removed from the controlled environment chamber and mixed before loading the dryers. Representative samples of peanuts in each column were taken for initial moisture determination. After preparing the dryers as given in the previous section, the drying experiments started at 1600 hours on October, 10, 1986. The fan speeds were set at 430 rpm. The opening of recirculating air doors were set for dryers 1 and 2 according to the schedule given in Table 5.1. Dryer 3 was run without recirculation for comparison purposes. The value of 'h' in Table 5.1 is the height of the unhinged edge of the door from the bottom surface of the duct as shown in Figure 5.1.

Heat inputs were collected and stored by the data acquisition system. The weighing of the top layer baskets was again not done. The duration of this test was 66 hours.

5.2.3. Test 3

This test was conducted by using another shipment of peanuts brought from Holland, Virginia. It arrived at the laboratory in the late evening on October, 16, 1986, and the drying started the following morning at 0800. The recirculation schedule given in Table 5.1 was repeated and the fans were set at 430 rpm. The duration of this test was 72 hours. Weighing of the top basket of dryer 3 was carried out, but weights of the other two baskets could not be recorded due to malfunctioning of the computer.

5.2.4. Test 4

This test was conducted by using peanuts from the second shipment. The procedure for this test run was exactly same as that of test 2. There were not enough peanuts for all three dryers; therefore, only dryers 2 and 3 were used. The fan speeds were set at 300 rpm. Dryers were started for this test at 2000 hours on October, 22, 1986. Dryer 2 was operated with the same recirculation schedule as before, while dryer 3 was run without recirculation. Duration of this test run 64 hours.

Table 5.1. Door position schedule used in tests.

Time	Height of the opening h (inches)		
	Dryer 1	Dryer 2	Dryer 3
0-24	6	8	-
25-48	4	6	-
49-72	2	4	-

5.3.0 Measurements in Drying tests

5.3.1 Wet Bulb and Dry Bulb Temperatures of Air Exiting the Peanut Bed

ASHRAE Standard 41-66 gives the procedure for dry bulb and wet bulb temperature measurements. Instrument accuracy for air dry bulb and wet bulb temperature should be ± 0.2 F for the dry bulb temperature range -20 to 140 F and wet bulb temperature range 0 to 90 F. Instrument precision for the given ranges should be ± 0.1 F. The thermister probes (Omega Type ON-910-44007) used in the experiments met these standards.

When measuring wet bulb temperature using mercury-in-glass thermometers and other sensing devices of similar diameter an air velocity of 700 to 2000 fpm, preferably near 1000 fpm, is recommended. For thermistors and thermocouples this velocity can be as low as 600 fpm. Cotton tubing of fairly soft, fine mesh weave is recommended as a suitable material for the wet bulb wick. The wick should be cleaned or replaced and the portion of the wick exposed to the air stream should extend one-half inch from the thermister bulb.

Since the air velocity above the peanut bed was low, an accurate reading of wet bulb temperature could not be taken by placing the thermister probe covered with a wick directly in the air stream. Therefore, a sampling duct shown in Figure 5.3 was constructed in all three dryers above the top layer baskets. A blower (Dayton model 1C939) rated at 60 cfm was used to circulate air from the area above the peanuts through the test section where the thermister probe was inserted.

Dry bulb temperature was measured by placing the thermister bulb in the middle of the air stream and measuring the resistance using an ohmmeter. The resistance was converted to temperature using the conversion formula for the thermister.

Wet bulb temperature was measured by placing the thermister bulb covered with a wetted wick in the middle of the air stream. At first, the resistance increased and reached a constant value for a short time, and then decreased. The constant value was the resistance corresponding to the wet bulb temperature.

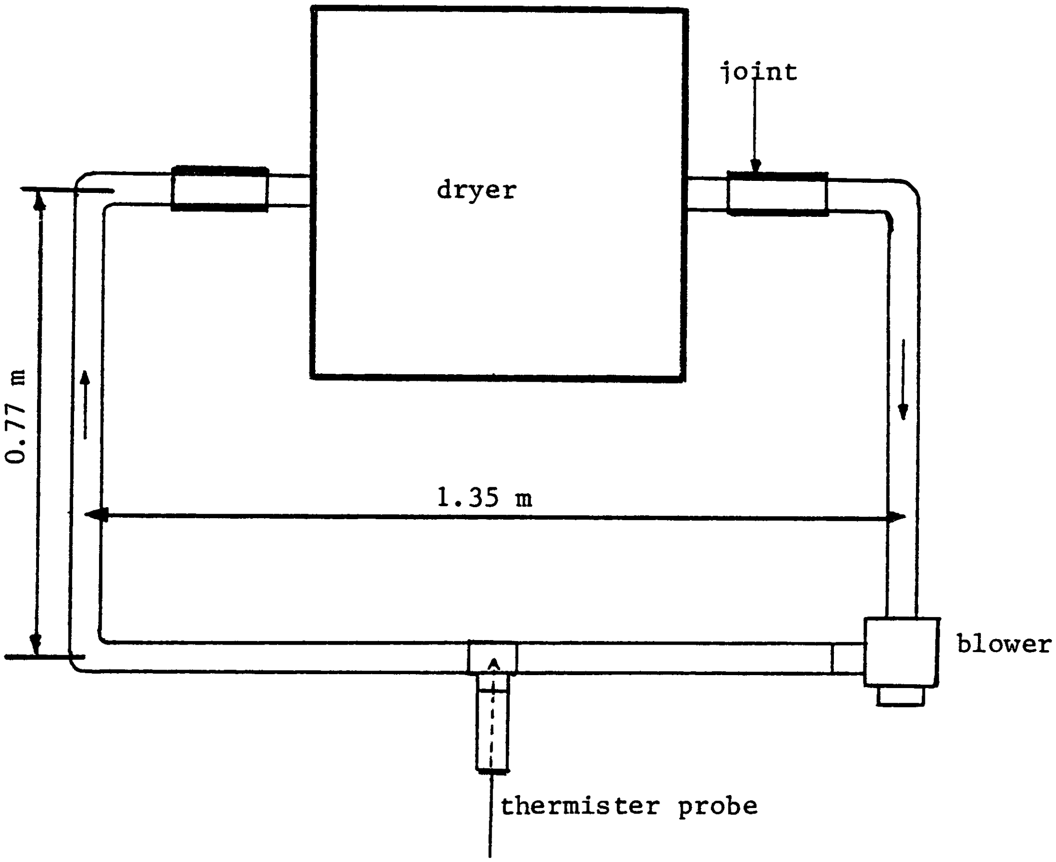

FIGURE 5.3. Sampling device to measure wet bulb and dry bulb temperatures of exiting air.

Ambient air temperatures were taken at a test stand between dryers 2 and 3 near the air inlets. To make the wet bulb measurements, a small blower was used to obtain the required airflow.

5.3.2. Heat Energy Measurements

A current transducer (Scientific Colombus Model CT510 A 2-2) was used to measure electrical energy input to the resistance heaters. The transducer produced a 0-1 mA output proportional to a 0-25 A input. The output current of the transducer was directed across a 1 $k\Omega$ resistor, and the voltage drop was recorded using the computer. The sampling rate was 128 samples per second and average of 10 seconds was taken. The computer logged this average value every 15 minutes.

5.3.3. Static Pressure Measurements

Static pressure beneath the peanuts was measured with an inclined manometer (Dwyer Model 400-5). The pressure was measured using a piezometer ring.

5.3.4. Moisture Content of Peanuts with Shells

Peanut samples were collected into paper bags and weighed. Tare weights of ten bags were obtained. Peanut bags were kept in a forced air oven at 105 C for 72 hours. Then the final weight of each bag was measured. Moisture content of peanuts were calculated from the weight loss.

5.4.0. Calibration of Vane-type Anemometers

5.4.1. Introduction

It is important to measure air flow rates in recirculation and main ducts with sufficient accuracy in order to use the thin layer drying model developed for peanuts. In the past, air flow rates in main ducts were determined using the fan curve and then recirculated air flow rates were calculated by applying mass balance equations. It was decided to measure these air flow rates directly to improve accuracy of predicted values from the model. Since vane-type anemometers are sensitive to very low air velocities and air flow rates involved in drying tests are quite low, a vane-type anemometer was chosen for this purpose. But, the anemometer should be calibrated beforehand for the range of air flow rates desired. For this purpose the configuration given in Figure 5.4 was used. This setup meets the AMCA standard 210-87. It consists of two duct sections, a flow straightener, variable supply fan, and a nozzle. The rpm of the anemometer for a given setting of the supply fan was read using a Hewlett Packard electronic counter, and the air flow rate was calculated by measuring the pressure drop across the nozzle. For low flow rates, the frequency counter did not read the rpm of the anemometer. Therefore, it was decided to measure the anemometer frequency using a micro-processor (SB 180). Application of the SB 180 has two advantages: (1) it measures cycles per second quite accurately, and (2) it can be used to create a data logger for flow measurements.

The signal from the amplifier which was connected to the anemometer was studied using the oscilloscope. Then, software necessary to measure frequency was developed and tested using a fan. Two nozzles (2.0 inch diameter and 3.0 inch diameter) were used in the test set up given in Figure 5.4. However, air velocity inside the duct was so low it did not move the anemometer blades. This was visually observed and confirmed by measurements. Therefore, either a larger nozzle was needed or the test set up would have to be changed to reduce the pressure loss in the duct. The anemometer started to rotate when a 4 inch nozzle was used. Therefore, 4-inch and 5-inch nozzles were used for the calibration.

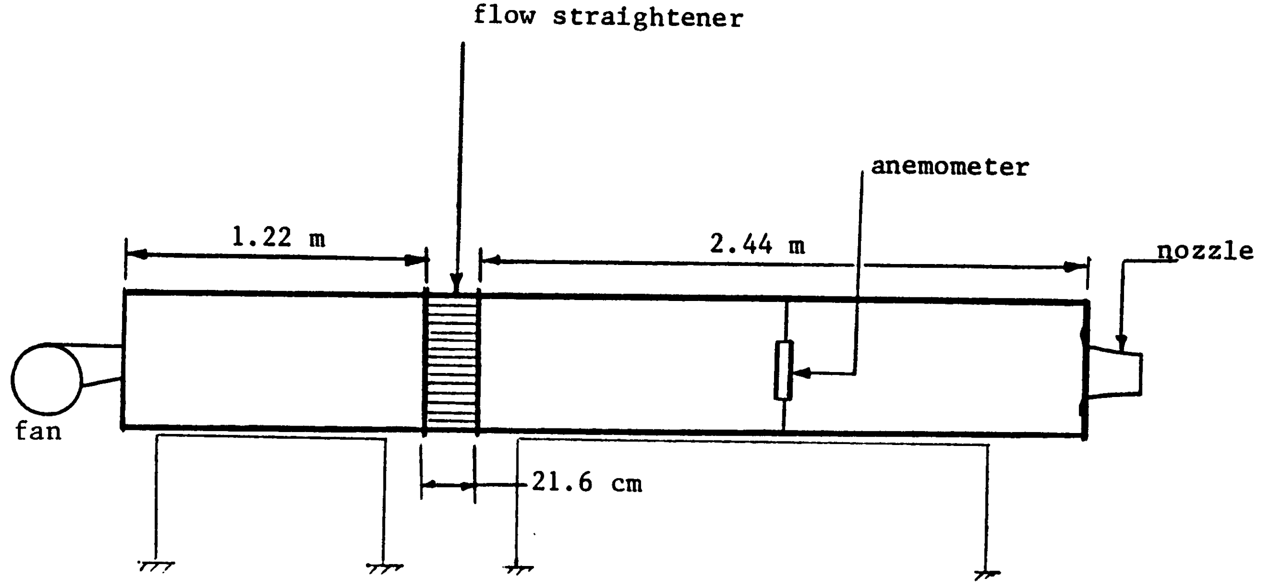

FIGURE 5.4. Test set up for calibration of anemometers.

5.4.2 Procedure and Observations

The amplifier output wire was connected to the channel 1 input wire of the scope and ground wires were connected. When the anemometer blades were rotated voltage pulses were observed.

The pulse amplitude was high when a blade was passed over the metal plate attached to the plastic base. The output is high on the leading edge of the plate and low on the other edge. The amplititude was approximately 3.5 volts. The period depended on the cycles per sec of the anemometer. For low frequencies, it was as high as 20 ms.

The SB 180 micro-processor was connected to the output signal of the amplifier through a digital I/O port device as shown in Figure 5.4a. Channel 8 of the I/O device was used to input data. A small program was written in Modula 2 to see whether two distinct numbers were read by the micro-processor when the output signal changed states (High or Low). It was observed that there were no intermidiate numbers between the two high and low numbers. A program named FLOWRATE.MOD was written to obtain the frequency and time. The program measures the time required for 100 revolutions of the anemometer and calculates the rpm. This program was tested using generated air flow rates. An appropriate number for wait loops was chosen by trial and error. It was determined that by using any number below 50 gave the same result for the same flow. The time lag given by the wait loop must be small enough to avoid skipping any jumps or falls at the highest frequency to be measured. Five wait loops were used to measure very high frequencies.

The calibration test set up shown in Figure 5.4 was prepared and the anemometer was installed in the center of the air stream. Two nozzles (4 inch and 5 inch) were used. A micro-manometer (Dwyer, microtector) was used to measure pressure drop across the nozzle and static pressure inside the duct. A thermistor probe was used to measure ambient temperature and wet-bulb temperature of the air. These data were used to calculate the air flow rate through the nozzle.

For a given setting of the fan speed, the flow rate through the duct was obtained and average rotational speed of the anemometer was stored in the computer. By varying the fan speed from the lowest value to the highest value, data points necessary for calibration curves

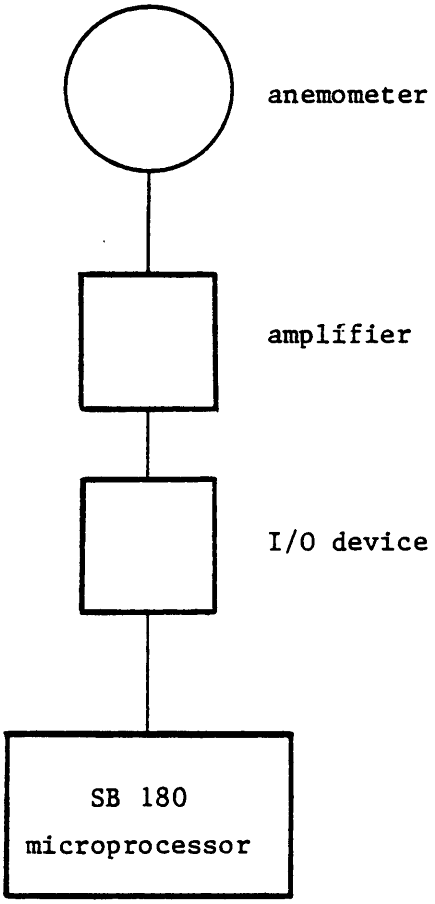

FIGURE 5.4a. Schematic diagram for the rotational speed measurements of the anemometers.

were obtained. This procedure was repeated to calibrate four different vane type anemometers.

The calibration curves were obtained by statistically analyzing the data. The analyses and the calibration curves for two anemometers are given in Appendix B.

5.4.3 Errors

The errors introduced in this experiment are (a) flow rate measurement error from the nozzle, and (b) measurement error in the anemometer. Since only pulses are counted, error from the amplifier does not have an effect. The measurement error of the nozzle affects the output error through the calibration curve. The error analysis can be simplified to find standard deviation for a number of flow rate data (N). The mean value is assumed as the 'true' value and error as three times the standard deviation.

5.5. *Fan Testing*

The test setup shown in Figure 5.5 was prepared to obtain the fan curves of the fans used in peanut drying at 650, 430 and 300 rpms. The fans used in three dryers were identical. Therefore, dryer 3 was used to build the test setup which met the AMCA standard 210- 87.

A unit consisting of two perforated plates which can be moved relative to each other was used to simulate the resistance of peanuts. First, fan speed was set at a desired value. Then at a particular position of the plates, static pressure below the plates, pressure drop across the nozzle and static pressure below the nozzle were obtained. Pressure measurements were taken using a micromanometer (Dwyer, microtector) which had an accuracy of ± 0.0254 mm of water. Dry bulb and wet bulb temperatures of air were measured. By changing the relative position of the plates, another set of readings could be taken. The values obtained were checked for repeatability. These readings were used to calculate flow rates. Graph of flow rate vs static pressure of the fan for the particular speed was drawn. This procedure was repeated to obtain fan curves for the three different speeds. The fan curves for the three rpms are given in Figures 5.6, 5.7 and 5.8.

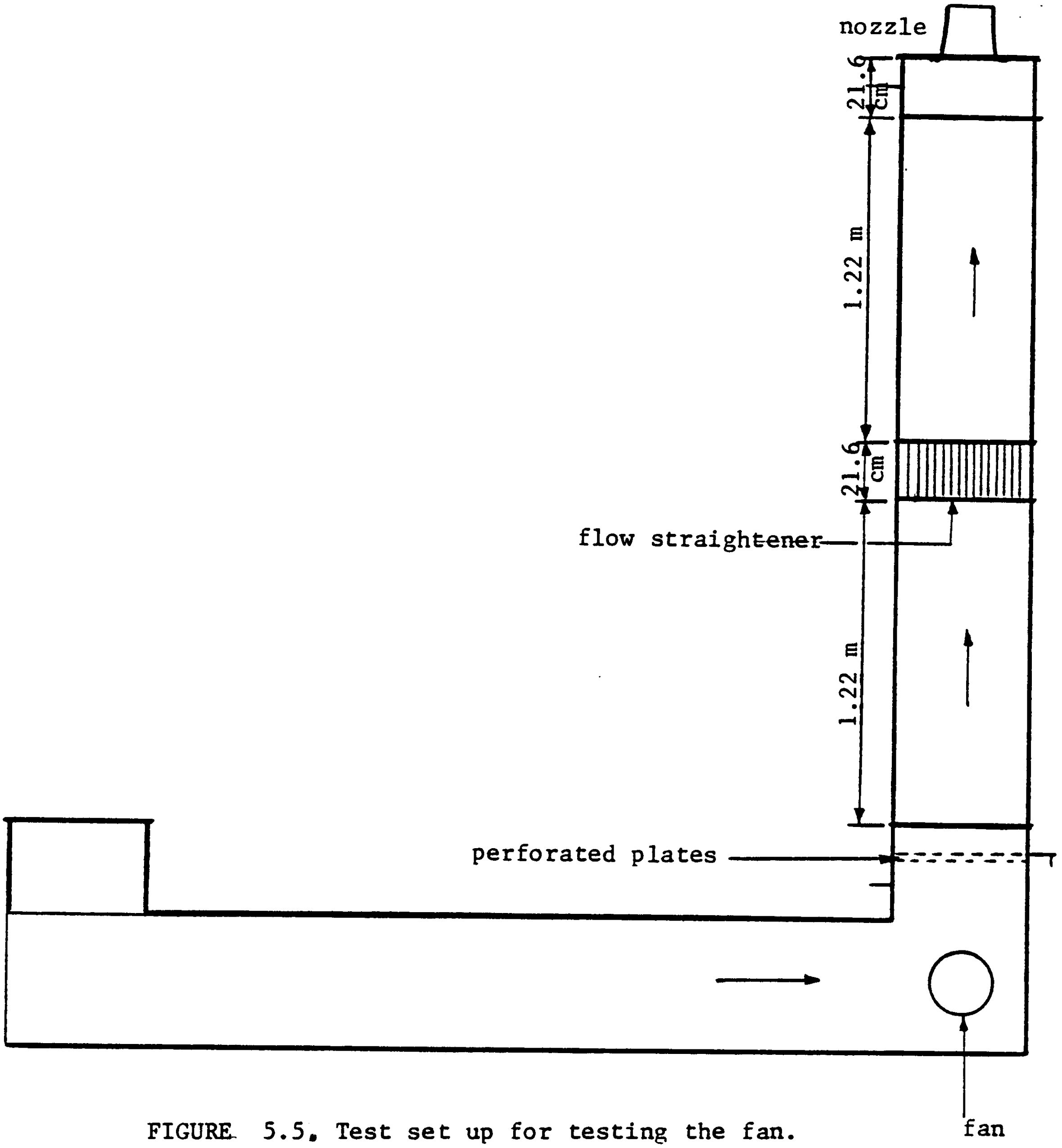

FIGURE 5.5. Test set up for testing the fan.

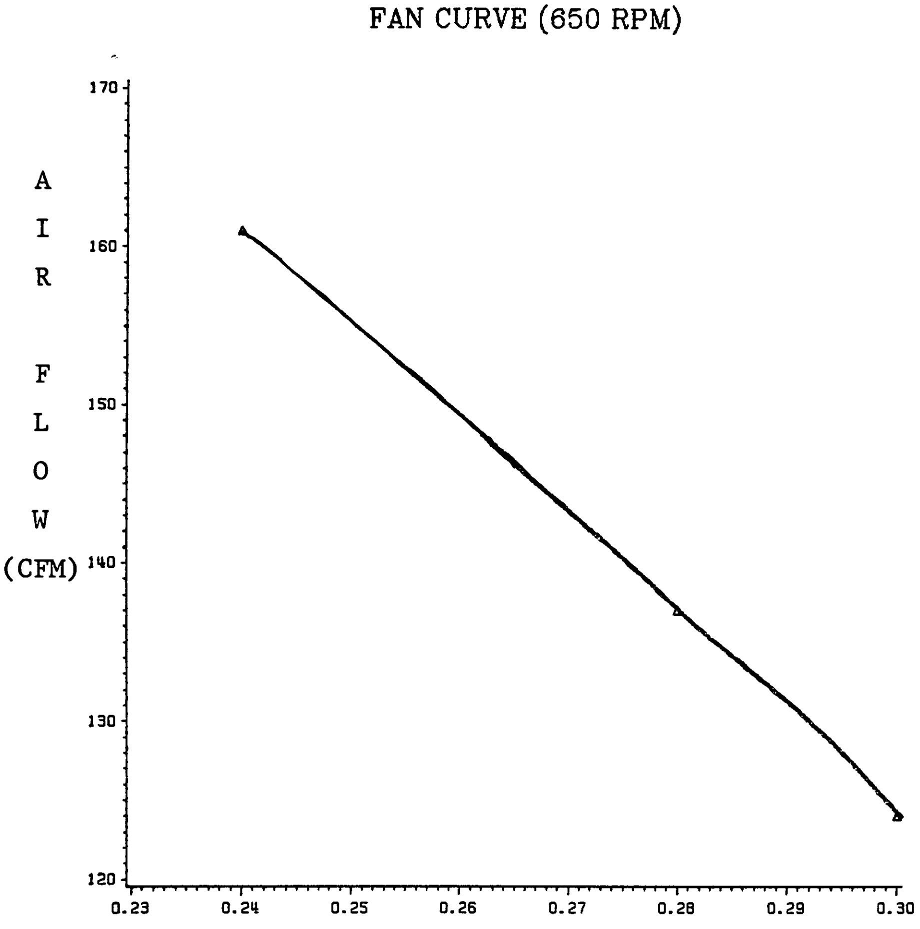

FIGURE 5.6. Variation of air flow with static pressure of the fan at 650 rpm.

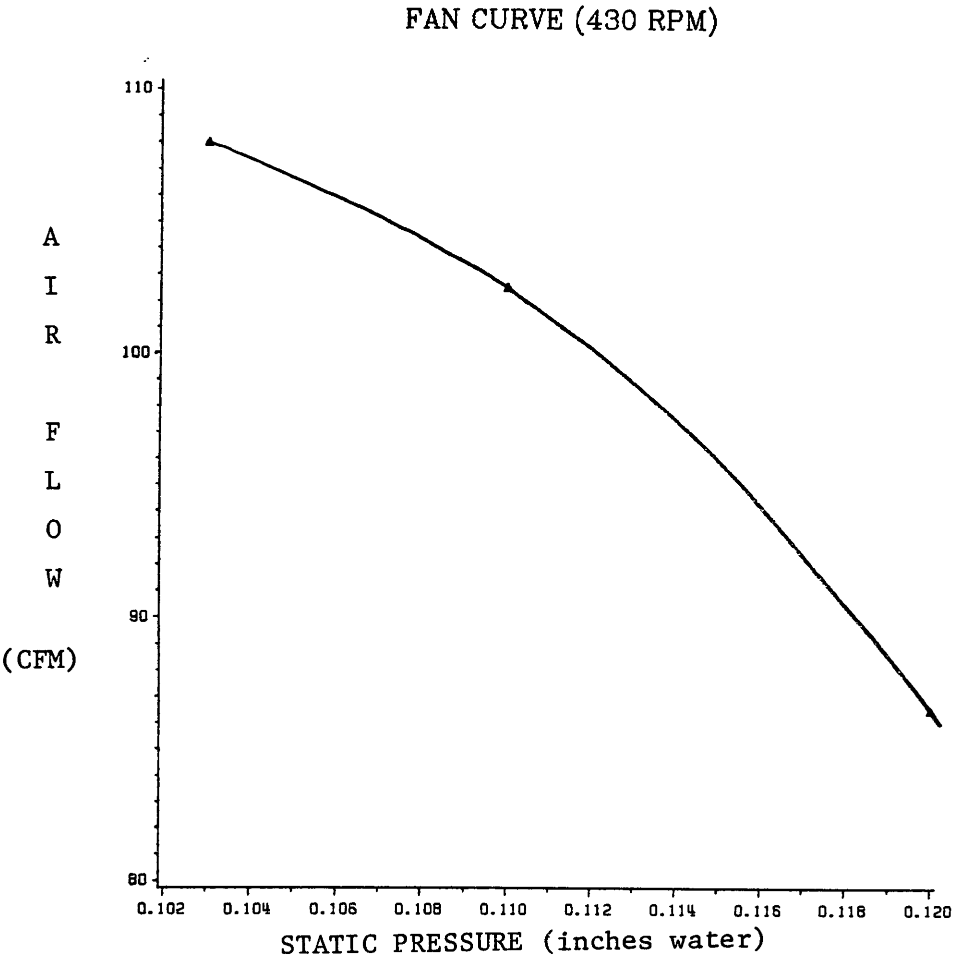

FIGURE 5.7. Variation of air flow with static pressure of the fan at 430 rpm.

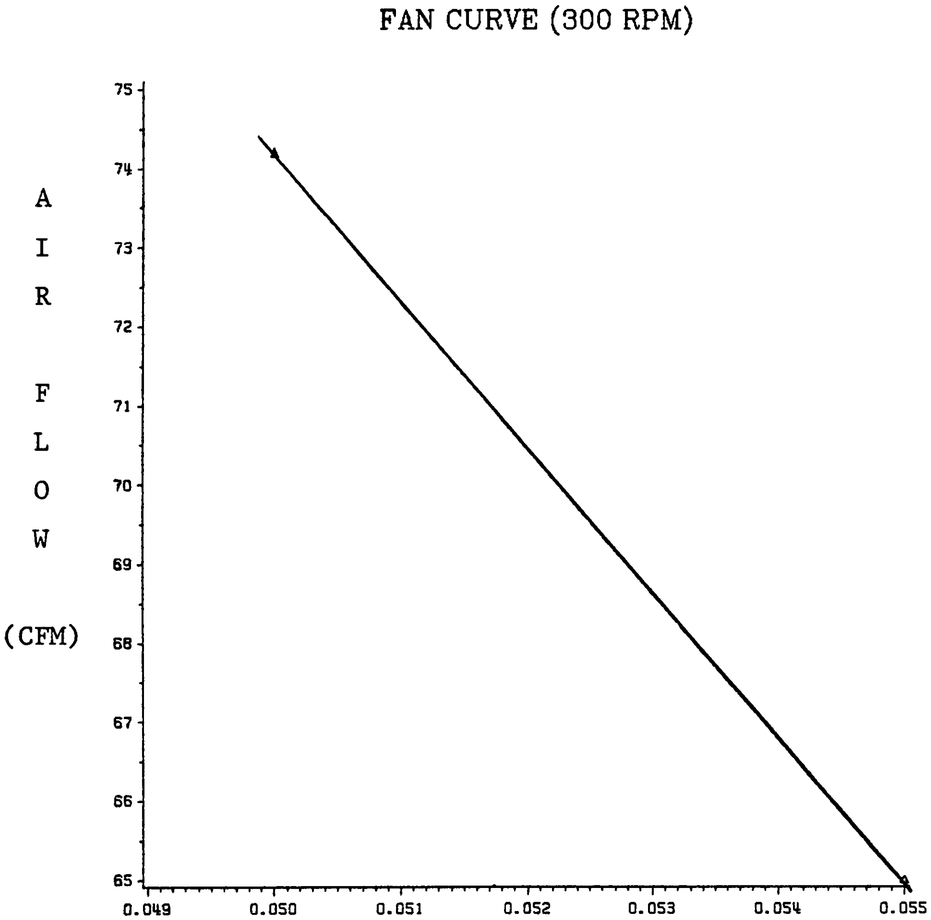

FIGURE 5.8 Variation of air flow with static pressure of the fan at 300 rpm.

Chapter 6. Results and Discussion

The data obtained from the eleven drying experiments were analyzed using the drying model and energy balance model. In test 1, all three dryers were run without recirculation of the exiting air. In the other tests, dryer 3 had no recirculation and served as a check for the other dryers. Hence, there were five experiments without recirculation. These experiments were used to verify the peanut drying simulation model. Energy saving potential of the two strategies was investigated by comparing dryer 3 results with the other two dryers.

6.1 Air Flow Curves

Three fan speeds (650 rpm, 430 rpm, and 300 rpm) were employed in drying tests. For these three fan speeds, fan curves were obtained experimentally as described in the previous chapter. The fan characteristics were assumed to be similar for all three fans at the same speed. The Statistical Analysis System (SAS) was used to find the best model for each fan curve. At 650 rpm, the following model represents the graph of air flow (cfm) vs. static pressure (inches of water) quite adequately.

For $0.240 \leq p \leq 0.300$,

$$Q = 227.065 - 1144.63p^2 \qquad [6.1]$$

where,

Q = Air flow (cfm)

p = Static pressure (inches of water)

The coefficient of determination (R^2) of this model is 0.9997 and is valid only for the given range of static pressure. At $p=0.270$, an error of 0.01 inches water in static pressure will cause ± 6.0 cfm change in air flow or an error of 4 percent at $p=0.270$.

For a fan speed of 430 rpm, the following model was obtained using SAS.

For $0.100 \leq p \leq 0.120$,

$$Q = 178.3836 - 6304.1415p^2 \qquad [6.2]$$

The notation is the same as in equation 6.1 and the coefficient of determination for this model was 0.9903. At $p=0.110$, an error of 0.01 inches of water static pressure will cause ± 14 cfm change in air flow which is an error of 13.5% at $p=0.110$.

For a fan speed of 300 rpm, the following linear model was found to be sufficiently accurate to model the flow within the narrow range of static pressure, $0.050 \leq p \leq 0.055$, observed during test 4.

$$Q = 166.2 - 1840.0p \qquad [6.3]$$

An error of 0.01 inches of water in static pressure will cause an error of 28% in the predicted air flow.

It should be noted that as the fan speed decreases, accuracy of measurement of static pressure becomes more important. It was observed during test 1 that the major factor affecting the static pressure was gradual reduction in fan speed. Therefore, the fan speeds were checked from time to time and adjusted to the original value during the tests.

Equations 6.1, 6.2 and 6.3 were used in the peanut drying model.

6.2 Determination of Recirculation Percentages

The amount of recirculated air is controlled by the position of the hinged door at the bottom of the vertical recirculating duct. It was planned to measure recirculated air flow rate by installing vane type anemometers in the recirculating ducts. Unfortunately, after calibrating the anemometers, it was found that the air speeds in the return duct were too low to be measured by the anemometers. The moisture balance procedure to determine recirculating percentages uses the psychrometric chart as shown in Figure 6.1. A_1 is ambient air humidity ratio which can be located using measured dry bulb and wet bulb temperatures. A_2 is humidity ratio of the exiting air. Therefore, the recirculation percentage is given by

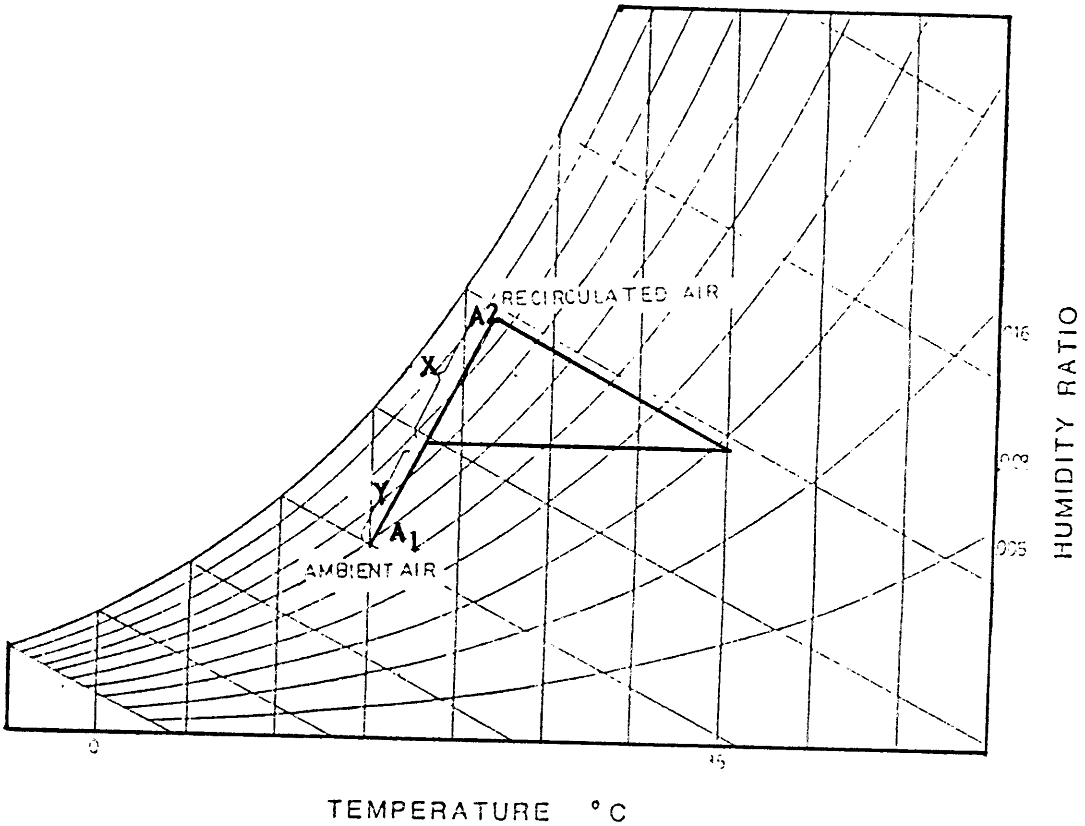

FIGURE 6.1. Determination of the recirculation percentage.

$$p = 100\frac{X}{X + Y}. \qquad [6.4]$$

For this equation to be valid, drying should be adiabatic. A slight change in humidity ratio of exiting air can cause a large change in p because X and Y are numerically small values. It was found that for a fixed position of the door, recirculation percentage calculated with equation 6.4 varied with time. Then assigning a single value for a particular door position is impossible. The recirculated air flow rate depended on (a) hinged door position, (b) positive pressure of exiting air, and (c) pressure drop across the recirculating duct. For the purpose of this analysis the recirculation percentages given in Table 6.1 were assumed to be correct for the two schedules. These values are based on most likely values calculated for a given door position, and it is assumed that the amount of recirculation is solely dependent on the relative position of the door. Schedule 1 was used for dryer 1 in tests 2 and 3, and schedule 2 was used for dryer 2 in tests 2 and 3. No recirculation was done in dryer 3.

Table 6.1. Recirculation percentages used in the analysis.

hour	schedule 0	schedule 1	schedule 2
0-24	0	40	25
25-48	0	60	40
49-72	0	75	60

6.3 Verification of the Drying Model

The computer program written for the peanut drying simulation model was run using prepared data files for all experiments. Cundiff et al. (1983) suggested that the break point moisture ratios in the Troeger model should be 0.20 and 0.70 for Virginia type peanuts rather than 0.12 and 0.40. Therefore, both these break points were used to compare predicted values. The peanut bed depth was 1.22 m and it was divided into 12 layers which gives a layer thickness of 0.101 m. There were no signifcant differences in predicted values by increasing the number of layers beyond 12. The initial peanut temperature was assumed to be equal to the ambient temperature at the start of an experiment.

6.3.1 Analysis of Simulation Results for Test 1

The three dryers were run without recirculation. The initial moisture content was 21.7 percent (w.b.) and some important input and output values are given in Table 6.2. The Troeger model predicted the final average moisture content more accurately with the break points at 0.20 and 0.70 than at 0.12 and 0.40. The calculated weights of water removed agreed well with the measured weights of water removed in all three dryers. Air flows were calculated within the model equation 6.1. A slight descrepancy in air flow can be expected when this equation is applied to the other two dryers. Solids losses were below 5 percent which is typical for agricultural materials.

The largest differences between the predicted values and the measured values occur in dry bulb temperature of exiting air. Figure 6.2, 6.3 and 6.4 show graphs of measured and predicted dry bulb temperatures of exiting air vs. time (h), and ambient temperature vs. time. It was thought that the exiting air lost heat while being sent through the pipe loop used to achieve sufficient velocity to measure the wet bulb temperature accurately. Dry bulb temperature was measured at the same location as wet bulb temperature. This pipe was 3.6 m long and the thermal conductivity of rigid pvc was 0.158 $\frac{W}{m-K}$. The air velocity in this pipe loop was 396 m per min (measured using a hot wire anemometer), which is ideal for accurate

Table 6.2. Some important parameters of test 1.

	Dryer 1	Dryer 2	Dryer 3
Initial moisture content (% w.b.)	21.7	21.7	21.7
Average air flow (m^3/min/m^3)	12.43	13.24	12.85
Initial peanut temperature (°C)	18.0	18.0	18.0
Initial bulk density of peanuts solids (kg/m^3)	221.11	221.11	221.11
Measured final moisture content (% w.b.)	5.37	5.80	5.57
Duration of drying (hr)	60.0	60.0	60.0
Predicted final moisture content (% w.b.) (1) break points 0.12 and 0.40 (2) break points 0.20 and 0.70	 7.40 5.70	 7.70 5.70	 7.50 5.80
measured weight of water removed (kg)	15.01	14.68	14.82
Solids loss (%)	3.05	2.75	1.94

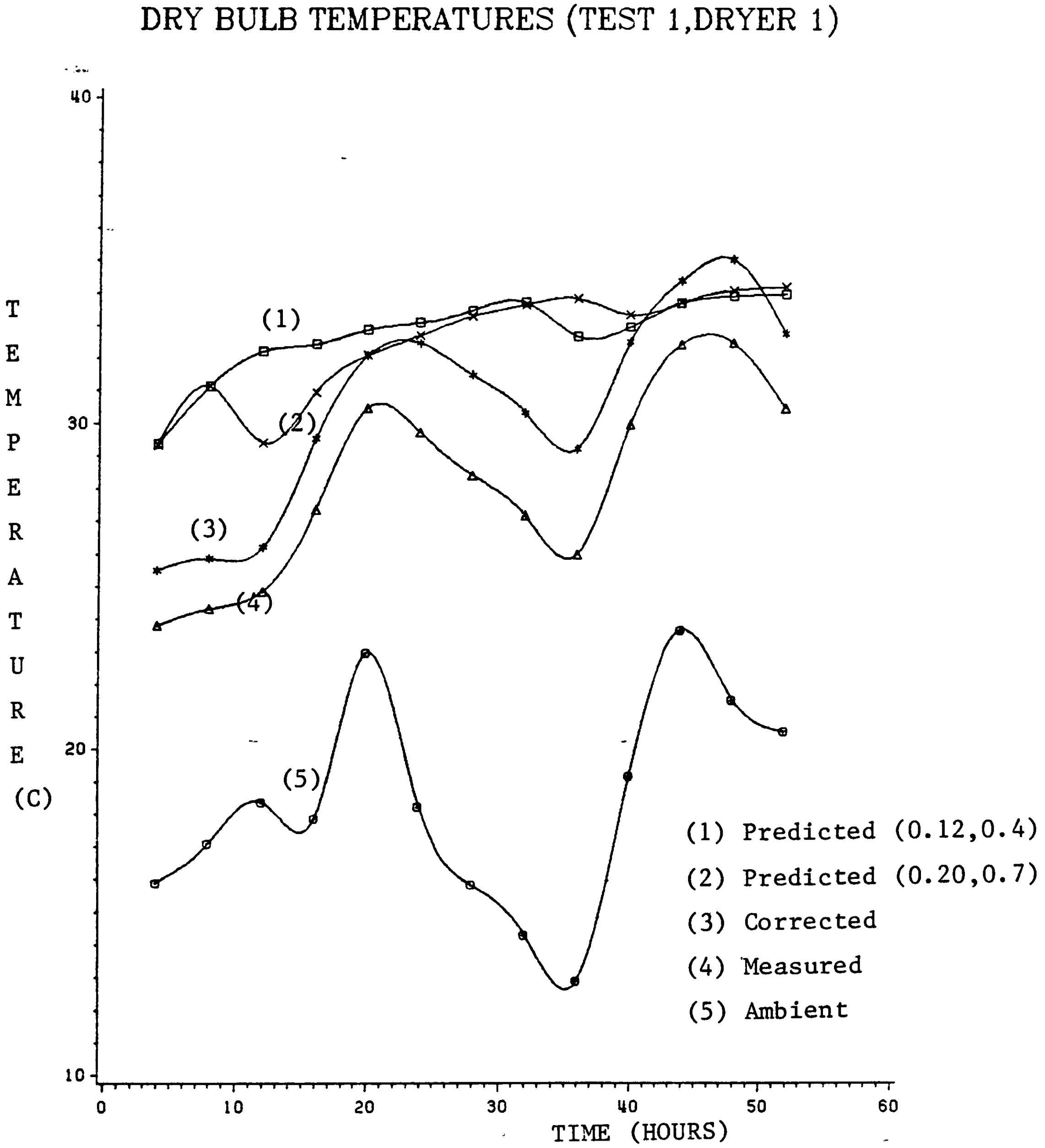

FIGURE 6.2. Variation of the Dry bulb temperature of Exiting Air and Ambient temperature with Time (Test 1, Dryer 1).

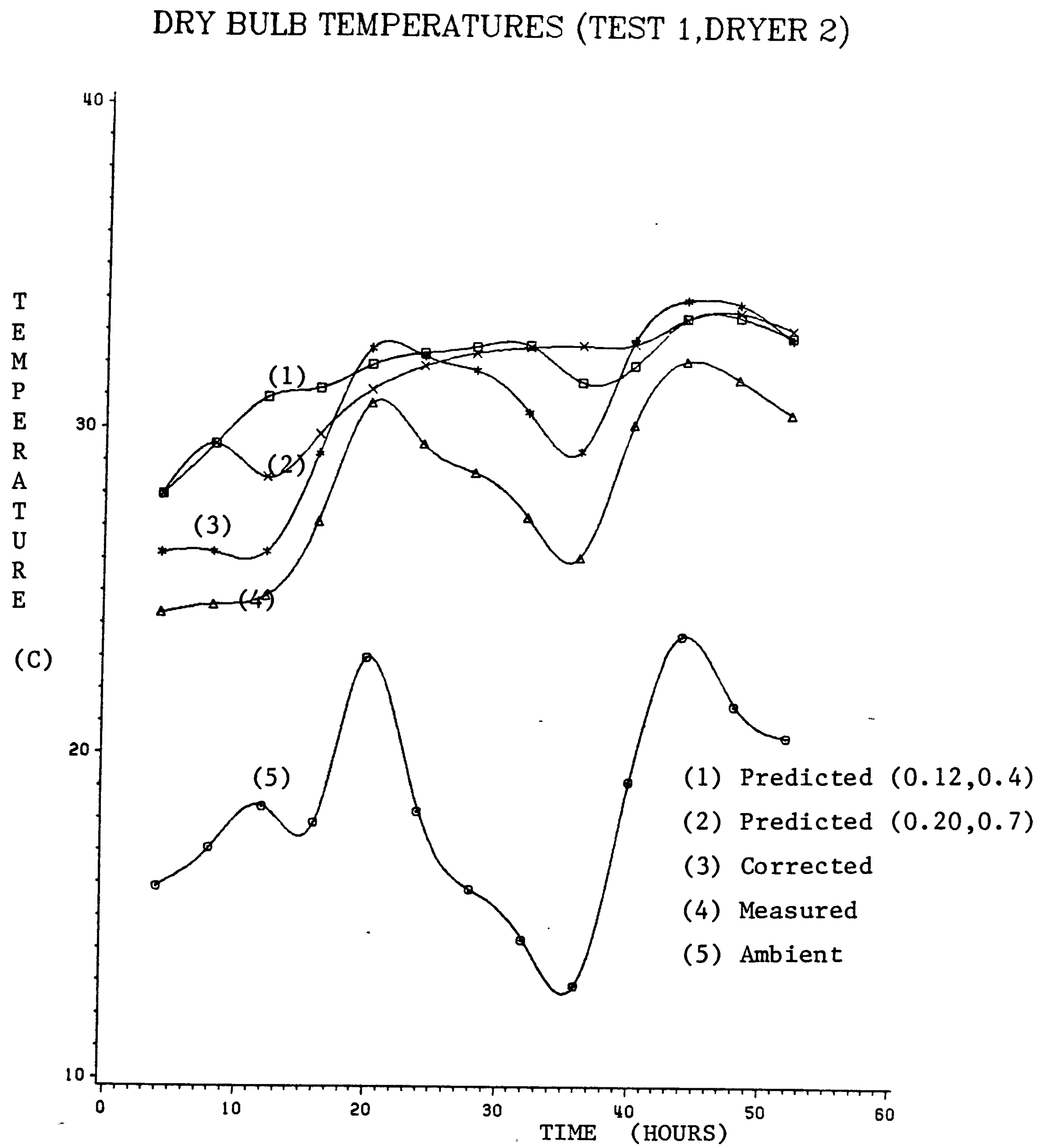

Figure 6.3. Variation of the Dry bulb temperature of Exiting Air and Ambient temperature with Time (Test 1, Dryer 2).

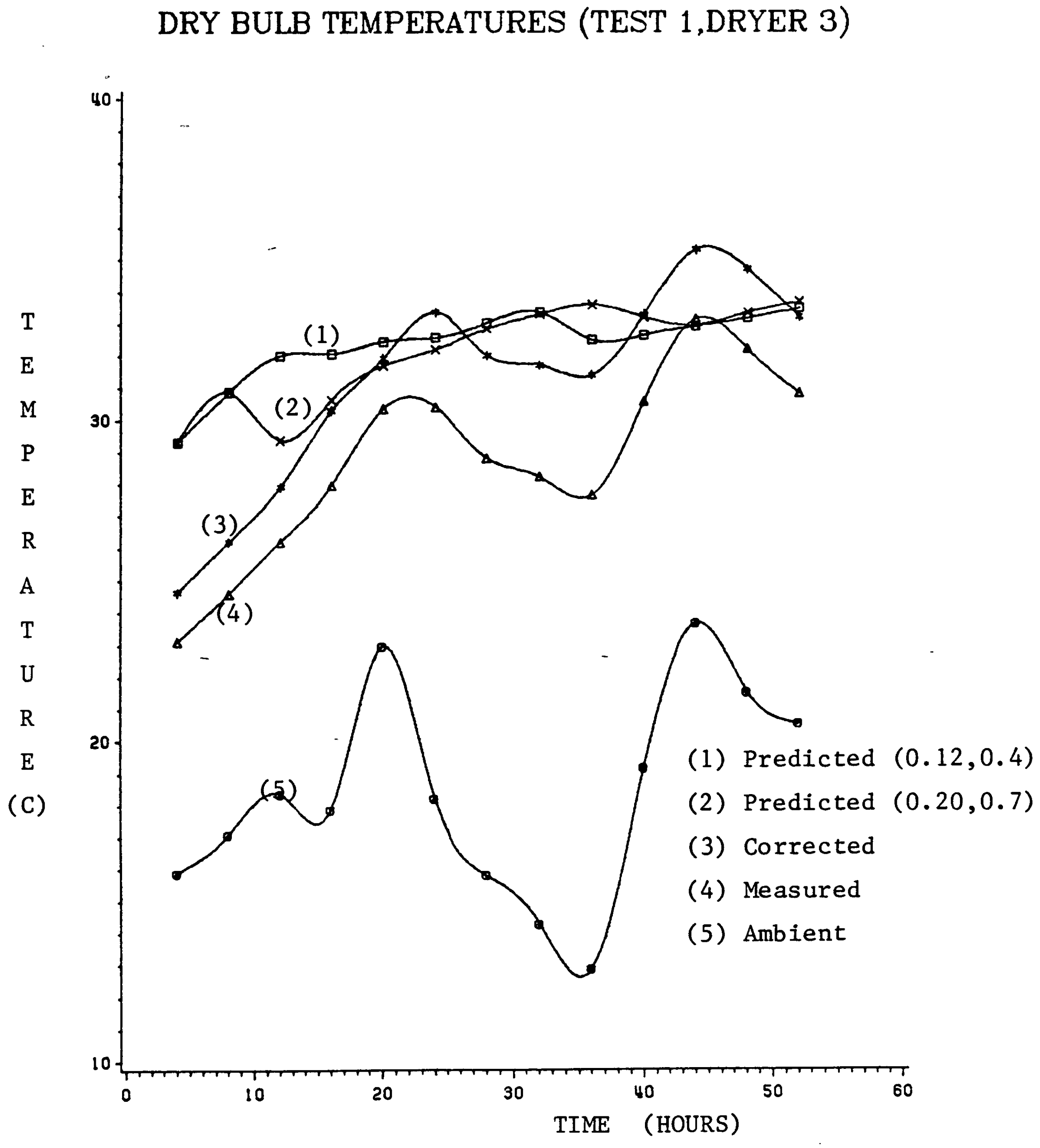

Figure 6.4. Variation of the Dry bulb temperature of Exiting Air and Ambient temperature with Time (test 1, Dryer 3).

wet bulb temperature measurements. The heat transfer mechanisms involved are thermal conduction and free convection. A heat transfer model was developed to correct measured dry bulb temperatures and is given in Appendix C. The corrected dry bulb temperatures are shown in Figures 6.2, 6.3, and 6.4. The average correction for the measured values was 3.0 C. From these figures the following remarks can be made.

1. The largest differences between predicted and corrected dry bulb temperatures occured during the first 16 hours of drying.

2. The graphs of corrected dry bulb temperature vs time had the similar pattern as the graph of ambient air vs time. Predicted values did not show the same pattern.

3. Changing the break points of the Troeger model from 0.12 and 0.40 to 0.20 and 0.70, respectively, gave improved results.

Figure 6.5 gives the relative humidity of exiting air based on measured dry bulb and wet bulb temperatures vs time. Figure 6.6 gives the predicted relative humidity values of exiting air for the three dryers. There was a rapid decrease in relative humidity of exiting air within the first 16 hours. The measured relative humidity dropped from 75 percent to 27 percent during this period. Then it remained low, around 30 percent, despite the changes in ambient relative humidity. The predicted relative humidity dropped from 60 percent to 19 percent during the first 10 hours. The predicted values were about 20 percentage points less than the experimental relative humidity values during the first 12 hours. The graphs of relative humidity of exiting air suggest that most drying took place during the first 16 hours. In other words, exiting air has a high drying potential for the rest of the drying period.

In the simulation model, the humidity ratio of air exiting the ith layer is calculated by writing a moisture balance for the layer. For some ith interval,

$$H_{exi} - H_{ei} = m_p \frac{(M_i - M_{i-1})}{\Delta m_{dai} \Delta t} \qquad [6.5]$$

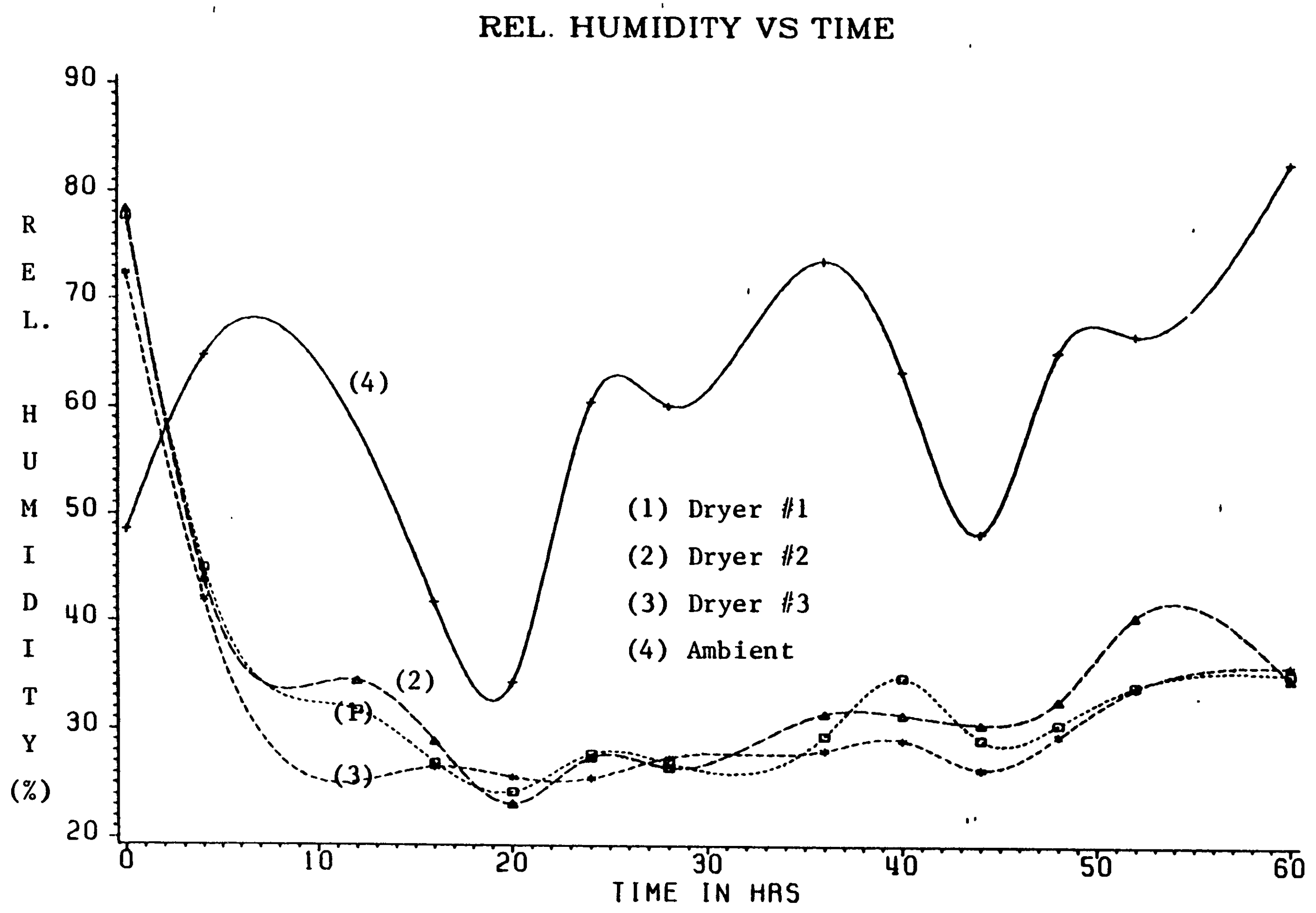

FIGURE 6.5 Variation of Relative Humidities of Exiting Air and Ambient Air with Drying Time (TEST 1).

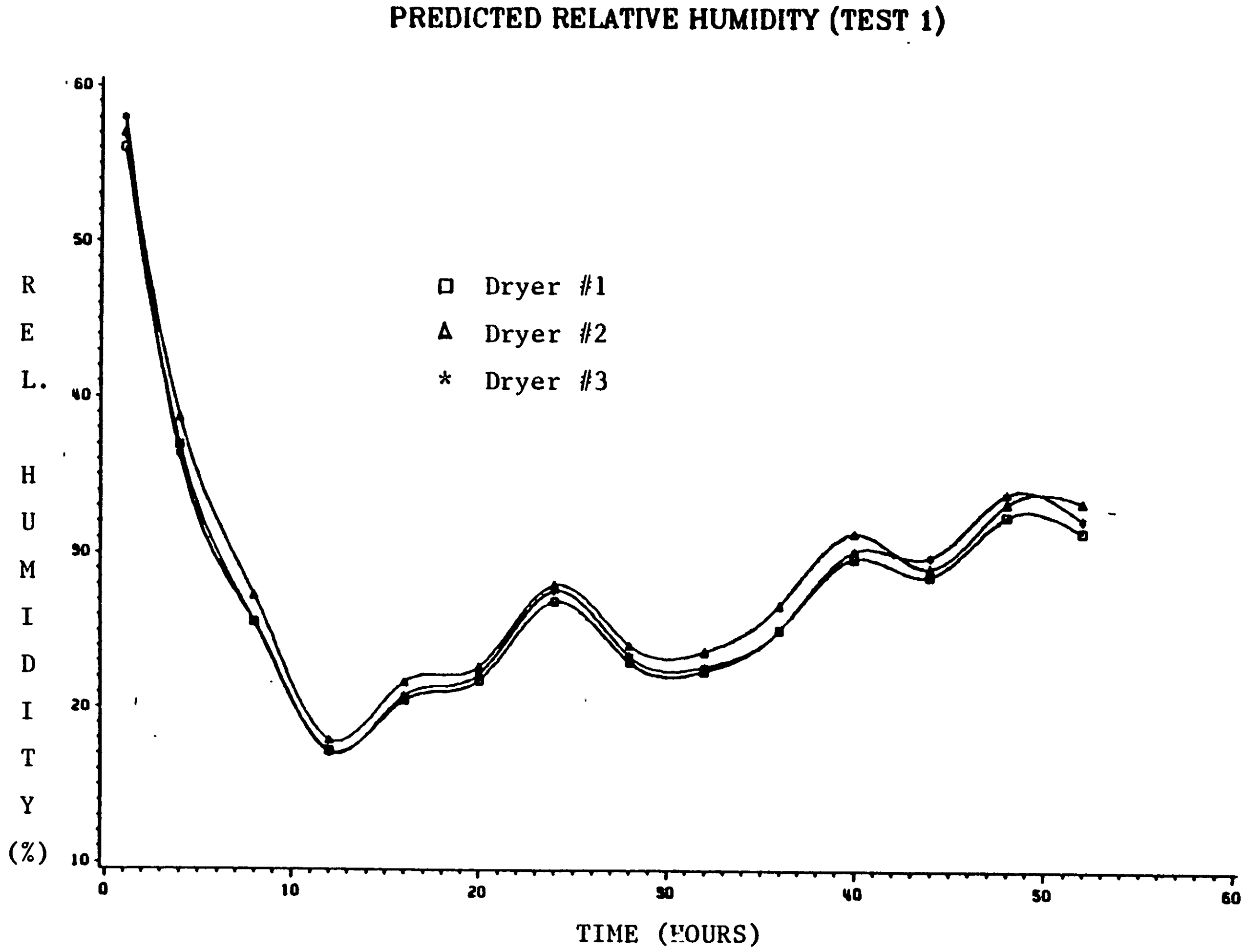

FIGURE 6.6 Relative Humidities of Exiting Air Predicted by the Model (TEST 1).

where,

H_{ei} = humidity ratio of entering air,

H_{ζ} = humidity ratio of exiting air,

M_i = moisture content (d.b.) of peanuts,

m_p = mass of peanut solids in a layer,

and,

Δm_{dai} = mass flow of dry air during the ith interval.

From equation 6.5, it is seen that for a given air flow and humidity ratio of entering air, the humidity ratio of the exiting air depends on the rate of moisture release of peanuts in that layer. If the rate of moisture release is high, then the exiting humidity ratio is high and vice versa. The rate of moisture release is calculated from the Troeger model.

The dry bulb temperature of exiting air from a layer is obtained by writing an energy balance. The resulting equation for the dry bulb temperature of exiting air is given below.

$$T_{exi} = \frac{\{h_{ei} - 4.1868 H_{exi} T_{dpxi} - h'_{fgi} 10^{-3} + 1.8756864 H_{exi} T_{dpxi} - Q_{si} - Q_{pi}\}}{(1.0069254 + 1.8756864 H_{exi})} \qquad [6.6]$$

where,

h_{ei} = enthalpy of the air-water mixture entering the jth layer during the ith interval

T_{dpxi} = dew point temperature of exiting air

H_{exi} = exiting humidity ratio

Q_{si} = structural heat loss during the ith interval

Q_{pi} = heat gain by peanuts during ith interval

and $h'_{fgi} = 2.5025353\text{x}10_6 - 2.385764\text{x}10^3 T_{dpxi}$

Substituting the expression for h'_{fgi} in equation 6.6 gives,

$$T_{exi} = \frac{\{h_{ei} - 2.5025353\text{x}10^3 H_{exi} - 0.074648 T_{dpxi} - (Q_{si} + Q_{pi})\}}{(1.0069254 + 1.8756864 H_{exi})} \qquad [6.7]$$

From simulation results it was observed that the maximum dew point temperature was well below 20 C and the minimum humidity ratio was about 0.005. Substituting these values gives,

$$(0.074648T_{dpxi})_{\max} = 1.49$$

,

and

$$(2.5025353x10^3xH_{exi})_{\min} = 12.51.$$

Therefore, $2.5025353x10_3xH_{exi} > 0.074648T_{dpxi}$.

The structural heat loss and the sensible heat gain of peanuts are both very small compared to enthalpy terms. For a given enthalpy of entering air, the humidity ratio of exiting air plays a dominant role in determining the dry bulb temperature of exiting air. For a given entering air condition, if the actual rate of moisture release is higher than the moisture release predicted by the Troeger model, then the actual exiting humidity ratio is higher than the predicted exiting humidity ratio. According to equation 6.7, a higher exiting humidity ratio gives a lower actual dry bulb temperature. The graphs of dry bulb temperatures vs time suggest that during the initial period of drying, the rate of moisture release predicted by the Troeger model is less than the actual rate of drying.

Figure 6.7 shows the graphs of measured exiting humidity ratios vs time for the three dryers along with the ambient humidity ratio. It should be noted that exiting humidity ratio followed the pattern of ambient air after the first 15-20 hours of drying because the peanuts were releasing less moisture.

Figure 6.8 shows wet bulb temperature of exiting air for dryer 3 along with the ambient wet bulb temperature. The discrepancy between the predicted and measured wet bulb temperatures are high during the first 12 hours of drying. This discrepancy was due to differences between predicted moisture removal and actual moisture removal from the peanuts during this period.

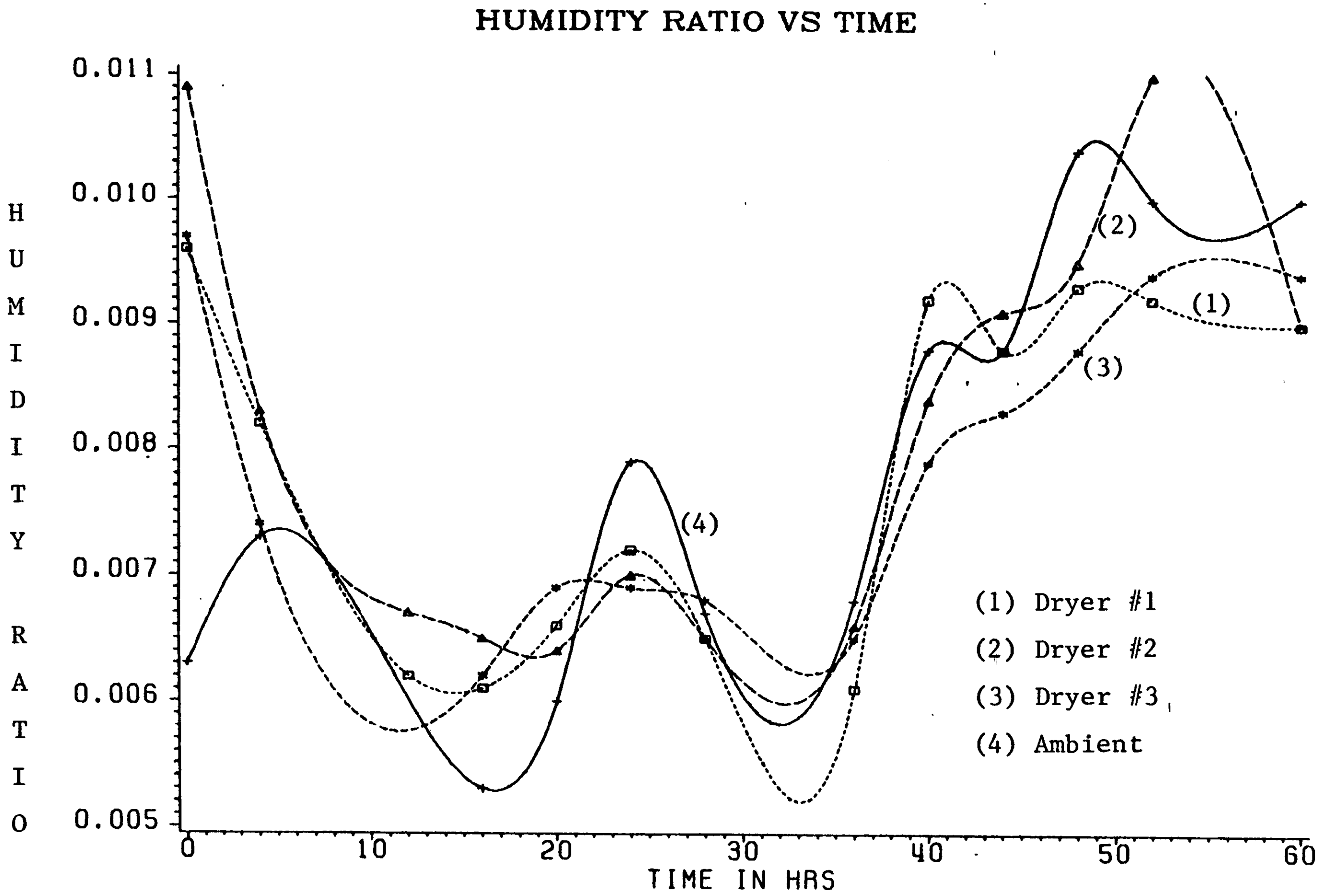

FIGURE 6.7 Variation of Humidity Ratios of Exiting Air and Ambient Air with Drying Time (TEST 1)

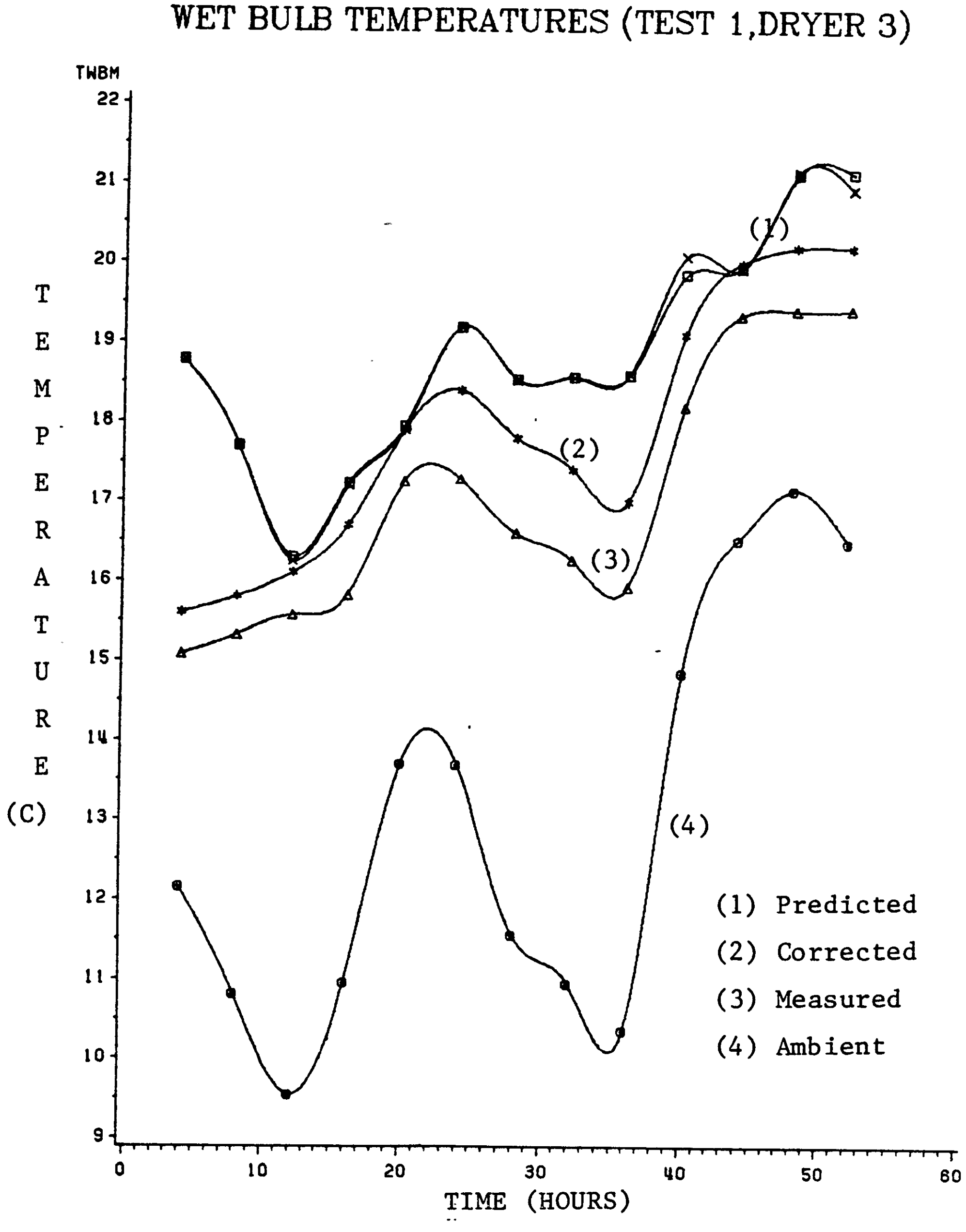

FIGURE 6.8 Variation of wet bulb temperature of exiting air and ambient air with time (Test 1, Dryer 3).

6.3.2. Analysis of Simulation Results of Test 2

In the test 2, dryers 1 and 2 were run employing the recirculation schedules 1 and 2, respectively. Fan speeds were 430 rpm and the average initial moisture content of peanuts was 15.89 percent (w.b). A summary of some input and output values are given in Table 6.3. The air flows employed were about 40 percentage points less than the air flows used in test 1. Therefore, a longer period of effective drying was expected. This extended drying time can be seen in Figure 6.9 and Figure 6.10. Figure 6.9 shows relative humidity of exiting air calculated from the measured dry bulb and wet bulb temperatures and Figure 6.10 shows the humidity ratio of exiting air. The overall drying rate was very low after about 30 hours of drying in all three dryers. The overall drying rate can be low when the drying rate is quite high in top layers and wetting occurs in the bottom layers. As in the case of test 1, the difference between predicted dry bulb temperatures and measured dry bulb temperatures was large in the first 30-40 hours of drying as shown in Figure 6.11. This result also shows that the Troeger model under predicts moisture release rate in the early part of drying. The Troeger model with break points 0.20 and 0.70 gave improved predictions for dry bulb temperature.

6.3.3 Analysis of Simulation Results of Tests 3 and 4

Test 3 was a repetition of test 2 with peanuts having an initial moisture content of 26.9 percent (w.b.). During this test, the weight of the top layer basket in dryer 3 was measured with time. Since the initial moisture content was high, exiting air relative humidity in dryer 1 remained above 70 percent for near 20 hours at the beginning as shown in Figure 6.12. The dryer 1 has the highest recirculation percentage. Drying potential of exiting air was quite high after about 40 hours. Table 6.4 gives some important parameters in this test. The average solids loss percentage for the three dryers was 6.21 percent which was higher than the other tests. As seen in Figure 6.14, drying of the top layer of peanuts in dryer 3 (without recirculation) started seven hours after the beginning of the experiment. During this period, the equilibrium moisture content corresponding to the relative humidity of drying air must have been higher than the actual moisture content of peanuts. Once started, drying occured at

Table 6.3. Some important parameters of test 2.

	Dryer 1	Dryer 2	Dryer 3
Recirculation schedule	1	2	0
Initial moisture content (% w.b.)	15.04	16.85	15.77
Average air flow (m^3/min/m^3)	6.85	7.16	8.38
Initial peanut temperature (°C)	15.0	15.0	15.0
Initial bulk density of peanuts solids (kg/m^3)	240.0	234.89	237.94
Measured final moisture content (% w.b.)	5.44	6.04	5.62
Duration of drying (hr)	66.0	66.0	66.0
Predicted final moisture content (% w.b.) (1) break points 0.12 and 0.40 (2) break points 0.20 and 0.70	 6.3 -	 6.9 -	 6.3 5.2
measured weight of water removed (kg)	8.92	9.43	9.37
Solids loss (%)	4.12	2.44	2.37

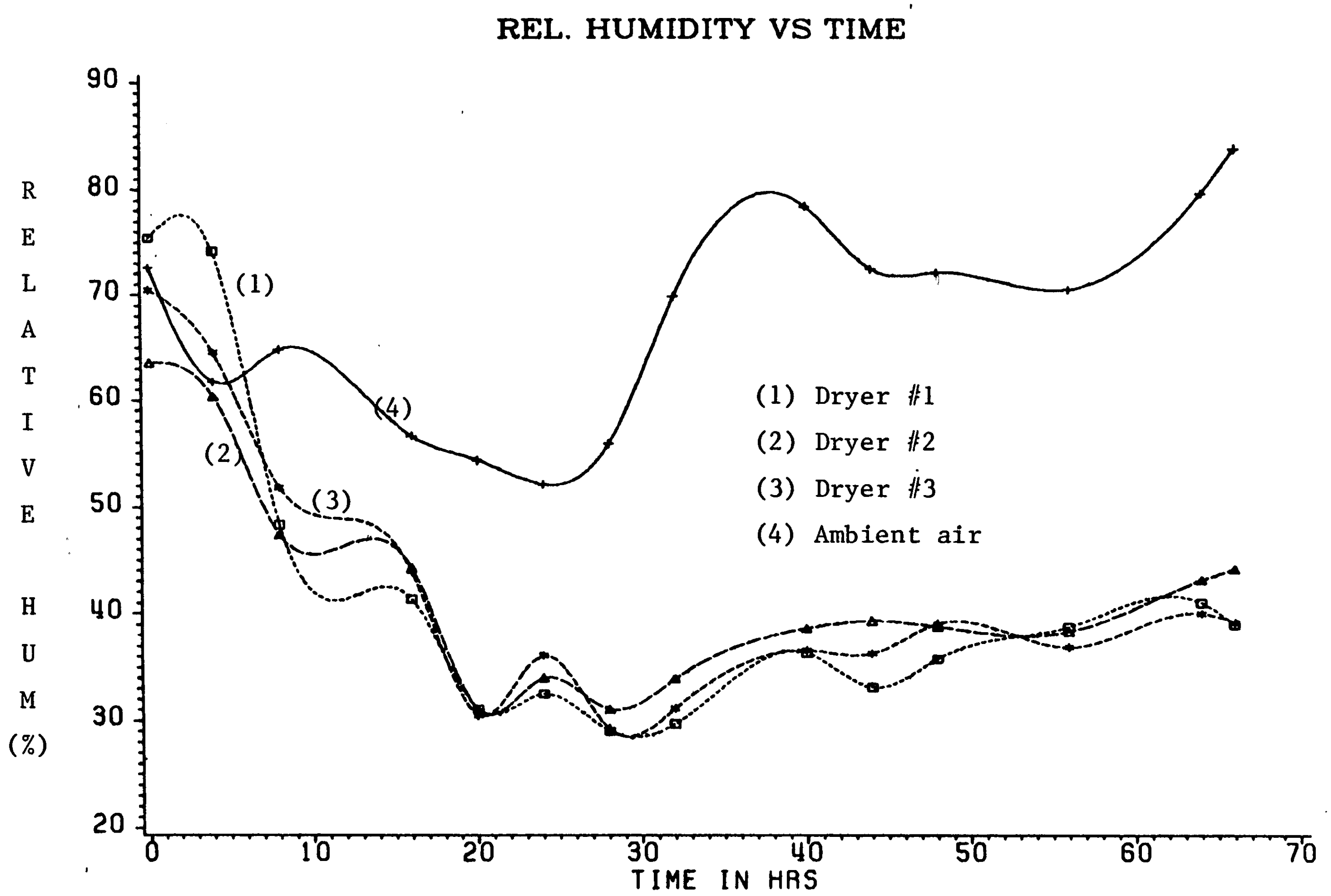

FIGURE 6.9 Variation of Relative Humidity of Exiting air and Ambient Air with time (TEST 2).

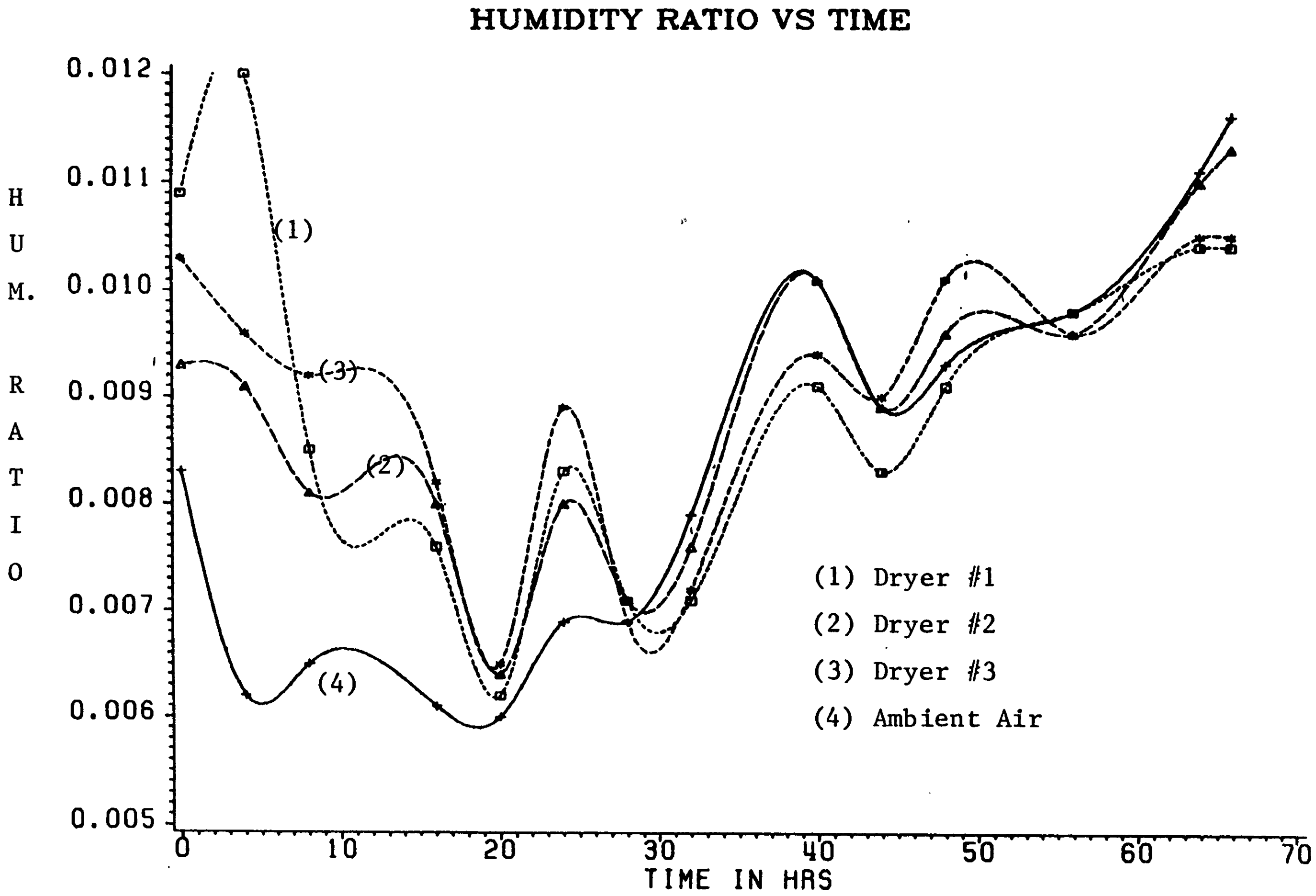

FIGURE 6.10 Variation of Humidity Ratio with Time in Exiting air and Ambient air (Test 2).

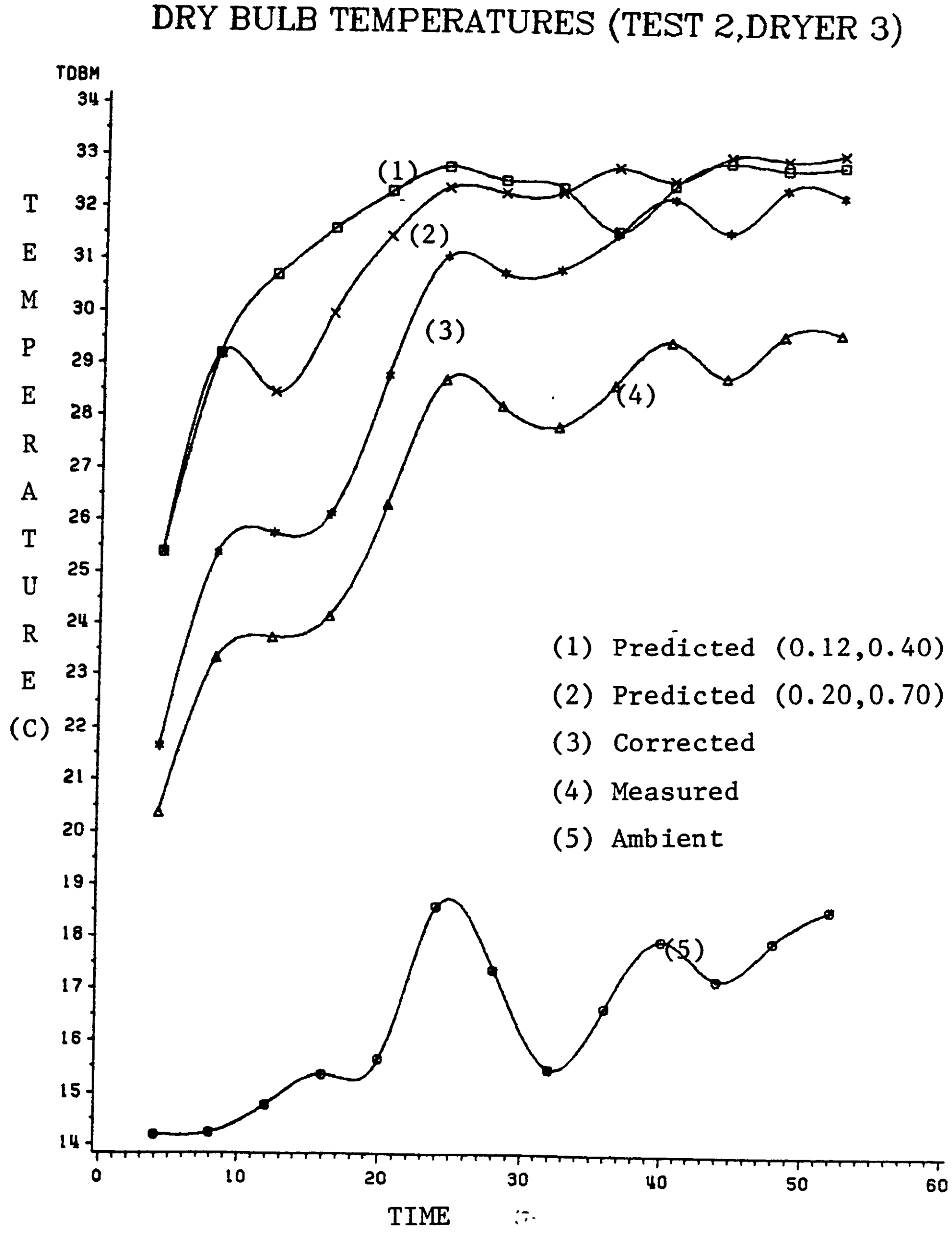

FIGURE 6.11 Variation of Dry bulb temperature of Exiting Air and Ambient air with drying time (Test 2, Dryer 3).

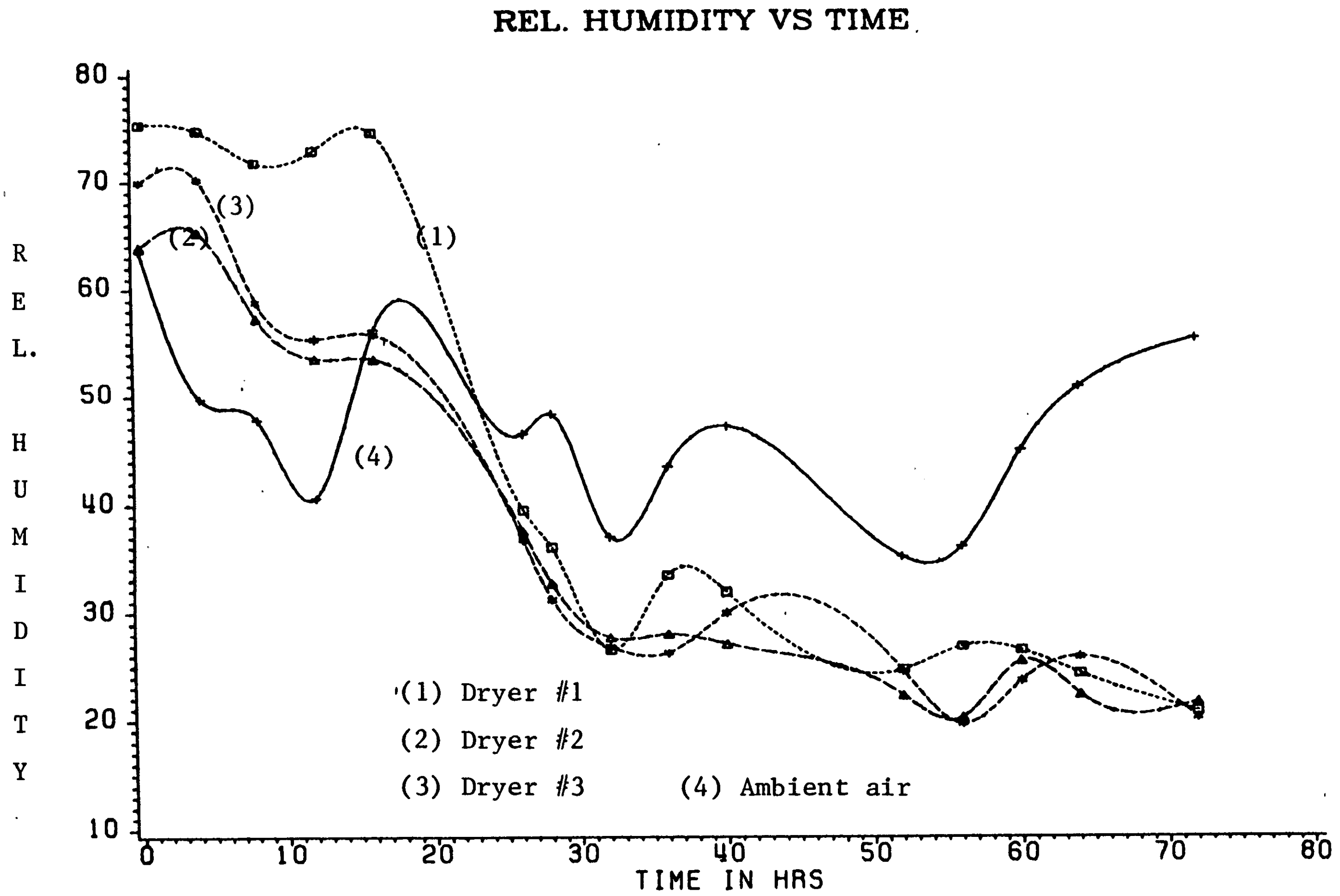

FIGURE 6.12 Variation of Relative Humidity of Exiting air and Ambient Air with Time (TEST 3).

Table 6.4. Some important parameters of test 3.

	Dryer 1	Dryer 2	Dryer 3
Recirculation schedule	1	2	0
Initial moisture content (% w.b.)	26.90	26.90	26.90
Average air flow (m^3/min/m^3)	8.20	8.42	9.48
Initial peanut temperature (°C)	15.0	15.0	15.0
Initial bulk density of peanuts solids (kg/m^3)	235.36	235.3	235.3
Measured final moisture content (% w.b.)	5.34	5.58	5.55
Duration of drying (hr)	72	72	72
Predicted final moisture content (% w.b.) (1) break points 0.12 and 0.40 (2) break points 0.20 and 0.70	 7.5 -	 7.9 -	 7.9 5.8
Measured weight of water removed (kg)	22.61	22.42	22.46
Solids loss (%)	6.74	5.88	6.02

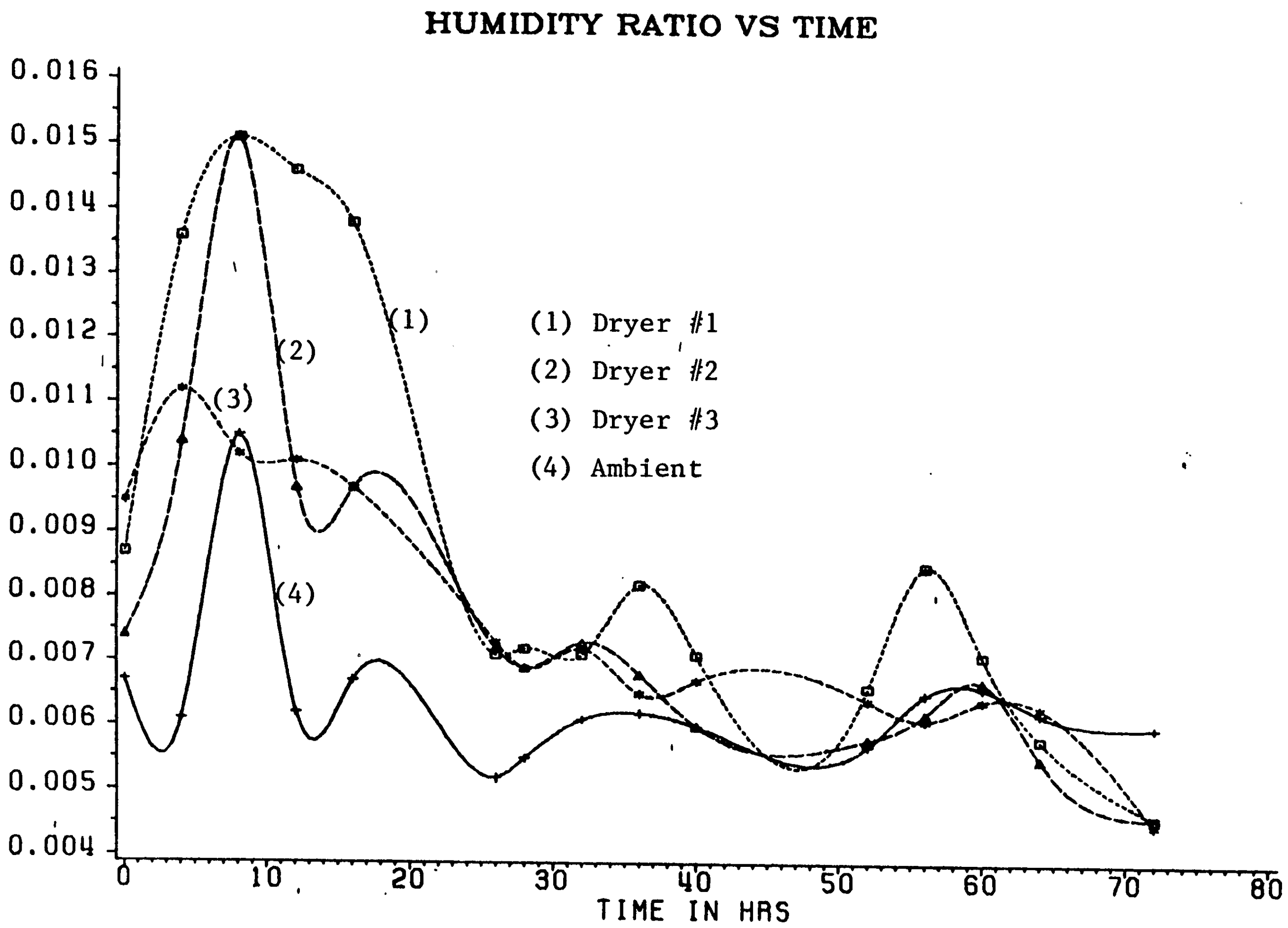

FIGURE 6.13 Variation of Humidity Ratio of Exiting air and Ambient Air with Time (TEST 3).

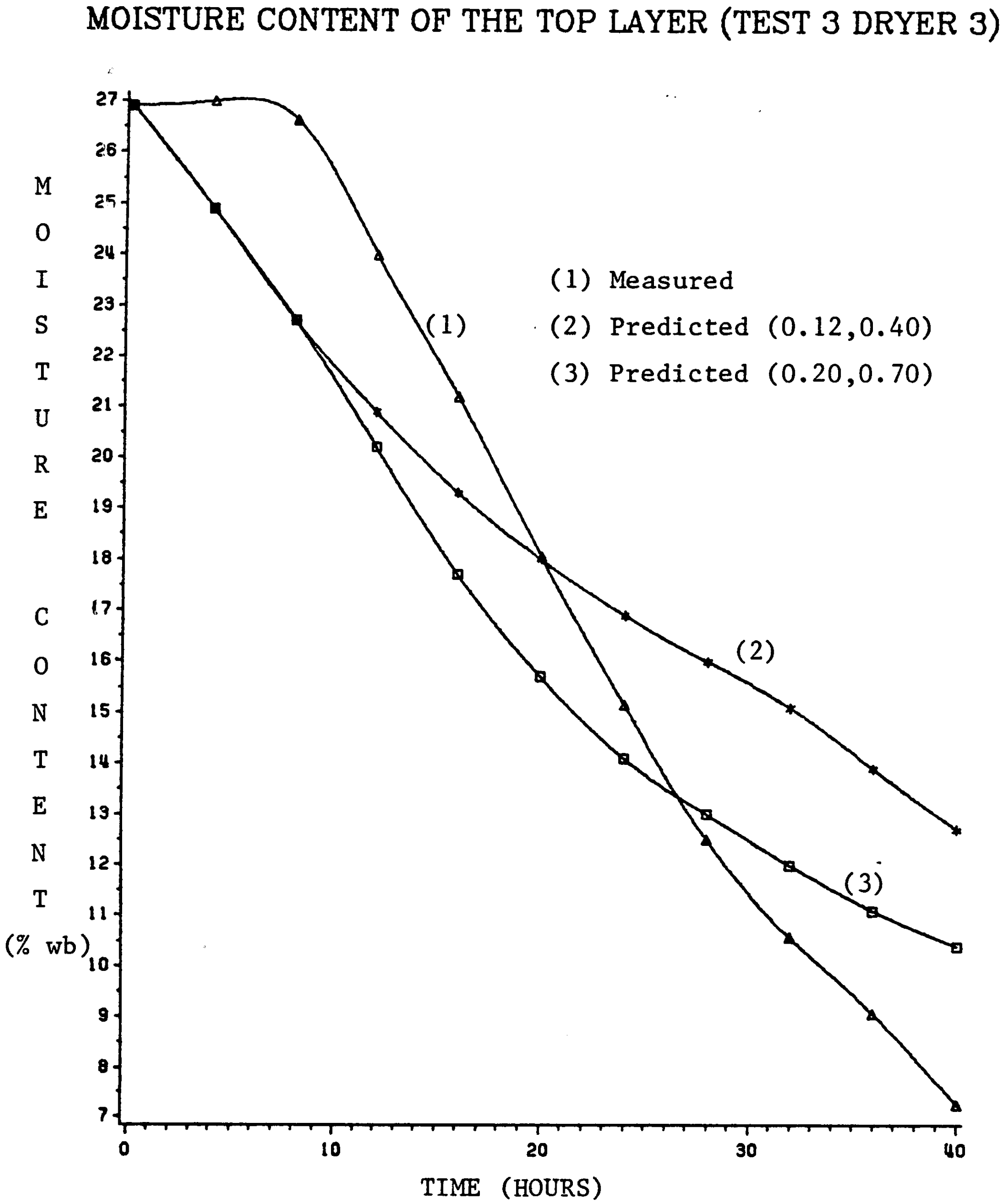

FIGURE 6.14 Variation of moisture content of peanuts in the top layer with Time (Test 3, Dryer 3).

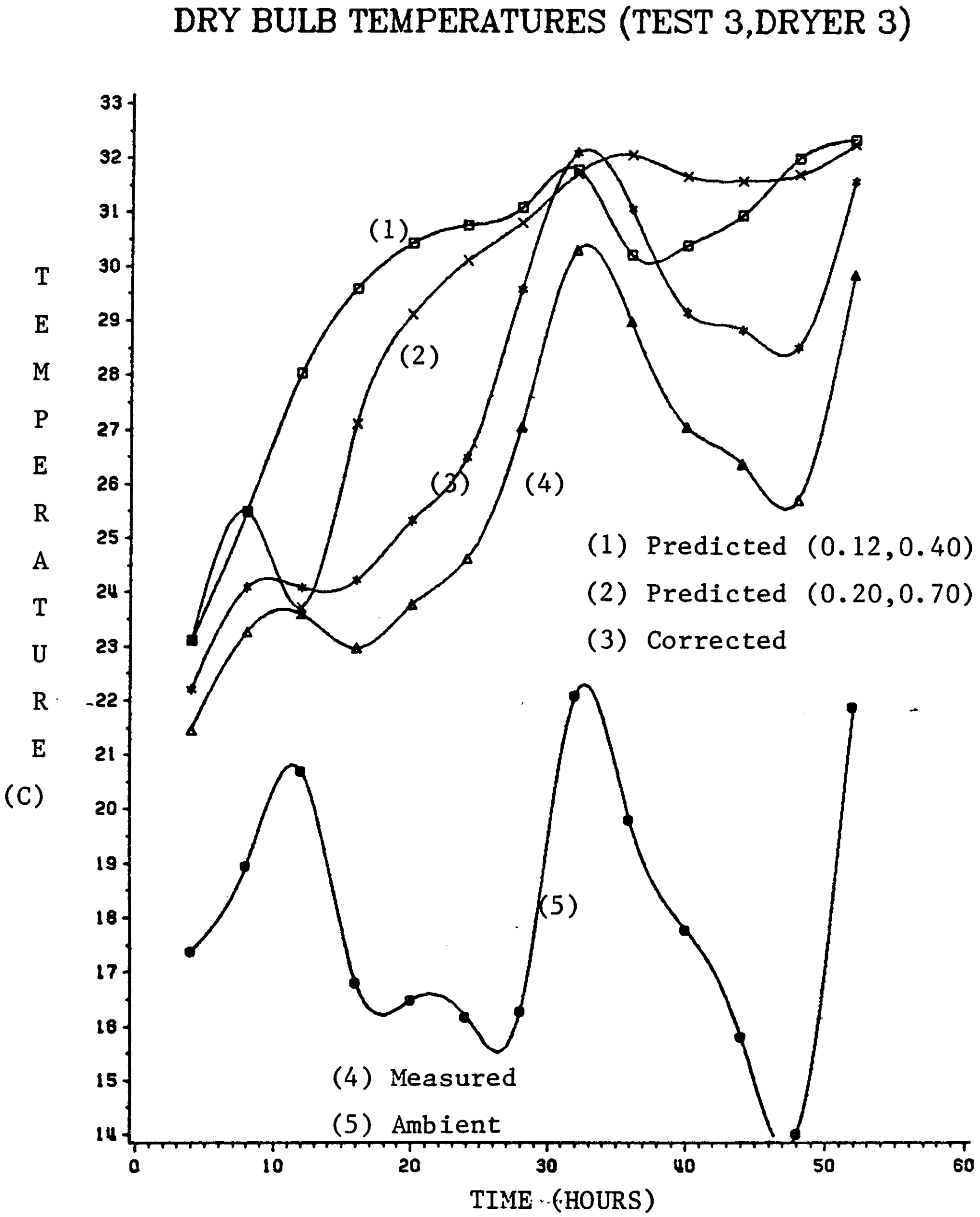

FIGURE 6.15 Variation of Dry bulb temperature of of exiting air and Ambient air with time (Test 3, Dryer 3).

much faster rate than predicted by the model. At 40 hours, the moisture content was almost 7 percent (w.b.). The Troeger model having break points 0.20 and 0.70 predicted a higher moisture removal rate after 8 hours of drying.

Test 4 consisted of two drying experiments using dryer 2 and 3. Dryer 2 was filled to depth of only 0.70 m due to lack of peanuts. Table 6.5 summarizes some important input and output values involved in dryer 3 (without recirculation). Fan speed was set at 300 rpm which gave an average air flow of 6.03 m^3 per min per m^3 of peanuts. This was the lowest in all drying experiments. As seen in Figure 6.16, the effective drying period was almost 50 hours for dryer 3. Again, the predicted dry bulb temperature differed from the measured dry bulb temperature when the humidity ratio in exiting air was high relative to ambient air humidity ratio. The Troeger model with break points 0.20 and 0.70 produced better results in this experiment than in other experiments. However, the predicted drying rate was lower than acual drying rate during the first 15 hours of the experiment.

Table 6.5. Some important parameters of test 4.

	Dryer 3
Initial moisture content (% w.b.)	12.95
Average air flow (m^3/min/m^3)	6.03
Initial peanut temperature (°C)	20
Initial bulk density of peanuts solids (kg/m^3)	248.88
Measured final moisture content (% w.b.)	5.40
Duration of drying (hr)	64.0
Predicted final moisture content (% w.b.) (1) break points 0.12 and 0.40 (2) break points 0.20 and 0.70	 5.80 5.90
measured weight of water removed (kg)	7.45

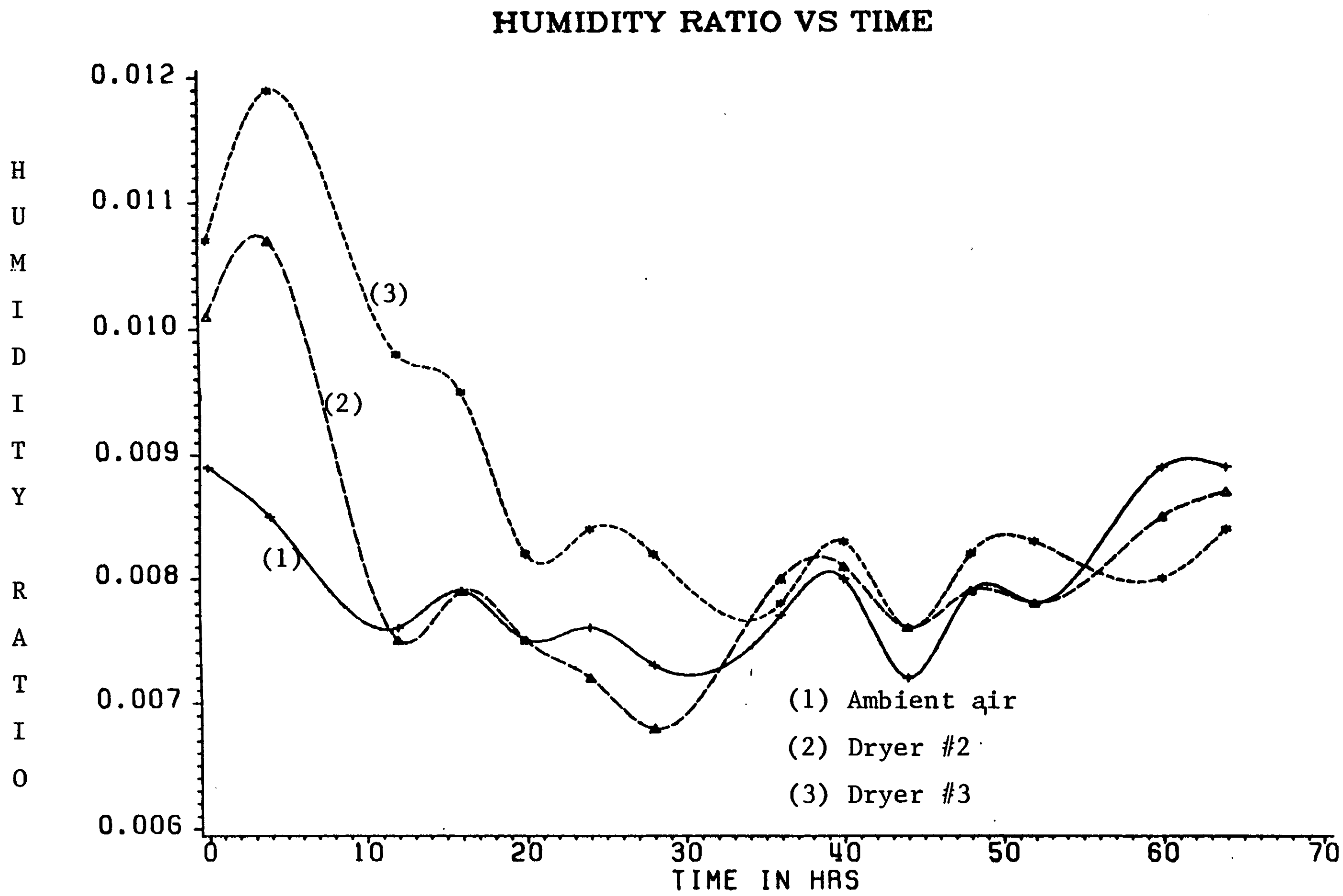

FIGURE 6.16 Variation of Humidity Ratio of exiting air and ambient air with time (TEST 4).

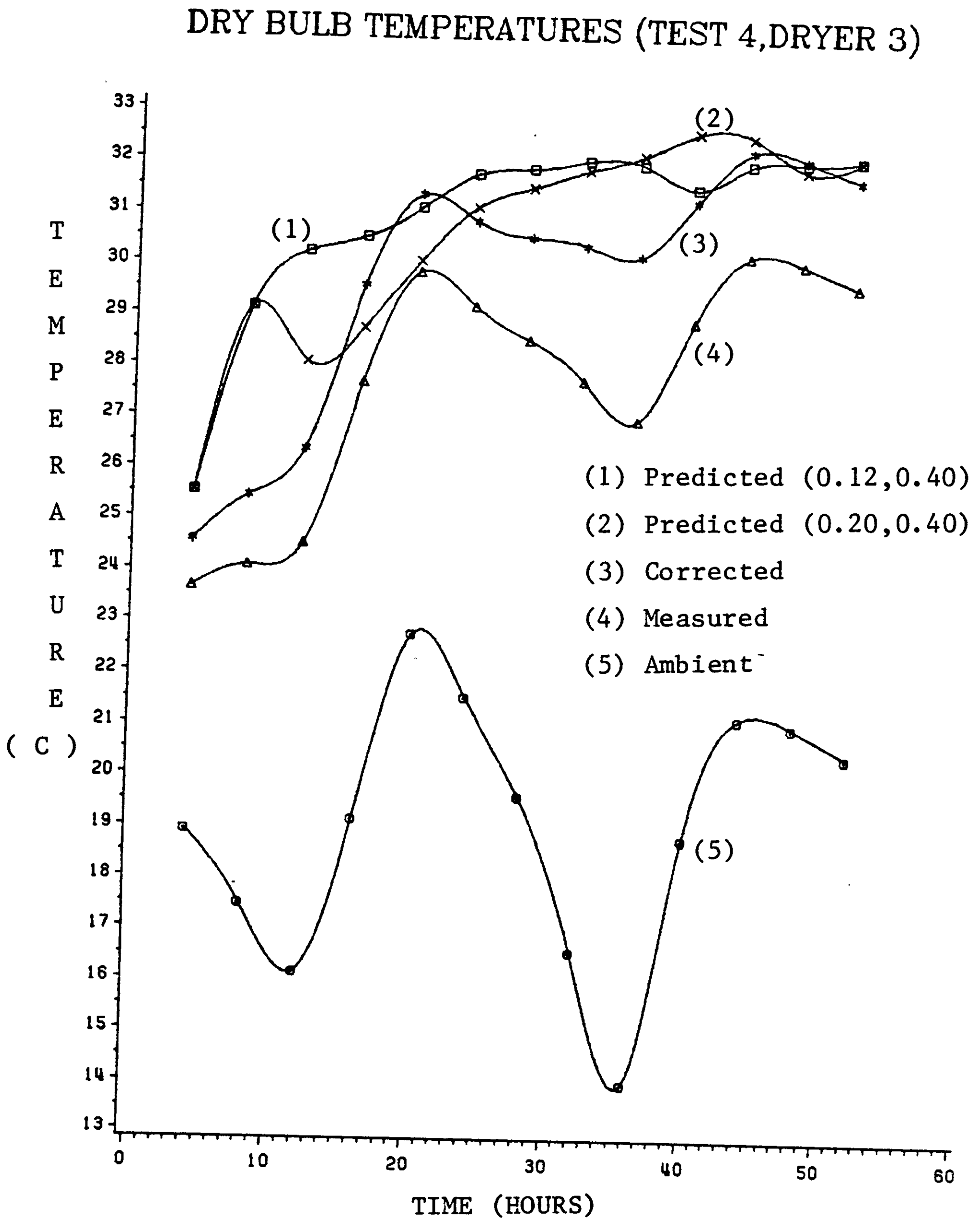

FIGURE (6.17) Variation of Dry bulb temperatures with time (test 4, dryer 3).

6.4 Energy Requirements for Drying Peanuts

Heater current inputs recorded with the data aquisition system were used to calculate the measured heat inputs to dryers. The current transducer produced 0 - 1 mA current which was directly proportional to the heater current varying from 0 to 25 A. This current was dropped across 1 kilohm resistance and the resultant voltage was stored in the computer. Actual heat energy input to a dryer was calculated using this data.

Sensible heat energy required for drying can also be calculated by applying the energy model given in Chapter 4. Figures 6.18 to 6.27 show calculated sensible heat energy inputs and measured sensible heat inputs. Table 6.6 gives energy requirements for drying along with air flow and weight of water removed in each experiment.

The measured heat energy inputs were higher than the calculated sensible heat values in all experiments in dryer 1 of test 3. The differences might be caused by the following reasons:

1. The model does not accurately calculate the sensible heat loss through the walls of the dryer. This is especially true for the heater section where radiation losses are also present. The radiation heat loss depends on the surface temperature of the heater and it can dramatically change the heat balance of the heater. When the inlet temperature to the heater section is low, heaters should provide more heat to air assuming a constant surface heat transfer coefficient. Depending upon the inlet temperature, the surface temperature of the heater may increase which in turn escalates the radiation heat release. The radiated heat may not be completely absorbed by air. Should radiation heat loss be present, the difference between calculated sensible heat energy and measured sensible heat should be relatively high when inlet temperatures are low. This fact is evident from Figures 6.18, 6.19, and 6.20.

2. If the air flow is different from the calculated air flow, calculated sensible heat differs from the actual value. However, in order to make calculated total sensible heat equal to the total measured heat input, the average air flow should be increased by more than 25%

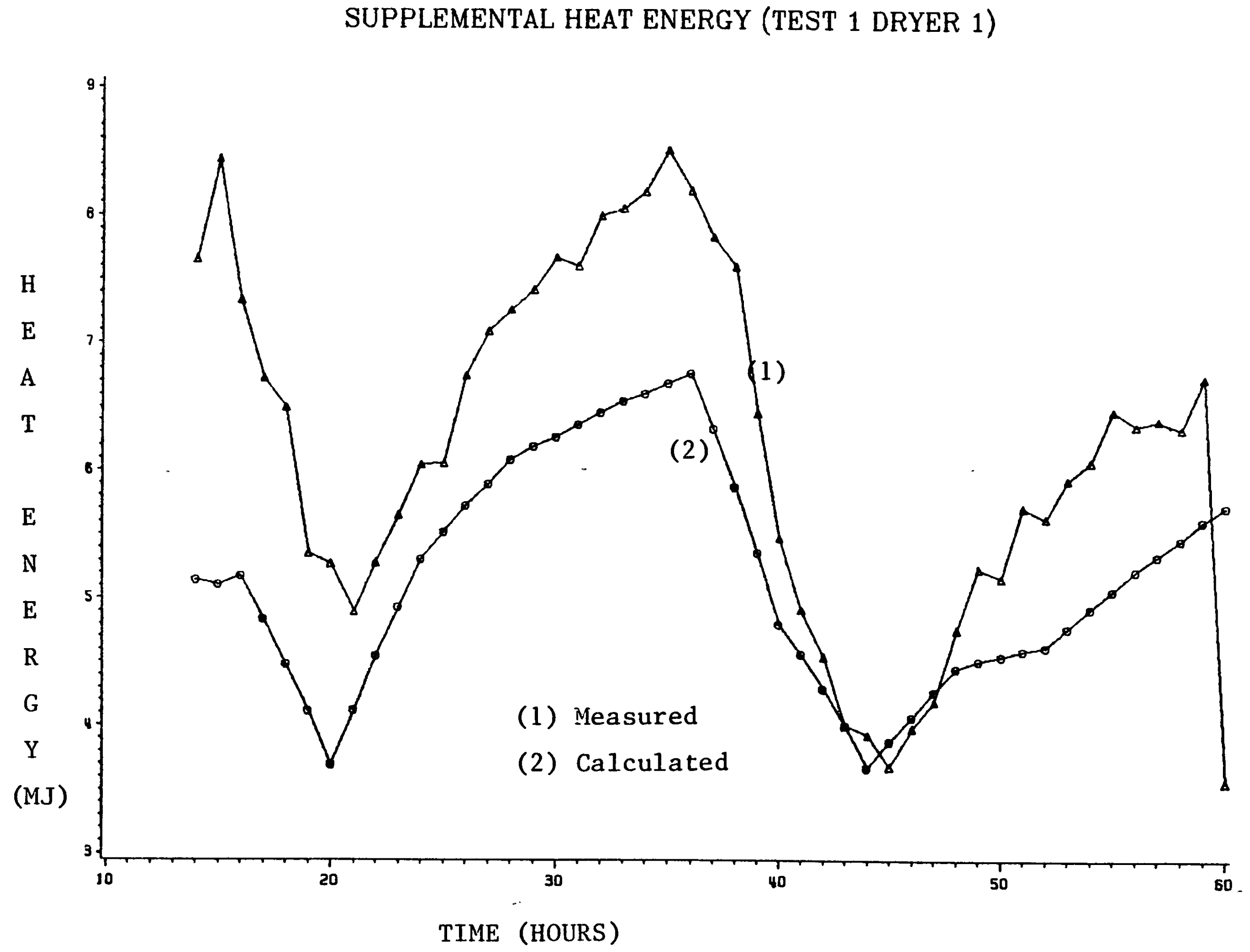

FIGURE 6.18 Variation of Measured and Calculated Supplemental Heat Inputs with Time (Test 1, Dryer 1).

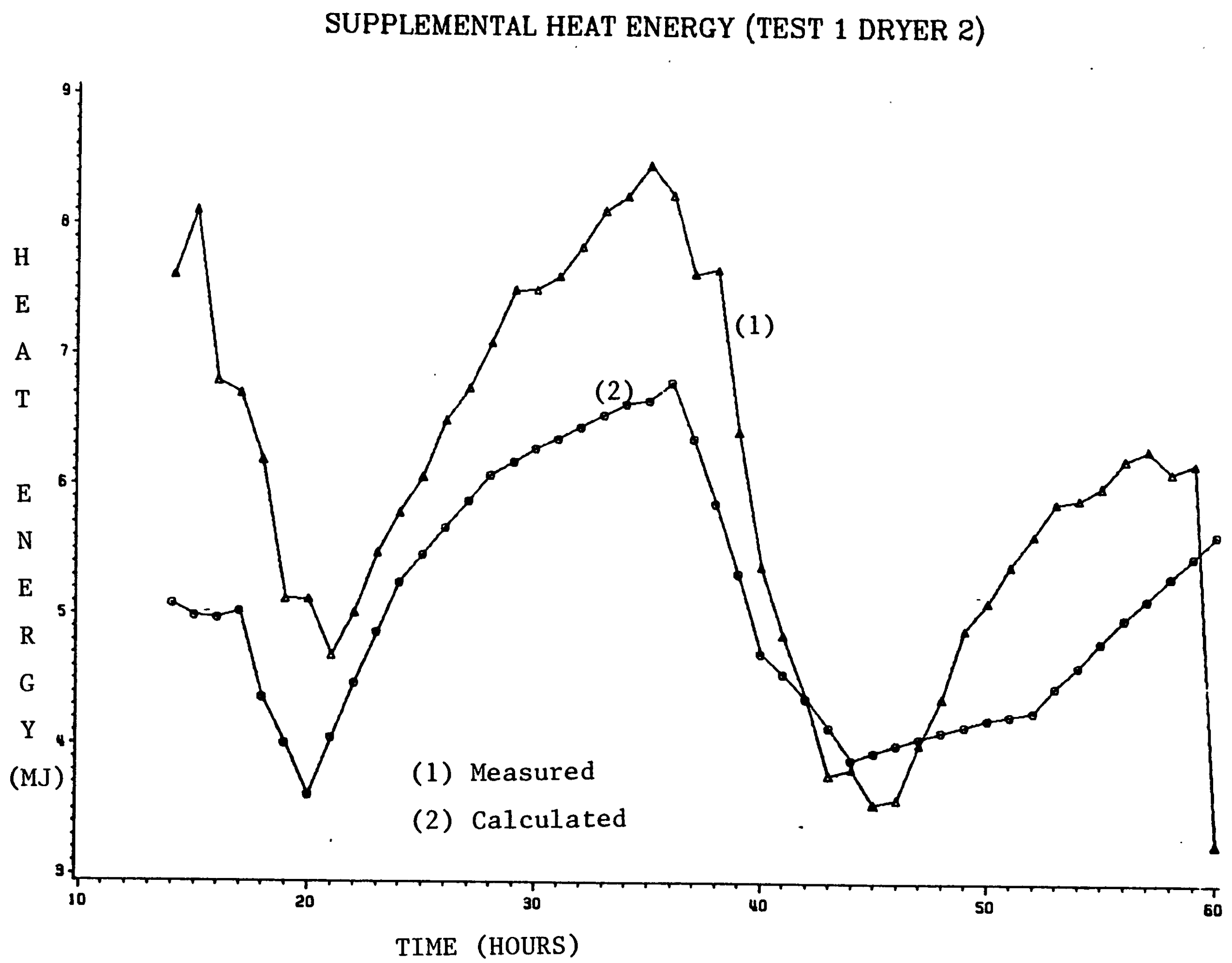

FIGURE 6.19 Variation of Measured and Calculated Supplemental Heat Inputs with Time (Test 1, Dryer 2).

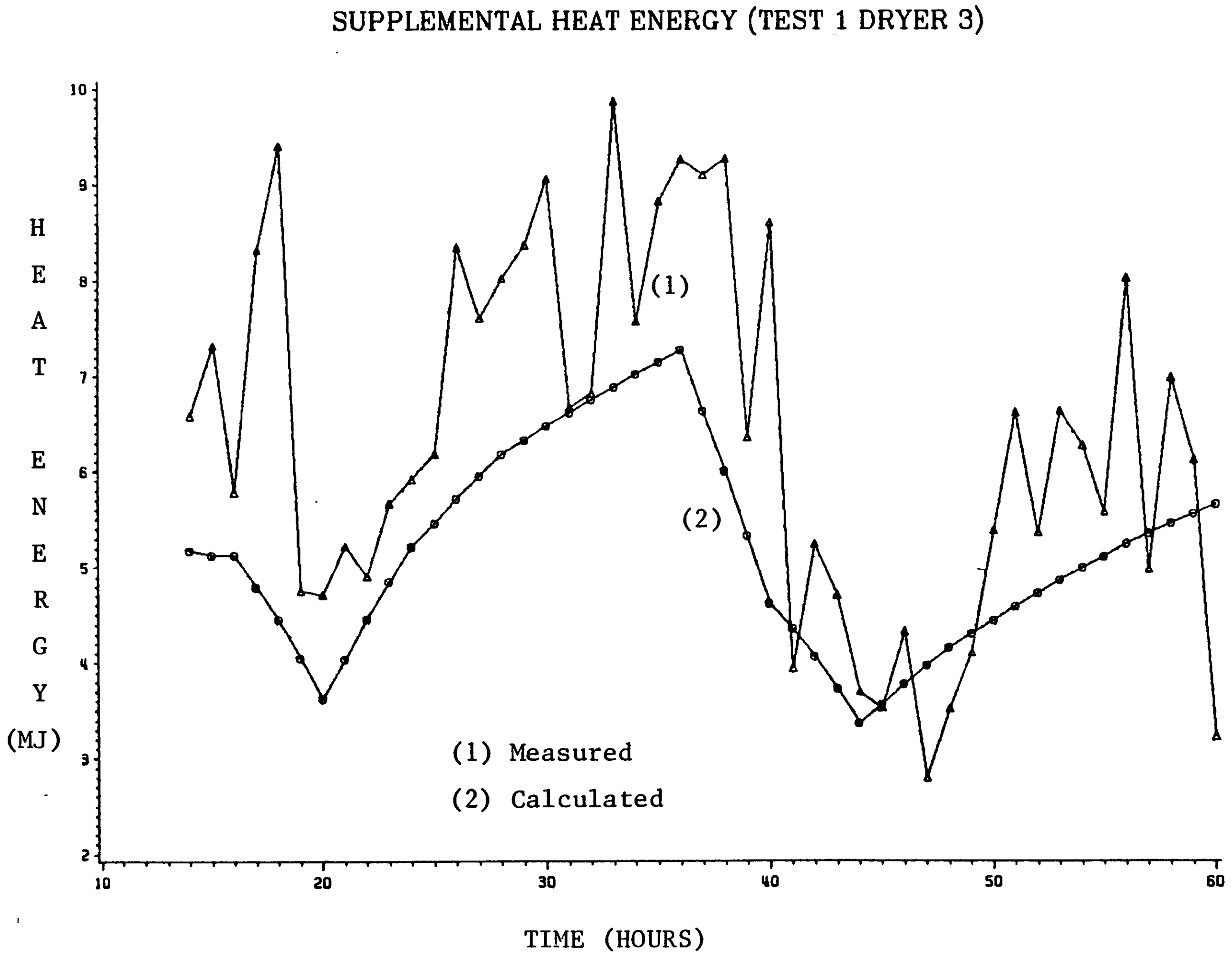

FIGURE 6.20 Variation of Measured and Calculated Supplemental Heat Inputs with Time (Test 1, Dryer 3).

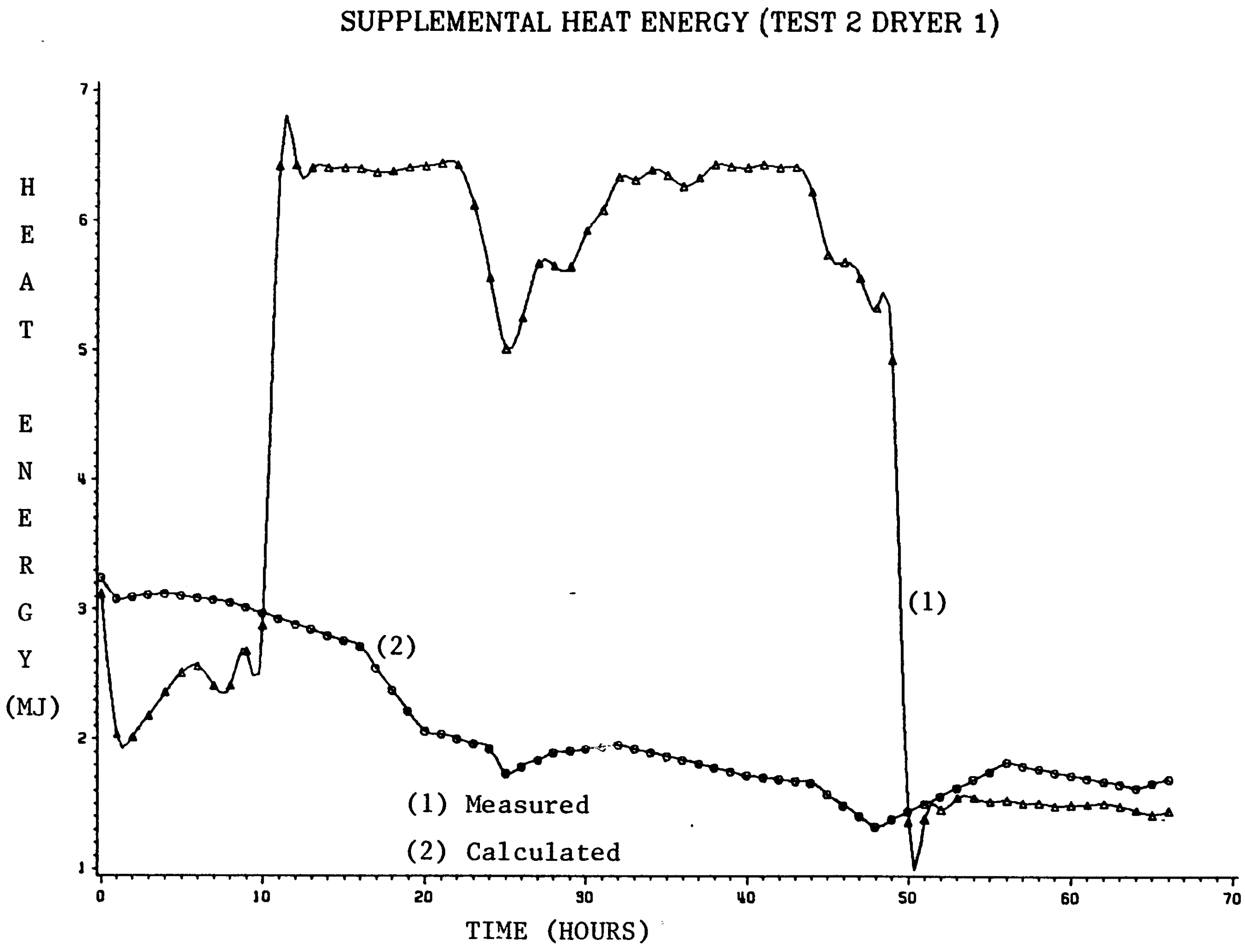

FIGURE 6.21 Variation of Measured and Calculated Supplemental Heat Inputs with Time (Test 2, Dryer 1).

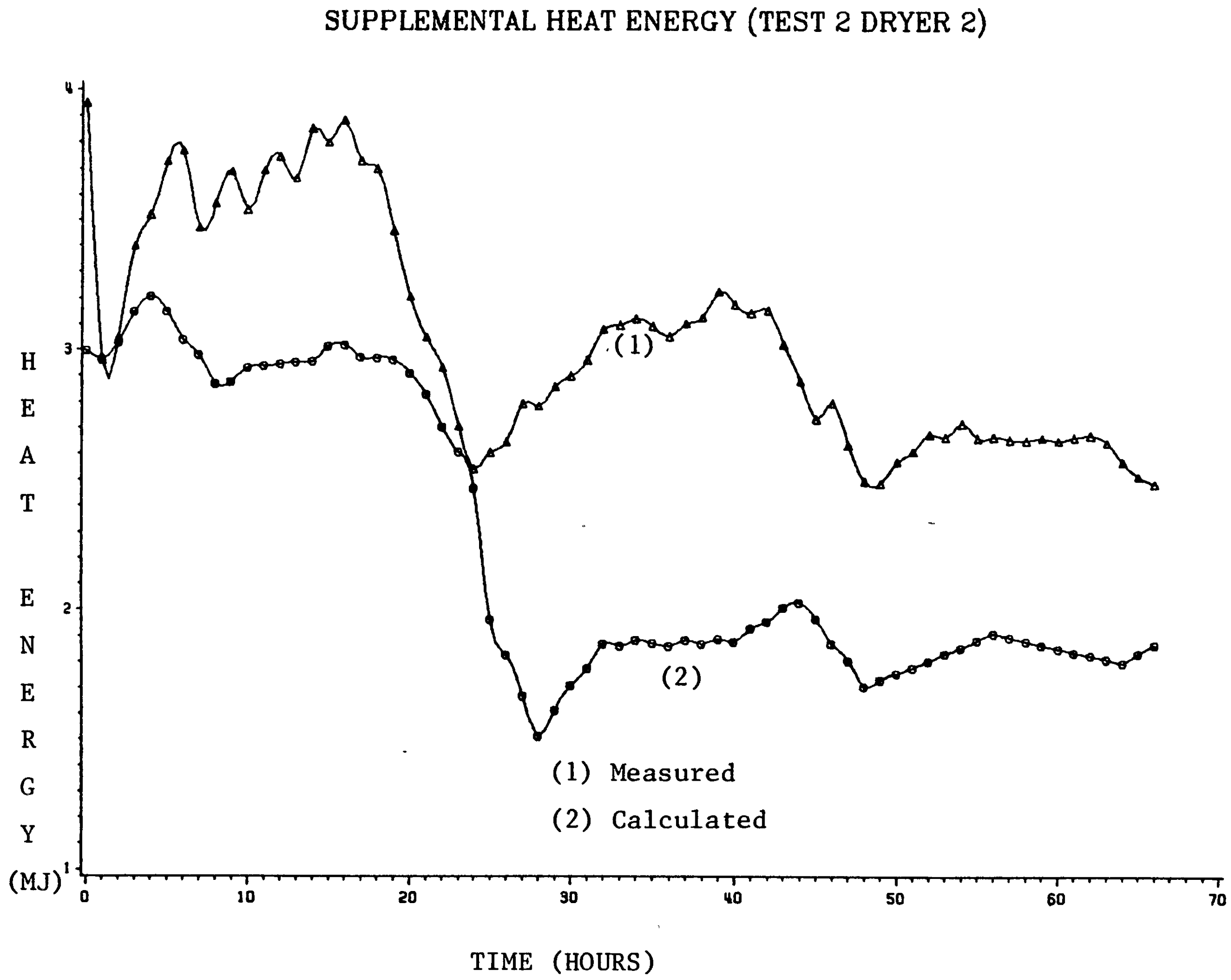

FIGURE 6.22 Variation of Measured and Calculated Supplemental Heat Inputs with Time (Test 2, Dryer 2).

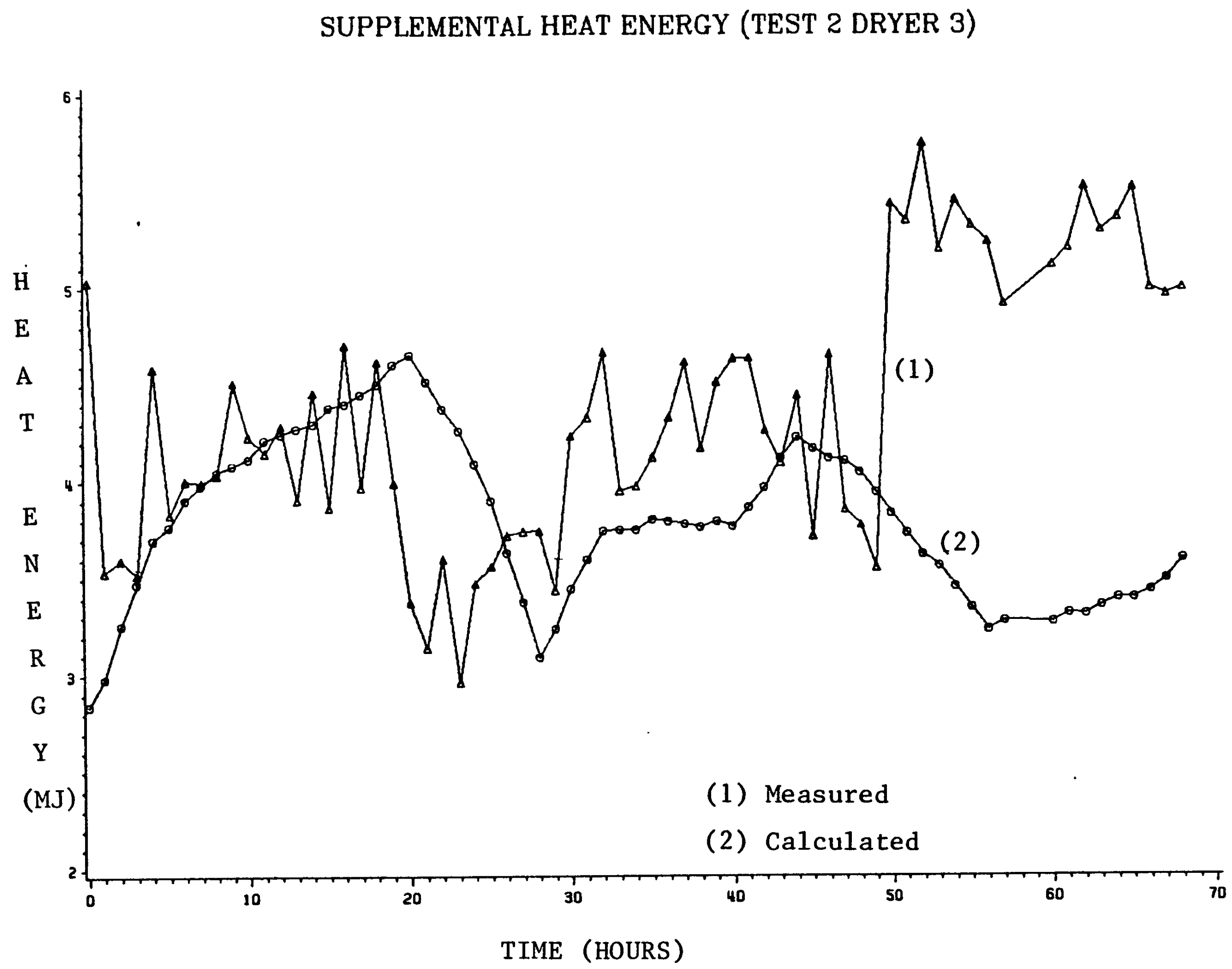

FIGURE 6.23 Variation of Measured and Calculated Supplemental Heat Inputs with Time (Test 2, Dryer 3).

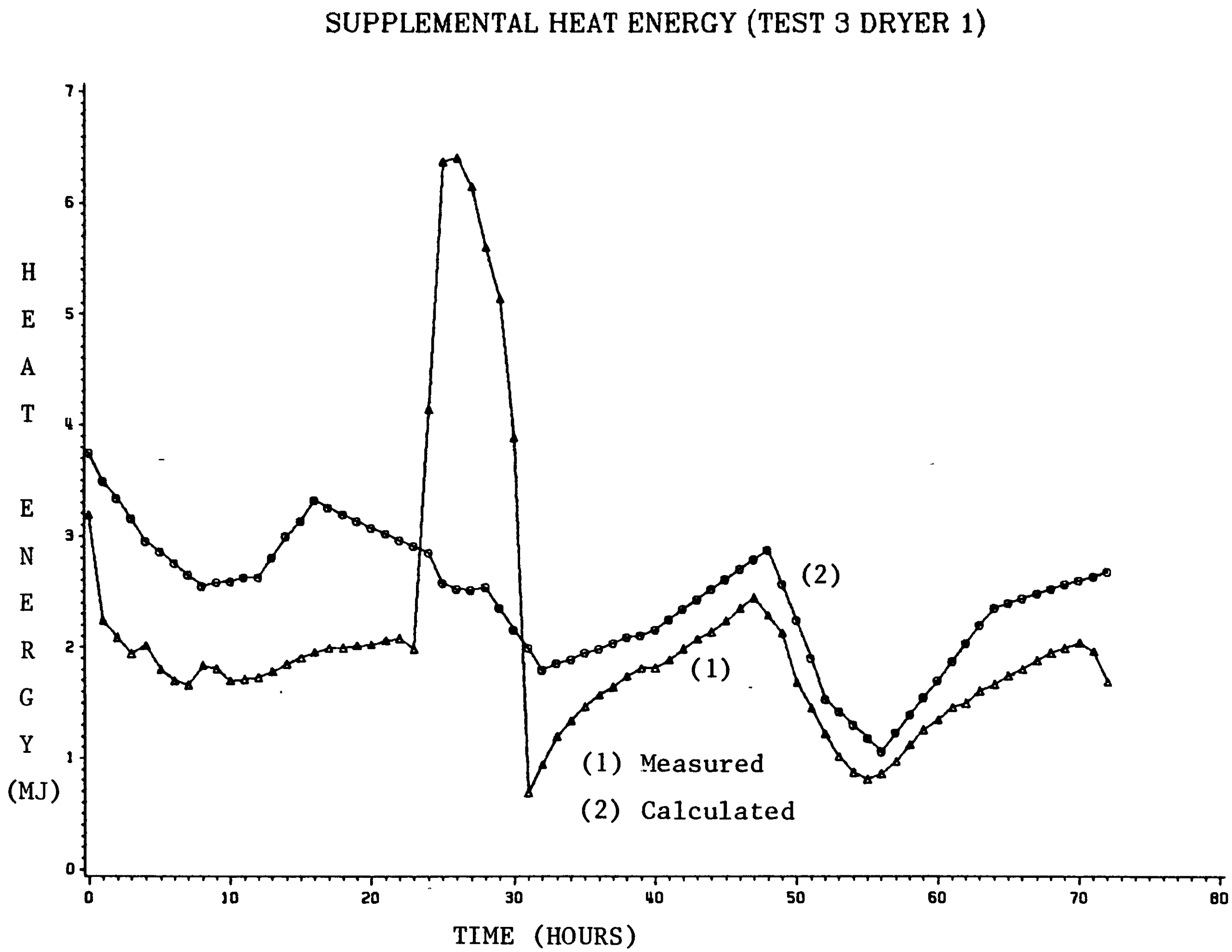

FIGURE 6.24 Variation of Measured and Calculated Supplemental Heat Inputs with Time (Test 3, Dryer 3).

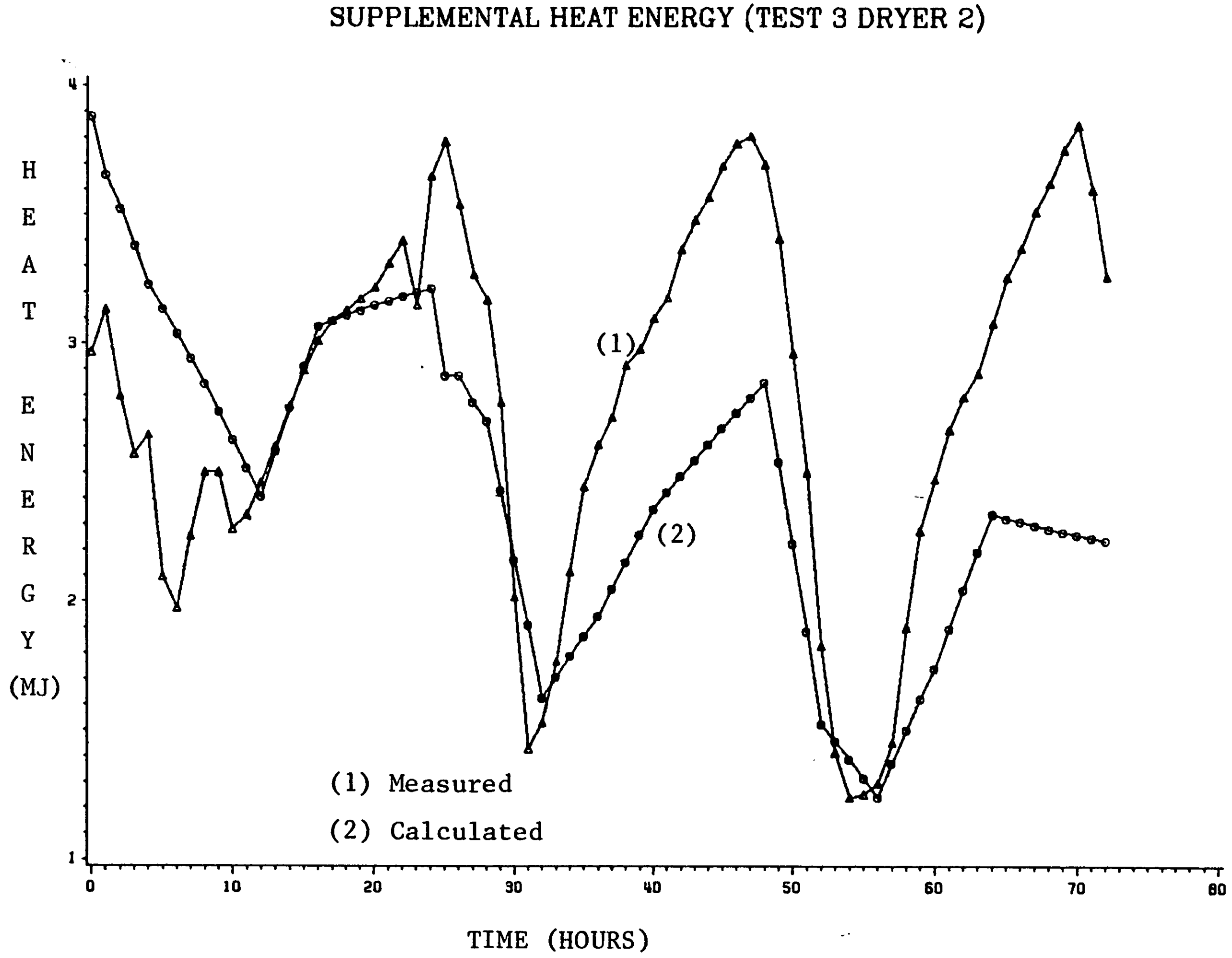

FIGURE 6.25 Variation of Measured and Calculated Supplemental Heat Inputs with Time (Test 3, Dryer 2).

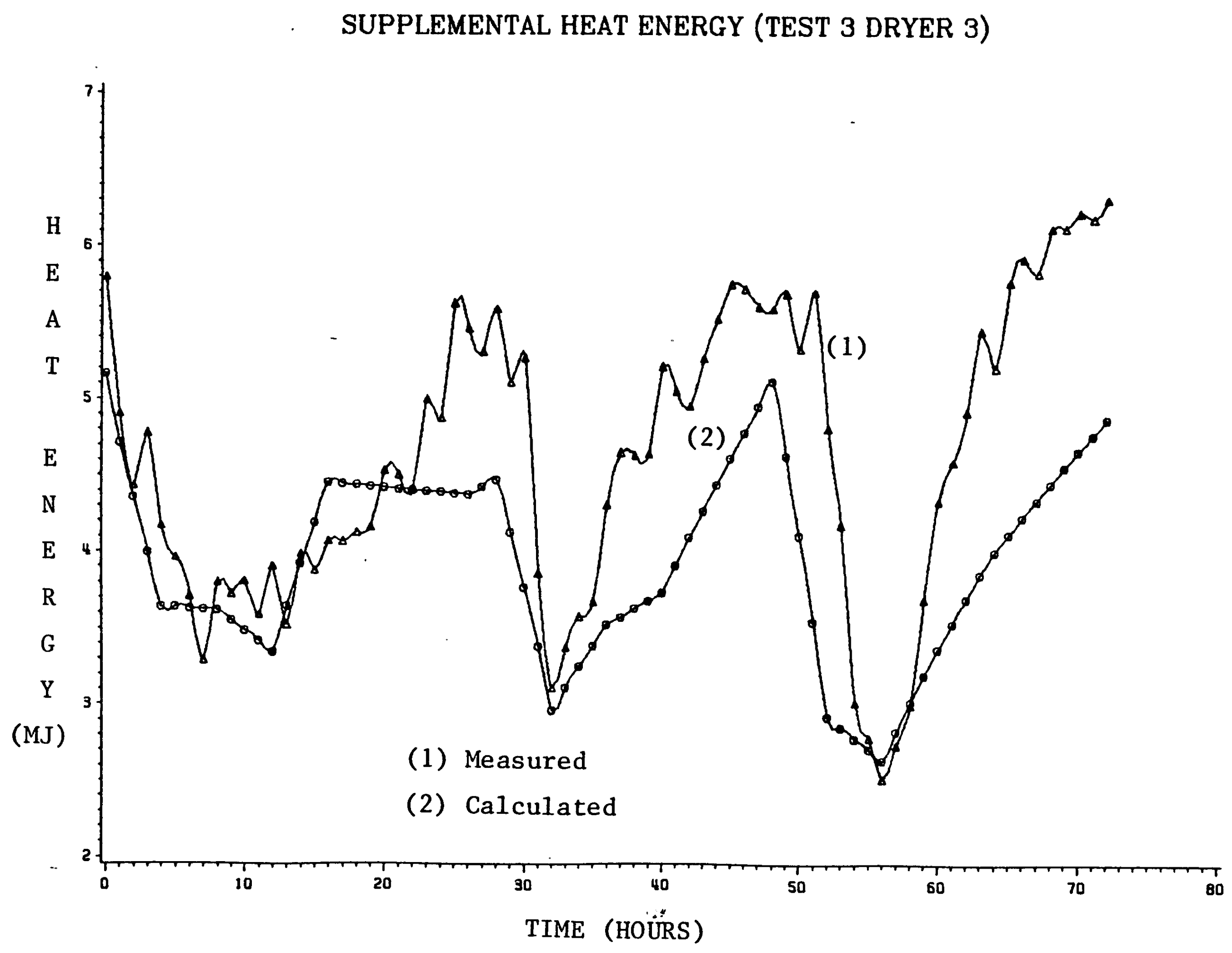

FIGURE 6.26 Variation of Measured and Calculated Supplemental Heat Inputs with Time (Test 3, Dryer 3).

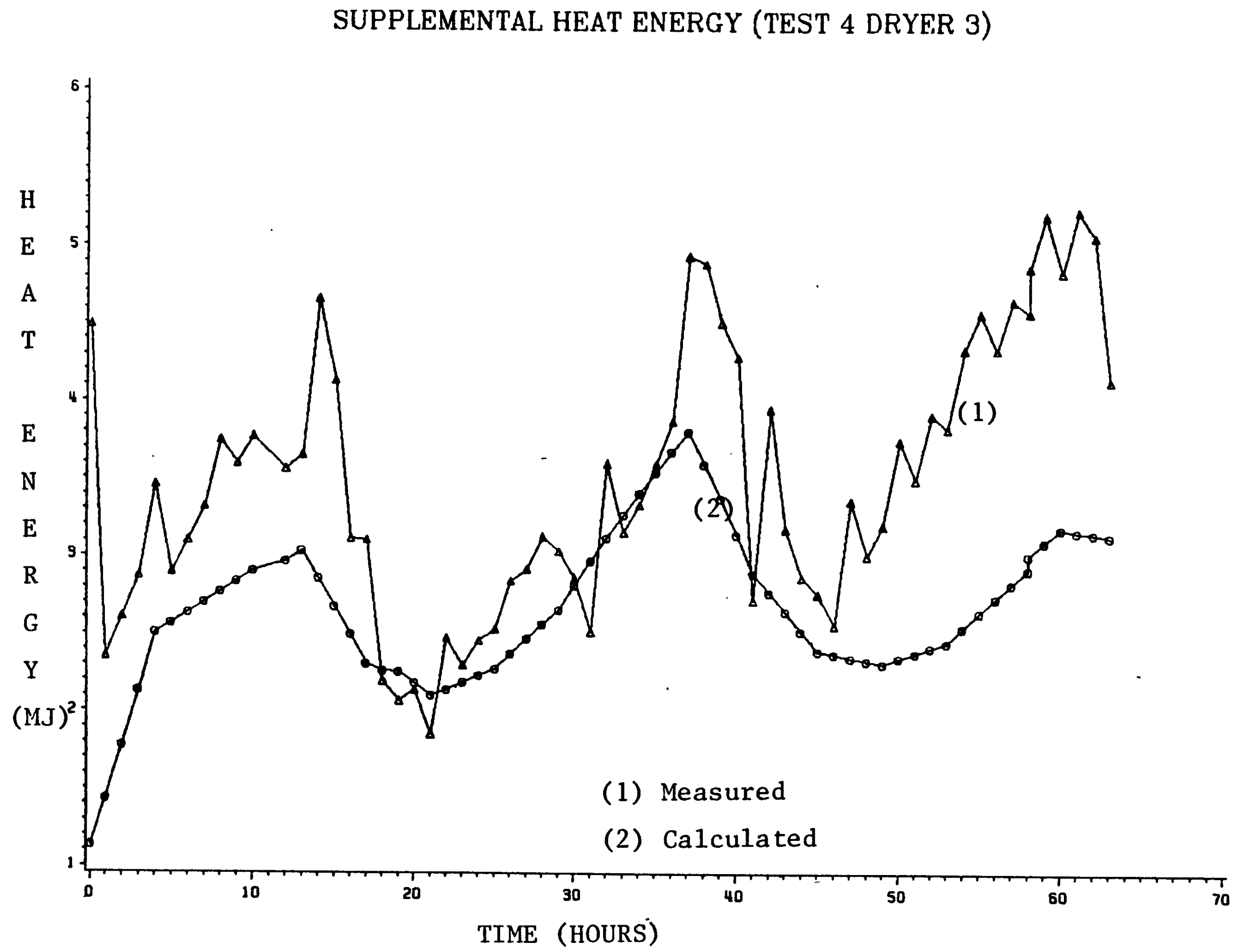

FIGURE 6.27 Variation of Measured and Calculated Supplemental Heat Inputs with Time (Test 4, Dryer 3).

in all experiments. This error is larger than the usual observation error in air flow. Therefore, correction of air flow to close the energy balance is not appropriate in these experiments.

3. For the experiments with exhaust air recirculation, the calculated sensible heat energy might be in error because of errors in the estimated recirculation percentage.

4. The possibility of ambient air mixing with recirculated air at the top of the peanut bed exists. During test 2, the actual heat energy inputs are unexplainably different from the calculated sensible heat values (Figures 6.21 and 6.22).

According to test 3 results, recirculation schedule 1 gave energy saving of 55 percent and schedule 2 gave energy saving of 39.6 percent. These values were based on the measured heat input values. As shown in Table 6.6, for test 2, schedule 1 saved 45 percent of energy required to dry peanuts and recirculation schedule 2 gave energy saving of 41 percent based on the calculated sensible heat values. Measured heat input values were not reliable for dryers 1 and 2 in test 2. These results show that the energy saving potential of recirculation of exiting air is more impressive than earlier reports in literature.

Table 6.6. Summary of energy inputs.

Test	Dryer	Recirculation schedule	Amount of water removed (kg)	Air flow (m^3/min/m^3)	Total calculated heat (MJ)	Total measured heat (MJ)
1	1	0	15.01	12.43	309.3	371.1
1	2	0	14.68	13.24	304.2	360.9
1	3	0	14.82	12.85	309.6	382.4
2	1	1	8.92	6.85	140.0	-
2	2	2	9.43	7.16	150.6	255.1
2	3	0	9.37	8.38	255.1	291.8
3	1	1	22.61	8.20	177.6	152.4
3	2	2	22.42	8.42	179.5	204.3
3	3	3	22.46	9.48	287.23	338.11
4	3	0	7.45	6.03	170.5	224.0

Chapter 7. Conclusions and Recommendations

Based on the results of this study the following conclusions can be made:

1. The Troeger model did not predict the rate of drying at high moisture contents accurately for Virginia type peanuts. The Troeger model predicted a lower moisture release rate than actually occured when high moisture peanuts were dried.

2. The air sampling device was not suitable for dry bulb temperature measurements of exiting air.

3. Accurate experimental determination of the fan curve at the fan speed used in drying provided more reliable data for the fan.

4. Recirculation schedule 1 provided a total energy savings of 50 percent on the average while recirculation schedule 2 gave a total energy savings of 40 percent on the average.

5. The energy balance model did not predict the heat loss in the heater section accurately.

The following recommendations can be made for future research:

1. The drying model for Virginia type peanuts should be improved using the data collected. The improved model should be tested using another set of data.

2. The instrumentation system to weigh the top layer peanut basket should be perfected.

3. The recirculated air flow rates should be measured instead of calculating from psychrometric charts.

4. The possible mixing of ambient air with the recirculated air at the top of the dryers should be prevented.

5. The dry bulb temperature of exiting air should be measured directly and the wet bulb temperature should be calculated from the dry bulb and wet bulb temperatures measured using the sampling device.

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Appendix A

Peanut Drying Simulation Model and Energy Balance Model

```
//A235PRO  JOB 50283,PROBM1,REGION=3500K
/*LONGKEY  AERSUX
/*ROUTE PRINT VPIVM1.PROBM1
/*PRIORITY IDLE
/*JOBPARM  LINES=15,CARDS=50000
//STEP1  EXEC FRTVCLGV
//FORT.SYSIN DD *
C$JOB
C***********************************************************************
C***                                                                  **
C***                    PEANUT                                        **
C***                                                                  **
C***********************************************************************
C***********************************************************************
C
C***********************************************************************
C***                                                                  **
C***       PROGRAMMER: DEBORAH F. COOK    LAST UPDATE: 1/30/85        **
C***  UPDATE JUNE-1986-----KULASIRI                                   **
C***********************************************************************
C
C***********************************************************************
C***********************************************************************
C***                                                                  **
C***                                                                  **
C***     PEANUT IS A COMPUTER SIMULATION MODEL WHICH DESCRIBES        **
C***     THE PEANUT DRYING PROCESS. IT IS BASED ON TROEGER            **
C***     AND BUTLER'S (1979) DRYING EQUATIONS. THE MODEL HAS BEEN     **
C***     ADAPTED TO INCLUDE THE ENERGY LOST TO THE SURROUNDINGS       **
C***     (CHHINNAN AND YOUNG, 1978). BEASLEY'S (1962) EQUATION FOR    **
C***     EQUILIBRIUM MOISTURE CONTENT OF VIRGINIA PEANUTS IS USED.    **
C***                                                                  **
C***                                                                  **
C***********************************************************************
C***********************************************************************
C
      DIMENSION TDBE(168),TWBE(168),TDBER(31),TWBER(31),TP1(20),XM(20)
      DIMENSION XM1(20),HX(20),IMOD1(20),SHX(20)
      DIMENSION XMP(20),POUT(10),OUT(168,10),TDPX(20)
      DIMENSION TWX(20),XMWB(20),XM1WB(20),RHX(20),XMEM(20),XMRM(20)
      DIMENSION TDBA(168),TWBA(168),TDBX(168),TWBX(168),TDBAR(31),TDBXR(
     &31),TWBXR(31),TWBAR(31),ITIME(168),SPI(20)
      DIMENSION TDBEI(20),TWBEI(20),TDBXI(20),TWBXI(20),TDBAI(20),TWBAI(
     &20)
      DIMENSION TP(16),TX(16),KTIME(31),JTIME(31),SPJ(31),SP(168)
      REAL TDX,TDA,ABS
C
C***********************************************************************
C***         CONSTANT AND INITIAL VALUES                              **
C***********************************************************************
C***                                                                  **
C***          1. CW = SPECIFIC HEAT OF WATER (KJ/KG C).               **
C***                                                                  **
C***          2. CP = SPECIFIC HEAT OF PEANUT SOLIDS (KJ/KG C).       **
C***                                                                  **
```

```
C***          3. AREA = CROSS SECTIONAL AREA OF DRYERS (SQ M).        **
C***                                                                  **
C***          4. TIMDRY = SIMULATION TIME (HR).                       **
C***                                                                  **
C***          5. PATM = ATMOSPHERIC PRESSURE (PA).                    **
C***                                                                  **
C***          6. CPV = SPECIFIC HEAT OF WATER VAPOR (KJ/KG C).        **
C***                                                                  **
C***          7. CPA = SPECIFIC HEAT OF AIR (KJ/KG.C)                 **
C***                                                                  **
C***********************************************************************
C
      DATA CW/4.1868/,CP/2.9308/,TIMDRY/-1./,ICHK/1/,K/0/
      DATA AREA/0.25/,PATM/101325./
      DATA CPA/1.00/,CPV/1.882/
C
C***********************************************************************
C***     INPUT/OUTPUT FILE DEFINITIONS                                **
C***********************************************************************
C
C     IPEA=05
C     MOUT=06
C     IPEPLT=27
C     FILEDEF 34 PEANUT2 DATA
C     FILEDEF 26 PEANUT2 OUTPUT
C
C***********************************************************************
C***     INPUT DATA READ FROM <FN> DATA(YR) A                          **
C***********************************************************************
C
C***********************************************************************
C*** INPUT DATA ON RECORD 1                                           **
C***  NTEST=TEST NO.                                                  **
C***  NCOL=COLUMN NO.
C***  NYEAR=YEAR(EXAMPLE 1983)                                        **
C***********************************************************************
C
      READ(05,114) NTEST,NCOL,NYEAR
  114 FORMAT(2I2,I5)
      WRITE(06,172) NTEST,NCOL,NYEAR
  172 FORMAT(/2X,'TEST NO.',I2,2X,'COLUMN NO.',I2,2X,I4)
C
C***********************************************************************
C*** INPUT DATA ON RECORD 2                                           **
C***  NRESP=NO. STATIC PRESS. READINGS                                **
C***  NREAD=NO. THERMISTER READINGS                                   **
C***  NHR=NO. HOURS IN DRYING TEST                                    **
C***  NR=1 TEST INCLUDES RECIRCULATION, NR=2 TEST DOES NOT INCLUDE    **
C***    RECIRCULATION                                                 **
C***  IPRT=INTERVAL AT WHICH A TABLE IS PRINTED GIVING THE EXITING    **
C***    CONDITIONS FOR EACH LAYER (EXAMPLE: IPRT=4,TABLE IS PRINTED   **
C***    EVERY 4TH HOUR                                                **
C***********************************************************************
C
      READ(05,103) NRESP,NREAD,NHR,NR,IPRT
```

```
  103 FORMAT(2I3,I4,I2,I2)
C*** INPUT DATA ON RECORD 3                                           **
C***  IPHR=NO. OF TIME INTERVALS PER HOUR (EXAMPLE: IF DELT=0.25,     **
C***   THEN IPHR=4)                                                   **
C***  M=NO. OF LAYERS                                                 **
C***********************************************************************
C
      READ(05,11) IPHR,M
   11 FORMAT(I2,I3)
C
C***********************************************************************
C*** INPUT DATA ON RECORD 4                                           **
C***  DELT=SIMULATION INTEGRATION INTERVAL(HR)                        **
C***  AMOWB=INITIAL MOISTURE CONTENT OF PRODUCT(WB,DECIMAL)           **
C***  TPO=INITIAL PRODUCT TEMPERATURE(C)                              **
C***  BD=BULK DENSITY AT ZERO MOISTURE CONTENT (KG/CUBIC M)           **
C***  DEPTH=DEPTH OF PRODUCT(M)                                       **
C***  WEIGHT=INITIAL(GREEN) WEIGHT OF PRODUCT(KG)                     **
C***  TERMR=THERMAL RESISTANCE DRYER WALLS(H.M2.C/MJ)                 **
C***  SPCORR=FACTOR DIVIDED INTO STATIC PRESS.(PA) TO OBTAIN          **
C***  INDEPENDENT VARIABLE FOR CONIC SECTION REPRESENTATION           **
C***  FAN CURVE                                                       **
C***********************************************************************
C
      READ(05,13) DELT,AMOWB,TPO,BD,DEPTH,WEIGHT,TERMR
   13 FORMAT(F6.3,F7.4,F5.1,F7.2,F5.2,F7.2,F6.1)
      WRITE(06,124) DELT
  124 FORMAT(/2X,'SIMULATION INTEGRATION INTERVAL(DELT)',F5.2,1X,'(HR)')
      WRITE(06,125) AMOWB
  125 FORMAT(/2X,'INITIAL MOISTURE CONTENT OF PRODUCT(AMO)',F6.3,
     &1X,'(W.B.)')
      WRITE(06,126) TPO,BD
  126 FORMAT(/2X,'INITIAL PEANUT TEMPERATURE(TPO)',F6.2,1X,'(C)',2X,
     &'BULK DENSITY(BD)',F7.2,1X,'(KG/CUBIC M)')
      WRITE(06,127) DEPTH,WEIGHT
  127 FORMAT(/2X,'PRODUCT DEPTH',F5.2,1X,'(M)',2X,'INITIAL(GREEN) WEIGHT
     &',F7.2,1X,'(KG)')
      WRITE(06,193) TERMR
  193 FORMAT(/2X,'THERMAL RESISTANCE OF DRYER WALLS(H.M2.C/MJ)',F8.1)
C
C***********************************************************************
C***                                                                  **
C***      INPUT OF DATA TAKEN MANUALLY                                **
C***                                                                  **
C***********************************************************************
C***                                                                  **
C***          1. TDBXR = AN ARRAY CONTAINING MANUAL DRY BULB TEMP-    **
C***             ERATURE READINGS OF AIR EXITING THE PEANUTS (KOHM)   **
C***                                                                  **
C***          2. TWBXR = AN ARRAY CONTAINING MANUAL WET BULB TEMP-    **
C***             ERATURE READINGS OF AIR EXITING THE PEANUTS (KOHM)   **
C***                                                                  **
C***          3. TDBER = AN ARRAY CONTAINING MANUAL DRY BULB TEMP-    **
C***             ERATURE READINGS OF AIR ENTERING THE FIRST LAYER(KOHM)*
C***                                                                  **
```

```
C***            4. TDBAR = AN ARRAY CONTAINING THE MANUAL DRY BULB           **
C***               AMBIENT AIR TEMPERATURES READINGS(KOHM)                   **
C***                                                                         **
C***            5. TWBAR = AN ARRAY CONTAINING THE MANUAL WET BULB           **
C***               AMBIENT AIR TEMPERATURE READINGS(KOHM)                    **
C***                                                                         **
C***            6. JTIME = AN ARRAY CONTAINING THE DRYING TIMES AT           **
C***               WHICH THE MANUAL TEMPERATURE READINGS WERE TAKEN.         **
C***                                                                         **
C***            7. KTIME = AN ARRAY CONTAINING THE DRYING TIMES AT           **
C***                WHICH THE STATIC PRESSURE READINGS WERE TAKEN.           **
C***                                                                         **
C***            8. SPJ = AN ARRAY CONTAINING MANUAL PRESSURE                 **
C***               READINGS(IN W.C.)                                         **
C****************************************************************************
C
C****************************************************************************
C*** READ IN AND WRITE OUT MEA. STATIC PRESSURE(IN.WC)                       **
C****************************************************************************
C
      READ(05,12)(KTIME(IQ),SPJ(IQ),IQ=1,NRESP)
   12 FORMAT(I4,F6.3)
      WRITE(06,82)
   82 FORMAT(/1X,'TIME',2X,'MEA. STATIC PRESS.(IN.W.C.)',/)
      WRITE(06,116)(KTIME(IQ),SPJ(IQ),IQ=1,NRESP)
  116 FORMAT(I5,F6.3)
C
C****************************************************************************
C*** READ IN AND WRITE OUT MEA. THERMISTOR RESISTANCES(KOHMS)                **
C****************************************************************************
C
      WRITE(06,83)
   83 FORMAT(/2X,'MEA. THERMISTOR RESISTANCES(KOHMS)')
      WRITE(06,84)
   84 FORMAT(/8X,'AMBIENT',6X,'BELOW',7X,'ABOVE')
      WRITE(06,85)
   85 FORMAT(/1X,'TIME',1X,'TDB',3X,'TWB',3X,'TDB',9X,'TDB',3X,'TWB'/)
      DO 102 IQ=1,NREAD
      READ(05,111) JTIME(IQ),TDBAR(IQ),TWBAR(IQ),TDBER(IQ),TDBXR(IQ),TWB
     &XR(IQ)
  111 FORMAT(I4,5F6.3)
  102 WRITE(06,131) JTIME(IQ),TDBAR(IQ),TWBAR(IQ),TDBER(IQ),TDBXR(IQ),TW
     &BXR(IQ)
  131 FORMAT(I5,5F6.3)
C
C****************************************************************************
C*** INTERPOLATION TO OBTAIN HOURLY STATIC PRESSURE AND TEMP. VALUES         **
C****************************************************************************
C
      NHRP1=NHR+1
      ITIME(1)=0
      DO 150 NN=2,NREAD
      IF(JTIME(NN-1).EQ.2400) GO TO 37
      ITOT=(JTIME(NN)-JTIME(NN-1))/100
   38 ITIME(NN)=(ITIME(NN-1)+ITOT)
```

```
      GO TO 47
   37 ITOT=JTIME(NN)/100
      GO TO 38
   47 IKOUNT=-1
      IBEGIN=ITIME(NN-1)+1
      IEND=ITIME(NN)
      RINT=FLOAT(ITIME(NN)-ITIME(NN-1))
      DIFDA=TDBAR(NN)-TDBAR(NN-1)
      DIFWA=TWBAR(NN)-TWBAR(NN-1)
      DIFDI=TDBER(NN)-TDBER(NN-1)
      DIFDE=TDBXR(NN)-TDBXR(NN-1)
      DIFWE=TWBXR(NN)-TWBXR(NN-1)
      IF(NN.EQ.NREAD) IEND=IEND+1
      DO 16 I=IBEGIN,IEND
      IKOUNT=IKOUNT+1
      AMULT=FLOAT(IKOUNT)
      IF(I.EQ.IBEGIN) AMULT=0.0
      AMULT=AMULT/RINT
      TDBA(I)=TDBAR(NN-1)+DIFDA*AMULT
      TWBA(I)=TWBAR(NN-1)+DIFWA*AMULT
      TDBE(I)=TDBER(NN-1)+DIFDI*AMULT
      TDBX(I)=TDBXR(NN-1)+DIFDE*AMULT
      TWBX(I)=TWBXR(NN-1)+DIFWE*AMULT
   16 CONTINUE
  150 CONTINUE
      IF(ICHK.GT.1) GO TO 303
      WRITE(06,96)
   96 FORMAT(/2X,'MEASURED THERMISTOR TEMP.(DEG.C)')
      WRITE(06,84)
      WRITE(06,85)
      DO 104 I=1,NHRP1
      HR=FLOAT(I-1)
      TDA=REST(TDBA(I))
      TWA=REST(TWBA(I))
      TDE=REST(TDBE(I))
      TDX=REST(TDBX(I))
      TWW=REST(TWBX(I))
  104 WRITE(06,133) HR,TDA,TWA,TDE,TDX,TWW
  133 FORMAT(F5.0,5F6.2)
  303 CONTINUE
      ITIME(1)=0
      DO 300 NN=2,NRESP
      IF(KTIME(NN-1).EQ.2400) GO TO 337
      ITOT=(KTIME(NN)-KTIME(NN-1))/100
  338 ITIME(NN)=ITIME(NN-1)+ITOT
      GO TO 347
  337 ITOT=KTIME(NN)/100
      GO TO 338
  347 IKOUNT=-1
      IBEGIN=ITIME(NN-1)+1
      IEND=ITIME(NN)
      RINT=FLOAT(ITIME(NN)-ITIME(NN-1))
      DIFF=SPJ(NN)-SPJ(NN-1)
      IF(NN.EQ.NRESP) IEND=IEND+1
      DO 316 I=IBEGIN,IEND
```

```
      IKOUNT=IKOUNT+1
      AMULT=FLOAT(IKOUNT)
      IF(I.EQ.IBEGIN) AMULT=0.0
      AMULT=AMULT/RINT
      SP(I)=SPJ(NN-1)+DIFF*AMULT
  316 CONTINUE
  300 CONTINUE
      IF(ICHK.GT.1) GO TO 302
      WRITE(06,186)
  186 FORMAT(/2X,'CHECK OF INTERPOLATION TO OBTAIN HOURLY VALUES FOR STA
     &TIC PRESS. AND TEMP.')
      WRITE(06,87)
   87 FORMAT(/2X,'HR',1X,'STATIC PRESS.',1X,'TDB(AMBIENT)',/)
      DO 301 I=1,NHRP1
      HR=FLOAT(I-1)
  301 WRITE(06,132) HR,SP(I),TDBA(I)
  132 FORMAT(F5.0,2X,F6.3,7X,F7.3)
  302 CONTINUE
C
C***********************************************************************
C***     CALCULATE THE SURFACE AREA OF THE DRYER AROUND EACH           **
C***     LAYER OF PEANUTS. THE CROSS SECTIION OF THE DRYERS IS         **
C***     0.5 BY 0.5 M.                                                 **
C***********************************************************************
C
      DD=DEPTH/FLOAT(M)
      AWALL=(DD*0.50)*4.0
C
C***********************************************************************
C**    INITIALIZE DRYING CONDITIONS                                    **
C***********************************************************************
C
C***********************************************************************
C***                                                                  **
C***          1. TIMDRY = SIMULATION TIME (HR).                       **
C***                                                                  **
C***          2. AMOWB = INITIAL MOISTURE CONTENT WET BASIS (DEC).    **
C***                                                                  **
C***          3. AMODB = INITIAL MOISTURE CONTENT DRY BASIS (DEC).    **
C***                                                                  **
C***          4. M = NUMBER OF LAYERS.                                **
C***                                                                  **
C***          5. AMP = PEANUT SOLIDS PER LAYER (KG).                  **
C***                                                                  **
C***          6. XMP = AN ARRAY CONTAINING THE DRY BASIS MOISTURE     **
C***             CONTENT OF EACH LAYER AT THE BEGINNING OF TIME       **
C***             INTERVAL DELT (DEC)                                  **
C***                                                                  **
C***          7. XM = AN ARRAY CONTAINING THE DRY BASIS MOISTURE      **
C***             CONTENT OF EACH LAYER AT THE BEGINNING OF TIME       **
C***             INTERVAL DELT (DEC)                                  **
C***                                                                  **
C***          8. XM1 = AN ARRAY CONTAINING THE DRY BASIS MOISTURE     **
C***             CONTENT OF EACH LAYER AT THE END OF TIME             **
C***             INTERVAL DELT (DEC)                                  **
```

```
C***
C***              9. TP = AN ARRAY CONTAINING THE PEANUT TEMPERATURE       **
C***                 OF EACH LAYER AT THE BEGINNING OF TIME INTERVAL       **
C***                 DELT (C)                                              **
C***                                                                       **
C***             10. TP1 = AN ARRAY CONTAINING THE PEANUT TEMPERATURE      **
C***                 OF EACH LAYER AT THE END OF TIME INTERVAL DELT (C)    **
C***                                                                       **
C**************************************************************************
C
      TENER=0.0
      TIMDRY=0.0
      AMODB=AMOWB/(1.-AMOWB)
      XMA=AMODB
C
C**************************************************************************
C***     CALCULATE PEANUT SOLIDS PER LAYER (KG)                          **
C**************************************************************************
C
      AMP=BD*AREA*DD
C
C**************************************************************************
C***     INITITALIZE THE XMP,XM,XM1,TP,TP1 ARRAYS                        **
C**************************************************************************
C
      DO 15 J=1,M
      XMP(J)=AMODB
      XM(J)=AMODB
      XM1(J)=AMODB
      TP(J)=TPO
   15 TP1(J)=TPO
C
C**************************************************************************
C***     THE PROGRAM LOOPS THROUGH ALL THE CALCULATIONS FOR EACH HOUR    **
C***     IOUT IS A COUNTER USED TO SELECT THE INTERVAL FOR PRINTING A    **
C***     TABLE WITH THE EXITING CONDITIONS FOR THE INDIVIDUAL LAYERS     **
C**************************************************************************
C
      IOUT=1
      DO 200 NN=2,NHRP1
C
C**************************************************************************
C***  CONTINUATION OF TEMPERATURE INTERPOLATION. HERE THE HOURLY         **
C***   VALUES ARE USED TO CALCULATE THE VALUES AT THE END OF EACH        **
C***   DELT INTERVAL                                                     **
C**************************************************************************
C
      IKOUNT=-1
      ADD=(TDBE(NN)-TDBE(NN-1))/FLOAT(IPHR)
      ADDAM=(TDBA(NN)-TDBA(NN-1))/FLOAT(IPHR)
      ADDWAM=(TWBA(NN)-TWBA(NN-1))/FLOAT(IPHR)
      ADDDAB=(TDBX(NN)-TDBX(NN-1))/FLOAT(IPHR)
      ADDWAB=(TWBX(NN)-TWBX(NN-1))/FLOAT(IPHR)
      ADDSP=(SP(NN)-SP(NN-1))/FLOAT(IPHR)
      DO 20 IN=1,IPHR
```

```
      IKOUNT=IKOUNT+1
      AMULT=FLOAT(IKOUNT)
      IF(IN.EQ.1) AMULT=0.0
      TDBEI(IN)=TDBE(NN-1)+ADD*AMULT
      TDBAI(IN)=TDBA(NN-1)+ADDAM*AMULT
      TWBAI(IN)=TWBA(NN-1)+ADDWAM*AMULT
      TDBXI(IN)=TDBX(NN-1)+ADDDAB*AMULT
      TWBXI(IN)=TWBX(NN-1)+ADDWAB*AMULT
      SPI(IN)=SP(NN-1)+ADDSP*AMULT
   20 CONTINUE
C
C***********************************************************************
C***     THE PROGRAM LOOPS THROUGH THE CALCULATIONS FOR EACH DELT     **
C***     INTERVAL WITHIN THE HOUR. NOTE THAT THE PRODUCT MOISTURE     **
C***     CONTENT AND TEMPERATURE AT THE BEGINNING OF ONE DELT         **
C***     INTERVAL IS SET EQUAL TO THE VALUES AT THE END OF THE        **
C***     PRECEEDING INTERVAL                                          **
C***********************************************************************
C
C***     LOOPING STARTS HERE ******************************************
      DO 100 I=1,IPHR
      TIMDRY=TIMDRY+DELT
      DO 21 J=1,M
      XM(J)=XM1(J)
   21 TP(J)=TP1(J)
C
C***********************************************************************
C***     THE AIRFLOW RATE(CUBIC M/MIN) IS CALCULATED BASED ON STATIC  **
C***      PRESSURE MEASURED BENEATH THE PRODUCT                       **
C***     THE STANDARD METHOD OF TESTING FANS (ASHRAE STANDARD 51-75)  **
C***      WAS USED TO MEASURE OF AIRFLOW RATES AT VARIOUS STATIC      **
C***      PRESSURES AND FAN RPMS.                                     **
C***     THE GENERAL EQUATION FOR A CONIC SECTION WAS FIT TO THE DATA **
C***     TO OBTAIN AN EQUATION OF THE FORM Y=E+D*X+SQRT(A+B*X+C*X**2) **
C***********************************************************************
C
C
      VDOT=(-1840.00*SPI(I)+166.20)*0.0283
C
C***********************************************************************
C***     VARIABLE DEFINITIONS                                         **
C***********************************************************************
C
C***********************************************************************
C***                                                                  **
C***          1. TDAMB = AMBIENT DRY BULB AIR TEMPERATURE (C).        **
C***                                                                  **
C***          2. TWBAM = AMBIENT WET BULB AIR TEMPERATURE (C).        **
C***                                                                  **
C***          3. POUT = AN ARRAY CONTAINING THE VALUES CALCULATED     **
C***             BY SUBROUTINE PSYC.                                  **
C***                                                                  **
C***          4. HE = HUMIDITY RATIO OF THE AIR ENTERING A            **
C***             LAYER (DEC).                                         **
C***                                                                  **
```

```
C***             5. TE = DRY BULB TEMPERATURE OF AIR ENTERING A        **
C***                LAYER (C).                                         **
C***                                                                   **
C***             6. RHE = RELATIVE HUMIDITY OF AIR ENTERING A          **
C***                LAYER (DEC).                                       **
C***                                                                   **
C***             7. TDPE = DEW POINT TEMPERATURE OF AIR ENTERING A     **
C***                LAYER (C).                                         **
C***                                                                   **
C***             8. TWBE = WET BULB TEMPERATURE OF AIR ENTERING A      **
C***                LAYER (C).                                         **
C***                                                                   **
C***             9. SHE = ENTHALPY OF AIR ENTERING A LAYER (J/KG).     **
C***                                                                   **
C***            10. TX = DRY BULB TEMPERATURE OF AIR EXITING A LAYER (C) **
C***                                                                   **
C***            11. PVX = PARTIAL VAPOR PRESSURE OF EXITING AIR (PA)   **
C***
C***            12. HX = HUMIDITY RATIO OF AIR EXITING A LAYER (DEC)
C***
C***            13. HS = HUMIDITY RATIO AT SATURATION (DEC).           **
C***                                                                   **
C***            14. VSA = SPECIFIC VOLUME OF AIR ENTERING A LAYER      **
C***                (CUBIC M/KG).                                      **
C***                                                                   **
C***            15. XME = DRY BASIS EQUILIBRIUM MOISTURE CONTENT OF A  **
C***                LAYER OF PEANUTS (DEC).                            **
C***                                                                   **
C***            16. XMDOT = RATE OF CHANGE IN MOISTURE CONTENT IN      **
C***                A LAYER.                                           **
C***                                                                   **
C***            17. DELM = MOISTURE CONTENT DIFFERENTIAL CALCULATED FOR **
C***                TIME INTERVAL DELT                                 **
C***                                                                   **
C***            18. DELMDA = MASS FLOW RATE OF DRYING AIR (KG/HR).     **
C***                                                                   **
C***            19. DELW = HUMIDITY RATIO DIFFERENTIAL OF AIR ENTERING **
C***                AND EXITING A LAYER (DEC).                         **
C***                                                                   **
C***            20. HFGDP = LATENT HEAT OF VAPORIZATION AT DEW POINT   **
C***                TEMPERATURE (J/KG).                                **
C***                                                                   **
C***            21. DELQS = ENERGY LOST TO SURROUNDINGS THROUGH DRYER  **
C***                WALLS SURROUNDING A LAYER(KJ)                      **
C***                                                                   **
C***            22. DELQM = CHANGE IN SENSIBLE HEAT IN A LAYER (KJ)    **
C***                                                                   **
C*********************************************************************
C
C*********************************************************************
C***      USE THE AMBIENT DRY BULB AND WET BULB TEMPERATURES TO        **
C***        CALCULATE THE HUMIDITY RATIO OF THE AIR ENTERING THE       **
C***        FIRST LAYER                                                **
C*********************************************************************
C
```

```
      TDAMB=REST(TDBAI(I))
      TWAMB=REST(TWBAI(I))
      CALL PSYC(1,TDAMB,TWAMB,POUT)
      SHA=POUT(8)/1000.
      HE=POUT(4)
      TDBEX=REST(TDBXI(I))
      TWBEX=REST(TWBXI(I))
      CALL PSYC(1,TDBEX,TWBEX,POUT)
      HE1=POUT(4)
      IF(TIMDRY.GE.25.0.AND.TIMDRY.LT.49.0) HE=(0.60*HE+.40*HE1)
      IF(TIMDRY.GE.49.0.AND.TIMDRY.LT.73.0) HE=(.40*HE+.60*HE1)
      IF(TIMDRY.LT.25.0) HE=(0.75*HE+0.25*HE1)
      TE=REST(TDBEI(I))
C
C***********************************************************************
C***     CALCULATE THE CONDITIONS ENTERING THE FIRST LAYER(EXITING  **
C***     THE 'ZERO' LAYER)                                            **
C***********************************************************************
C
      CALL PSYC(2,TE,HE,POUT)
      TX0=TE
      HX0=HE
      RHX0=POUT(1)
      TDPX0=POUT(2)
      TWBX0=POUT(3)
      SHX0=POUT(8)/1000.
      XME0=XMEF(TX0,RHX0)
C
C***********************************************************************
C***     THE PROGRAM LOOPS THROUGH THE CALCULATIONS FOR EACH LAYER   **
C***********************************************************************
C
      DO 75 J=1,M
C
C***********************************************************************
C***     CALCULATE PSYCHROMETRIC PROPERTIES OF AIR ENTERING A LAYER  **
C***********************************************************************
C
      CALL PSYC (2,TE,HE,POUT)
      RHE=POUT(1)
      TDPE=POUT(2)
      TWE=POUT(3)
      HE=POUT(4)
      HS =POUT(5)
      SHE=POUT(8)/1000.
      VSA=POUT(9)
C
C***********************************************************************
C***     CALCULATE EQUILIBRIUM MOISTURE CONTENT                       **
C***********************************************************************
C
      XME =XMEF(TE,RHE)
      XMEM(J)=XME
C
C***********************************************************************
```

```
C***     PROPERTIES OF THE AIR AND PEANUTS ARE EVALUATED TO DETERMINE **
C***     IF HEATING OR COOLING AND WETTING OR DRYING ARE OCCURING.    **
C***  MOD1:  1=HEAT,DRY   2=HEAT,WET   3=COOL,DRY   4=COOL,WET       **
C***********************************************************************
C
      MOD1=1
C
C***********************************************************************
C***     IF THE AIR TEMPERATURE ENTERING A LAYER OF PEANUTS IS        **
C***     LESS THAN THE PEANUT TEMPERATURE THEN THE PEANUTS ARE COOLED **
C***********************************************************************
C
      IF(TE.LT.TP(J)) MOD1=3
C
C***********************************************************************
C***     IF THE EQUILIBRIUM MOISTURE CONTENT IS GREATER THAN THE      **
C***     MOISTURE CONTENT OF THE PEANUTS THEN THE PEANUTS ARE WETTED  **
C***********************************************************************
C
      IF(XME.GT.XM(J)) MOD1=MOD1+1
      IMOD1(J)=MOD1
C
C***********************************************************************
C***     CALCULATE THE MOISTURE RATIO                                 **
C***********************************************************************
C
      XMR=(XM(J)-XME)/(XMP(J)-XME)
      XMRM(J)=XMR
C
C***********************************************************************
C***     IF THE MOISTURE RATIO IS LESS THAN 0 AN ERROR MESSAGE IS     **
C***     GENERATED.                                                   **
C***********************************************************************
C
      IF(XMR.GT.0) GO TO 28
      WRITE(06,500) XMR,XMP(J),XM(J),XME
  500 FORMAT(1H0,'*ERROR*XMDOT*',2X,'XMR=',F6.3,2X,'XMO=',F6.3,2X,'XM='
     &,F6.3,2X,'XME=',F6.3)
   28 CONTINUE
      DELT1=DELT
      DELTS=0
      XMS=XM(J)
C
C***********************************************************************
C***    FUNCTION XMDOTF CALCULATES THE RATE OF MOISTURE LOSS OR GAIN. **
C***********************************************************************
C
   30 XMDOT=XMDOTF(TE,TDPE,XMP(J),XME,XM(J),A,B)
C  30 XMDOT=-0.0536*(XM(J)-0.066)
      XM1(J)=XMS+XMDOT*DELT1
      XMDOT1=XMDOTF(TE,TDPE,XMP(J),XME,XM1(J),A,B)
      XM2=XMS+((XMDOT+XMDOT1)/2.)*DELT1
      TERM=XM1(J)-XM2
C
C***********************************************************************
```

```
C***      IF XMDOT DOES NOT CONVERGE, TIME STEP IS HALVED             **
C***********************************************************************
C
   33 IF(TERM.LT.1.E-2) GO TO 31
      IF(DELT1.LT..01) GO TO 31
      DELT1=DELT1/2.
      GO TO 30
   31 CONTINUE
      DELTS=DELTS+DELT1
      IF(DELTS.GE.DELT) GO TO 312
      XMS=XM2
      GO TO 30
  312 XM1(J)=XM2
C
C***********************************************************************
C***      ERROR MESSAGE IS GENERATED IF THE CALCULATED MOISTURE CONTENT**
C***      AT THE END OF TIME INTERVAL DELT DOES NOT FALL BETWEEN      **
C***      0 AND 2.00                                                  **
C***********************************************************************
C
      IF(XM1(J).GT.0.AND.XM1(J).LT.2.) GO TO 32
      WRITE(06,501)
      WRITE(06,502)
      WRITE(06,503)TIMDRY,J,XM(J),XM1(J),XME,XMR,HE,RHE,TE,TDPE,TWBE,T
     &P(J)
  501 FORMAT(1H0,'*ERROR*')
  502 FORMAT(/2X,'TIMDRY',2X,'LAYER NO.',4X,'XM',8X,'XM1',7X,'XME',8X,
     &'XMR',7X,'HE',8X,'RHE',7X,'TE',6X,'TDPE',6X,'TWBE',6X,'TP')
  503 FORMAT(/,F10.2,4X,I2,4X,4F10.3,1X,E9.4,F10.3,4F10.2)
   32 CONTINUE
C
C***********************************************************************
C***      MOISTURE CONTENT DIFFERENTIAL(D.B.) DURING A TIME INTERVAL  **
C***********************************************************************
C
      DELM=XM(J)-XM1(J)
C
C***********************************************************************
C***      MASS FLOW RATE OF AIR (KG/H)                                **
C***********************************************************************
C
      DELMDA=VDOT*60./VSA
C
C***********************************************************************
C***      MASS BALANCE: MOISTURE GAINED BY THE AIR IS EQUAL TO THAT   **
C***      LOST BY THE PRODUCT                                         **
C***********************************************************************
C
      HX(J)=HE+DELM*AMP/(DELMDA*DELT)
C
C***********************************************************************
C***      MAXIMUM MOISTURE LOSS IS LIMITED TO SATURATING THE AIR      **
C***********************************************************************
C
      IF(HX(J).LT.HS) GO TO 40
```

```
      HX(J)=HS
      DELW=HX(J)-HE
      XM1(J)=XM(J)-DELW*DELMDA*DELT/AMP
C
C***********************************************************************
C***     FUNCTION TPF CALCULATES AN INITIAL ESTIMATE OF THE PEANUT     **
C***     TEMPERATURE                                                   **
C***********************************************************************
C
   40 TP1(J)=TPF(TP(J) ,TE,I)
      GO TO (42,42,46,46),MOD1
C
C***********************************************************************
C***     IF THE PEANUT TEMP. CALCULATED IS LESS THAN THE PREVIOUS      **
C***     PEANUT TEMPERATURE, THE NEW TEMPERATURE IS SET EQUAL TO THE   **
C***     OLD. MOD1 IS EQUAL TO 1 OR 2, THERFORE HEATING IS OCCURING    **
C***     AND THE PEANUT TEMPERATURE SHOULD NOT BE LOWER THAN IT WAS    **
C***     DURING THE PREVIOUS TIME INTERVAL.                            **
C***********************************************************************
C
   42 IF(TP1(J).LT.TP(J)) TP1(J)=TP(J)
C
C***********************************************************************
C***     IF THE RESULTING PEANUT TEMPERATURE IS GREATER THAN THAN THE  **
C***     ENTERING AIR TEMPERATURE, THEN THE PEANUT TEMPERATURE IS      **
C***     SET EQUAL TO THE ENTERING AIR TEMPERATURE. THE PEANUT         **
C***     TEMPERATURE CAN NOT BE HIGHER THAN THE ENTERING AIR           **
C***     TEMPERATURE SINCE WE ARE NOT CONSIDERING ANY ENERGY RELEASED  **
C***     BY THE PEANUTS.                                               **
C***********************************************************************
C
      IF(TP1(J).GT.TE) TP1(J)=TE
      GO TO 50
C
C***********************************************************************
C***     IF THE PEANUT TEMPERATURE CALCULATED IS GREATER THAN THE      **
C***     PREVIOUS PEANUT TEMPERATURE THEN THE NEW TEMPERATURE IS SET   **
C***     EQUAL TO THE PREVIOUS PEANUT TEMPERATURE. MOD1 IS EQUAL       **
C***     TO 3 OR 4 THEREFORE COOLING IS OCCURING AND NO TEMPERATURE    **
C***     RISE SHOULD OCCUR IN THE PEANUTS.                             **
C***********************************************************************
C
   46 IF(TP1(J).GT.TP(J)) TP1(J)=TP(J)
C
C***********************************************************************
C***     IF THE RESULTING PEANUT TEMPERATURE IS LESS THAN THE EN-      **
C***     TERING AIR TEMPERATURE THEN IT IS SET EQUAL TO THE ENTERING   **
C***     AIR TEMPERATURE. WE DO NOT ALLOW THE PEANUT TEMPERATURE TO    **
C***     BE LOWER THAN THE ENTERING AIR TEMPERATURE AT THIS POINT.     **
C***********************************************************************
C
      IF(TP1(J).LT.TE) TP1(J)=TE
C
C***********************************************************************
C***     MOD2 IS A COUNTER THAT IS SET EQUAL TO ZERO AT THIS INITIAL   **
```

```
C***     DETERMINATION OF PEANUT TEMPERATURE                          **
C***********************************************************************
C
   50 MOD2=0
C
C***********************************************************************
C***     CALCULATE PARTIAL VAPOR PRESSURE OF EXITING AIR              **
C***********************************************************************
C
      PVX=HX(J)*PATM/(HX(J)+0.6219)
C
C***********************************************************************
C***     CALCULATE DEW POINT TEMPERATURE OF EXITING AIR (C)           **
C***********************************************************************
C
      TDPX(J)=DEW(PVX)-273.16
C
C***********************************************************************
C***   CALCULATE LATENT HEAT OF VAPORIZATION AT DEW POINT TEMPERATURE **
C***    (KJ/KG)                                                       **
C***********************************************************************
C
      HFGDP=2.502535E3-2.385764*TDPX(J)
C
C***********************************************************************
C*** CALCULATE CHANGE IN ENERGY STORED IN PRODUCT (KJ)
C***********************************************************************
C
   51 CONTINUE
      XCAP=(CP+XM(J)*CW)*TP(J)
      XCAP1=(CP+XM1(J)*CW)*TP1(J)
      DELQM=(XCAP1-XCAP)*AMP
C
C***********************************************************************
C***     CALCULATE STRUCTURAL HEAT LOSS (KJ)                          **
C***********************************************************************
C
      DELQS=(AWALL/TERMR)*(TP(J)-TDAMB)*DELT*1000.0
C
C***********************************************************************
C***     CALCULATE EXITING AIR TEMPERATURE (C)                        **
C***********************************************************************
C
      R1=SHE-4.1868*HX(J)*TDPX(J)-HFGDP*HX(J)
      R2=1.8757*HX(J)*TDPX(J)-4*((DELQM+DELQS)/(DELMDA*DELT))
      R3=1.00692540+1.8757*HX(J)
      TX(J)=(R1+R2)/R3
      GO TO (52,52,56,56),MOD1
C
C***********************************************************************
C***     GO TO 52 IF MOD1 REPRESENTS HEAT, DRY OR HEAT, WET           **
C***     (THIS MEANS THAT THE PEANUTS ARE WARMING AND THE AIRSTREAM   **
C***     IS COOLING.)                                                 **
C***     GO TO 56 IF MOD1 REPRESENTS COOL,DRY OR COOL,WET             **
C***     (THIS MEANS THAT THE PEANUTS ARE COOLING AND THE AIRSTREAM   **
```

```
C***     IS WARMING.)                                                 **
C***********************************************************************
C
C***********************************************************************
C***     IF THE EXITING AIR TEMPERATURE IS LESS THAN THE PEANUT TEMP- **
C***     ERATURE CALCULATED THEN THE PEANUT TEMPERATURE IS SET EQUAL  **
C***     TO THE EXITING AIR TEMPERATURE.                              **
C***********************************************************************
C
   52 IF(TX(J).GE.TP1(J)) GO TO 53
      TP1(J)=TX(J)
C
C***********************************************************************
C***     IF THE ENTERING WET BULB TEMPERATURE IS GREATER THAN THE     **
C***     EXITING AIR TEMPERATURE THEN THE PEANUTS ARE WETTING. NO     **
C***     EVAPORATIVE COOLING TAKES PLACE. SET TPI = TWE AND THEN      **
C***     RECALCULATE TX USING THE NEW TP1.                            **
C***********************************************************************
C
      IF(TWE.GT.TX(J)) TP1(J)=TWE
      IF(MOD2.EQ.1)GO TO 53
      MOD2=1
      GO TO 51
C
C***********************************************************************
C***     IF THE EXITING AIR TEMPERATURE IS GREATER THAN THE ENTERING  **
C***     AIR TEMPERATURE THEN THE EXITING AIR TEMPERATURE IS SET      **
C***     EQUAL TO THE ENTERING AIR TEMPERATURE.                       **
C***********************************************************************
C
   53 IF(TX(J).GT.TE) TX(J)=TE
C
C***********************************************************************
C***     IF THE EXITING AIR TEMPERATURE IS LESS THAN THE PREVIOUS     **
C***     PEANUT TEMPERATURE THEN THE EXITING AIR TEMPERATURE IS SET   **
C***     EQUAL TO THAT PEANUT TEMPERATURE.                            **
C***********************************************************************
C
      IF(TX(J).LE.TP(J)) TX(J)=TP(J)
      GO TO 70
C
C***********************************************************************
C***     IF THE EXITING AIR TEMPERATURE IS GREATER THAN THE PEANUT    **
C***     TEMPERATURE CALCULATED THEN THE PEANUT TEMPERATURE IS SET    **
C***     EQUAL TO THE EXITING AIR TEMPERATURE.                        **
C***********************************************************************
C
   56 IF(TX(J).LE.TP1(J)) GO TO 57
      TP1(J)=TX(J)
C
C***********************************************************************
C***     IF THE ENTERING WET BULB TEMPERATURE IS LESS THAN THE EXIT-  **
C***     ING AIR TEMPERATURE THEN THE PEANUTS ARE DRYING. EVAPORATIVE **
C***     COOLING TAPES PLACE. SET TP1 = TWE AND THEN RECALCULATE      **
C***     TX USING THE NEW TP1.                                        **
```

```
C***********************************************************************
C
      IF(TWE.LT.TX(J)) TP1(J)=TWE
      IF(MOD2.EQ.1)GO TO 57
      MOD2=1
      GO TO 51
C
C***********************************************************************
C***     IF THE EXITING AIR TEMPERATURE IS LESS THAN THE ENTERING     **
C***     AIR TEMPERATURE THEN THE EXITING AIR TEMPERATURE IS SET      **
C***     EQUAL TO THE ENTERING AIR TEMPERATURE.                       **
C***********************************************************************
C
   57 IF(TX(J).LT.TE) TX(J)=TE
C
C***********************************************************************
C***     IF THE EXITING AIR TEMPERATURE IS GREATER THAN THE PEANUT    **
C***     TEMPERATURE THEN THE EXITING AIR TEMPERATURE IS SET EQUAL    **
C***     TO THE PEANUT TEMPERATURE.                                   **
C***********************************************************************
C
      IF(TX(J).LE.TP(J)) GO TO 70
      TX(J)=TP(J)
   70 CONTINUE
C
C***********************************************************************
C***     COMPUTE PSYCHROMETRIC PROPERTIES OF AIR EXITING A LAYER      **
C***********************************************************************
C
C***********************************************************************
C***                                                                  **
C***          1. TWX = AN ARRAY CONTAINING THE VALUES OF WET BULB     **
C***             TEMPERATURE EXITING A LAYER.                         **
C***                                                                  **
C***          2. RHX = AN ARRAY CONTAINING THE RELATIVE HUMIDITY      **
C***             VALUES OF AIR EXITING A LAYER.                       **
C***                                                                  **
C***          3. SHX = AN ARRAY CONTAINING THE ENTHALPY VALUES OF     **
C***             AIR EXITING A LAYER.                                 **
C***                                                                  **
C***********************************************************************
C
      CALL PSYC(2,TX(J),HX(J),POUT)
      TWX(J)=POUT(3)
      RHX(J)=POUT(1)
      SHX(J)=POUT(8)/1000.
C
C***********************************************************************
C***     ENTERING CONDITIONS FOR A LAYER ARE THE EXITING              **
C***     CONDITIONS OF THE PREVIOUS LAYER.                            **
C***********************************************************************
C
      TE=TX(J)
      HE=HX(J)
   75 CONTINUE
```

```
     &  ',2X,' TWBX ',2X,' TDPX ',2X,'  RHX ',2X,'  HX  ',2X,'   SHX ',2
     &X,'   XME ',2X,'  XMR',/)
      DO 402 J=1,M
      JK=M+1-J
  402 WRITE(06,403)JK,XMWB(JK),XM1WB(JK),TX(JK),TWX(JK),TDPX(JK),RHX(J
     &K),HX(JK),SHX(JK),XMEM(JK),XMRM(JK)
  403 FORMAT(5X,I2,10X,F5.3,8X,F5.3,5X,F5.2,4X,F5.2,3X,F5.2,3X,F5.3,2X,F
     &6.4,3X,F7.2,3X,F5.3,3X,F5.3)
      WRITE(06,407) TX0,TWBX0,TDPX0,RHX0,HX0,SHX0,XME0
  407 FORMAT(/2X,'ENTERING AIR CONDITIONS',15X,F5.2,4X,F5.2,3X,F5.2,3X,F
     &5.3,2X,F6.4,3X,F7.2,3X,F5.3)
      WRITE(06,404) M,XMA
  404 FORMAT(/3X,'AVG.MC(W.B.) LAYERS(1-',I2,')',F7.3)
  310 CONTINUE
      IOUT=IOUT+1
      K=K+1
      OUT(K,1)=SHA
      OUT(K,2)=SHX(M)
      OUT(K,3)=DELMDA
      OUT(K,4)=TX(M)
      OUT(K,5)=XM1WB(M)
      OUT(K,6)=TWX(M)
      OUT(K,7)=TP1(M)
      OUT(K,8)=HS
      OUT(K,9)=HX(M)
      OUT(K,10)=SHX0
  200 CONTINUE
      WRITE(06,406)
  406 FORMAT(/2X,'HR',4X,'SHA',4X,'SHX',2X,'DELMDA',2X,'TX',2X,'XM1WB(10
     &)',2X,'TWX',5X,'TP1',5X,'HS',6X,'HX',6X,'SHX0',/)
      DO 201 K=1,NHR
      HR=FLOAT(K)
  201 WRITE(06,405) HR,(OUT(K,IK),IK=1,9)
  405 FORMAT(F5.0,2F7.2,F7.1,F6.2,F6.3,3X,F6.2,F8.2,F8.4,F8.4,F7.2)
C     DO 202 K=1,NHR
C     HR=FLOAT(K)
C     IF(K.LT.25) THEN DO
C     SHX1=0.0
C     SHA1=OUT(K,1)
C     END IF
C     IF(K.GE.25.AND.K.LT.49) THEN DO
C     SHX1=.3*OUT(K-1,2)
C     SHA1=.7*OUT(K,1)
C     END IF
C     IF(K.GE.49.AND.K.LT.60) THEN DO
C     SHX1=.35*OUT(K-1,2)
C     SHA1=.65*OUT(K,1)
C     END IF
C     IF(K.GT.60) THEN DO
C     SHX1=.4*OUT(K-1,2)
C     SHA1=.6*OUT(K,1)
C     END IF
C     ENER=(OUT(K,10)-(SHA1+SHX1))*OUT(K,3)
C     TENER=TENER+ENER
C     WRITE(29,2000) HR,OUT(K,10),SHA1,SHX1,OUT(K,3),ENER,TENER
```

```
C     FORMAT(8X,F4.0,4(2X,F7.2),2X,F8.2,2X,F10.2)
      STOP
      END
C
C************************************************************************
C***     PSYC                                                          **
C************************************************************************
C
C************************************************************************
C***     SUBROUTINE PSYC CALCULATES THE PSYCHROMETRIC PROPERTIES OF    **
C***     THE DRYING AIR BASED ON THE ASAE DATA SHEET D271.2 IN THE     **
C***     AGRICULTURAL ENGINEERING YEARBOOK.                            **
C************************************************************************
C***                                                                   **
C***     RECEIVES:                                                     **
C***                                                                   **
C***          1. MODE = FLAG TO SIGNAL WHICH VALUES ARE TO BE EN-      **
C***             TERED.                                                **
C***                                                                   **
C***                = 1 THEN DRY BULB AND WET BULB TEMPERATURES        **
C***                  ARE TO BE INPUT.                                 **
C***                                                                   **
C***                = 2 THEN DRY BULB TEMPERATURE AND HUMIDITY RATIO   **
C***                  ARE TO BE INPUT.                                 **
C***                                                                   **
C***          2. P1 = ENTERING DRY BULB TEMPERATURE (C).               **
C***                                                                   **
C***          3. P2 = WET BULB TEMPERATURE (C) OR HUMIDITY RATIO       **
C***             DEPENDING ON THE MODE (MODE).                         **
C***                                                                   **
C***     RETURNS:                                                      **
C***                                                                   **
C***          1. POUT AN ARRAY CONSISTING OF:                          **
C***                                                                   **
C***          2. RH = RELATIVE HUMIDITY (DEC).                         **
C***                                                                   **
C***          3. TDP = DEW POINT TEMPERATURE (C).                      **
C***                                                                   **
C***          4. TWB = WET BULB TEMPERATURE (C).                       **
C***                                                                   **
C***                                                                   **
C***          6. HS = SATURATION PRESSURE (PA).                        **
C***                                                                   **
C***          7. PV = PARTIAL VAPOR PRESSURE (PA).                     **
C***                                                                   **
C***          8. PS = SATURATION PRESSURE (PA).                        **
C***                                                                   **
C***          9. SH = ENTHALPY (J/KG).                                 **
C***                                                                   **
C***         10. VSA = SPECIFIC VOLUME (CUBIC M/KG).                   **
C***                                                                   **
C************************************************************************
C
      SUBROUTINE PSYC   (MODE,P1,P2,POUT)
      LOGICAL ERROR
```

```
      DIMENSION POUT(9)
      DATA PATM/101325./
      ERROR=.FALSE.
      TE=P1
      PS=PWS(TE)
      HS=0.6219*PS/(PATM-PS)
      GOTO(10,20),MODE
C
C***********************************************************************
C**      MODE 1   TA,TWBA --->  RH,TDP,TWB,H,HS,PV,PS,SH,VSA          **
C***********************************************************************
C
   10 CONTINUE
      TWBA=P2
      TWB=TWBA
      PSWB=PWS(TWBA)
      PV=PVWBDB(TE,TWBA,PSWB)
      H=0.6219*PV/(PATM-PV)
   14 PV=H*PATM/(H+.6219)
C
C***********************************************************************
C***     IF THE PARTIAL VAPOR PRESSURE IS LESS THAN ZERO AN ERROR     **
C***     MESSAGE IS GENERATED.                                        **
C***********************************************************************
C
      IF (PV.LE.0) GOTO 96
      TDP=DEW(PV)-273.16
   16 RH=PV/PS
   17 SH=ENTHAL(H,TDP,TE)
      VSA=287*(TE+273.16)/(PATM-PV)
      GOTO (90,24,24,24),MODE
C
C***********************************************************************
C***     MODE 2   TE,HE ---> RH,TDP,TWB,H,HS,PV,PS,SH,VSA             **
C***********************************************************************
C
C***********************************************************************
C***     IF MODE = 2 THEN P2 = H (HUMIDITY RATIO)                     **
C***********************************************************************
C***           5. H = HUMIDITY RATIO (DEC).                           **
C
   20 CONTINUE
      H=P2
      GOTO14
C
C***********************************************************************
C***     AN ITERATIVE PROCEDURE IS USED TO CALCULATE THE WET BULB     **
C***     TEMPERATURE.                                                 **
C***********************************************************************
C
   24 JN=0
      TWB=(TE+2*TDP)/3
   26 CONTINUE
      PSWB=PWS(TWB)
      B=BP(PSWB,PATM,PV,TWB)
```

```
      TWB1=TE+(PSWB-PV)/B
C
C***********************************************************************
C***     A DIFFERENCE OF LESS THAN 0.012 BETWEEN THE PREVIOUS WET     **
C***     BULB TEMPERATURE AND THE ONE BEING CALCULATED MUST BE OB-    **
C***     TAINED TO SATISFY THE CONVERGENCE CRITERIA.                  **
C***********************************************************************
C
      TWCV=ABS(TWB-TWB1)/TWB
      IF(TWCV.LT..012)GOTO 28
      TWB=(TWB1+2*TWB)/3
C***********************************************************************
C***     IF THE NUMBER OF ITERATIONS IS GREATER THAN 10 AN ERROR      **
C***     MESSAGE IS GENERATED.                                        **
C***********************************************************************
C
      JN=JN+1
      IF(JN.LT.10) GOTO 26
      GOTO 96
   28 TWB=TWB1
      GOTO 90
   96 CONTINUE
      ERROR=.TRUE.
   90 CONTINUE
C
C***********************************************************************
C***     IF THE RELATIVE HUMIDITY IS GREATER THAN 1.00  IT IS         **
C***     SET EQUAL TO 0.999.                                          **
C***********************************************************************
C
      IF(RH.GE..999) RH=.999
      POUT(1)=RH
      POUT(2)=TDP
      POUT(3)=TWB
      POUT(4)=H
      POUT(5)=HS
      POUT(6)=PV
      POUT(7)=PS
      POUT(8)=SH
      POUT(9)=VSA
      IF(ERROR) GOTO 98
      RETURN
C
C***********************************************************************
C***     ERROR MESSAGE IS GENERATED IF THE PARTIAL VAPOR PRESSURE     **
C***     IS LESS THAN 0 OR THE NUMBER OF ITERATIONS REQUIRED TO       **
C***     CALCULATE THE WET BULB TEMPERATURE IS GREATER THAN 10.       **
C***********************************************************************
C
   98 WRITE(MOUT,500) MODE,JN,P1,P2
  500 FORMAT(1H0,'**ERROR**PSYC**',2X,'MODE=',I2,2X,'ITER. NO.=',I2,2X,
     &'P1=',F8.4,2X,'P2=',F8.4)
      WRITE(MOUT,501) TWB,TWB1,TWCV
  501 FORMAT(2X,'TWB=',F6.2,2X,'TWB1=',F6.2,2X,'TWCV=',F8.4)
      RETURN
```

```
      END
C
C***********************************************************************
C***          XMEF                                                    **
C***********************************************************************
C
C***********************************************************************
C***     EQULIBRIUM MOISTURE CONTENT IS CALCULATED USING BEASLEY'S    **
C***     (1962) EQUATION FOR VIRGINIA BUNCH PEANUTS.                  **
C***********************************************************************
C
C***********************************************************************
C***                                                                  **
C***          1. TF1 = FARENHEIT TEMPERATURE USED IN CALCULATIONS.    **
C***                                                                  **
C***          2. AN = PARAMETER DEFINED BY BEASLEY.                   **
C***                                                                  **
C***          3. AK = PARAMETER DEFINED BY BEASLEY.                   **
C***                                                                  **
C***          4. TE = DRY BULB TEMPERATURE OF ENTERING AIR (C).       **
C***                                                                  **
C***          5. RHE = RELATIVE HUMIDITY OF ENTERING AIR (DEC).       **
C***                                                                  **
C***          6. XMEF = DRY BASIS EQUILIBRIUM MOISTURE CONTENT (DEC). **
C***                                                                  **
C***********************************************************************
C
      FUNCTION XMEF(TE,RHE)
      TF1 = (9./5. * TE) + 32.0
      IF (TF1.LT.70.0) GO TO 30
      AN = 1.94 - 0.0045 * (TF1 - 70.0)
      AK = (2.81 + 0.05 * (TF1 - 70.0))*1.0E-05
      GO TO 50
   30 AN = 1.94 + 0.0025 * (TF1 - 70.0)
      AK = (2.81 - 0.0025 * (TF1 - 70.0))*1.0E-05
   50 CONTINUE
      AX = 1.0/AN
      ARG=-ALOG(1.0-RHE)/(AK*(TF1+459.67))
      XMEFWB=ARG**AX/100.
      XMEF=XMEFWB/(1.0-XMEFWB)
      RETURN
      END
C
C***********************************************************************
C***          BP                                                      **
C***********************************************************************
C
C***********************************************************************
C***     AN EQUATION REPRESENTING THE WET BULB LINE                   **
C***     (ASAE D271.2).                                               **
C***********************************************************************
C
C***********************************************************************
C***                                                                  **
C***          1. HFGP = LATENT HEAT OF VAPORIZATION AT WET BULB       **
```

```
C**              TEMPERATURE (J/KG).                                  **
C***                                                                  **
C***          2. PSWB = SATURATION VAPOR PRESSURE (PA).               **
C***                                                                  **
C***          3. PATM = ATMOSPHERIC PRESSURE (PA).                    **
C***                                                                  **
C***          4. PV = VAPOR PRESSURE (PA).                            **
C***                                                                  **
C***          5. TWB = WET BULB TEMPERATURE (C).                      **
C***                                                                  **
C***          6. BP = WET BULB LINE ON PSYCHROMETRIC CHART.           **
C***                                                                  **
C***********************************************************************
C
      FUNCTION BP(PSWB,PATM,PV,TWB)
      B1=1006.9254*(PSWB-PATM)*(1.+0.15577*PV/PATM)
      HFGP=2.502553E6-2.385764E3*TWB
      BP=B1/(0.62194*HFGP)
      RETURN
      END
C
C***********************************************************************
C**           DEW                                                     **
C***********************************************************************
C
C***********************************************************************
C***     DEW POINT TEMPERATURE CALCULATED (ASAE D271.2)               **
C***********************************************************************
C
C***********************************************************************
C***                                                                  **
C***          1. PS = SATURATION VAPOR PRESSURE (PA).                 **
C***                                                                  **
C***          2. DEW = DEW POINT TEMPERATURE (K).                     **
C***                                                                  **
C***********************************************************************
C
      FUNCTION DEW(PS)
      X=ALOG(0.00145*PS)
      ARG1=13.6626*X+1.17678*X**2-0.189693*X**3
      ARG2=0.087453*X**4-0.0174053*X**5+2.14768E-3*X**6
      ARG3=-0.138343E-3*X**7+0.38E-5*X**8
      DEW=255.38+19.5322+ARG1+ARG2+ARG3
      RETURN
      END
C
C***********************************************************************
C***         ENTHAL                                                   **
C***********************************************************************
C
C***********************************************************************
C***     ENTHALPY OF AIR CALCULATED (ASAE D271.2)                     **
C***********************************************************************
C
C***********************************************************************
```

```
C***                                                                  **
C***         1. HFGDP = LATENT HEAT OF VAPORIZATION AT DEW POINT      **
C***            TEMPERATURE (J/KG).                                   **
C***                                                                  **
C***         2. HR = HUMIDITY RATIO (DEC).                            **
C***                                                                  **
C***         3. TDP = DEW POINT TEMPERATURE (C).                      **
C***                                                                  **
C***         4. TDB = DRY BULB TEMPERATURE (C).                       **
C***                                                                  **
C***         5. ENTHALPY = ENTHALPY (J/KG).                           **
C***                                                                  **
C***********************************************************************
C
      FUNCTION ENTHAL(HR,TDP,TDB)
      HFG2P=2.502535E6-2.385764E3*TDP
      ARG1=1.006925E3*TDB+4.1868E3*HR*TDP+HFG2P*HR
      ENTHAL=ARG1+1.875686E3*HR*(TDB-TDP)
      RETURN
      END
C
C***********************************************************************
C***         PVWBDB                                                   **
C***********************************************************************
C
C***********************************************************************
C***    PARTIAL VAPOR PRESSURE OF AIR IS CALCULATED (ASAE D271.2)     **
C***********************************************************************
C
C***********************************************************************
C***                                                                  **
C***         1. HFGP = LATENT HEAT OF VAPORIZATION (J/KG).            **
C***                                                                  **
C***         2. TDB = DRY BULB TEMPERATURE (C).                       **
C***                                                                  **
C***         3. TWB = WET BULB TEMPERATURE (C).                       **
C***                                                                  **
C***         4. PSWB = SATURATION VAPOR PRESSURE (PA).                **
C***                                                                  **
C***         5. PVWBDB = PARTIAL VAPOR PRESSURE OF AIR (PA).          **
C***                                                                  **
C***********************************************************************
C
      FUNCTION PVWBDB(TDB,TWB,PSWB)
      HFGP=2.502553E6-2.385764E3*TWB
      ARG1=0.62194*HFGP*PSWB-1.006925E3*(PSWB-101325.0)*(TWB-TDB)
      ARG2=0.62194*HFGP+156.8488*(PSWB-101325.)*(TWB-TDB)/101325.
      PVWBDB=ARG1/ARG2
      RETURN
      END
C
C***********************************************************************
C***    PWS                                                           **
C***********************************************************************
C
```

```
C***********************************************************************
C***     SATURATION VAPOR PRESSURE IS CALCULATED (ASAE D271.2)        **
C***********************************************************************
C
C***********************************************************************
C***                                                                  **
C***          1. TC = DRY BULB AIR TEMPERATURE (C).                   **
C***                                                                  **
C***          1. PWS = SATURATION VAPOR PRESSURE (PA).                **
C***                                                                  **
C***********************************************************************
C
      FUNCTION PWS(TC)
      T=TC+273.16
      ARG1=-27405.53+97.5413*T-0.146244*T**2
      ARG2=0.12558E-3*T**3-0.48502E-7*T**4
      ARG3=4.34903*T-0.39381E-2*T**2
      PWS=22105650.*EXP((ARG1+ARG2)/ARG3)
      RETURN
      END
C
C***********************************************************************
C***          TPF                                                     **
C***********************************************************************
C
C***********************************************************************
C***     THE CHANGE IN THE TEMPERATURE OF THE PEANUTS IS ESTIMATED    **
C***     BY ASSUMING THE PEANUT SHAPE CAN BE REPRESENTED AS A FINITE  **
C***     CYCLINDER. THE SOLUTION FOR THE TRANSIENT TEMPERATURE AT     **
C***     THE CENTER OF THE CYCLINDER CAN BE OBTAINED BY COMBINING     **
C***     THE SOLUTIONS FOR THE TRANSIENT TEMPERATURE OF AN INFINITE   **
C***     PLATE AND AN INFINITE CYCLINDER (TROEGER AND BUTLER, 1979).  **
C***********************************************************************
C
C***********************************************************************
C***                                                                  **
C***          1. SAO = THERMAL DIFFUSIVITY OF A PEANUT (SQ M/H).      **
C***                                                                  **
C***          2. TIME = DRYING TIME (H).                              **
C***                                                                  **
C***          3. EL = LENGTH OF PEANUT (M).                           **
C***                                                                  **
C***          4. D = DIAMETER OF PEANUT (M).                          **
C***                                                                  **
C***          5. TPO = INITIAL PEANUT TEMPERATURE (C).                **
C***                                                                  **
C***          6. TDB = DRY BULB TEMPERATURE (C).                      **
C***                                                                  **
C***          7. I = COUNTER WHICH REPRESENTS DRYING TIME.            **
C***                                                                  **
C***          8. TPF = PEANUT TEMPERATURE (C).                        **
C***                                                                  **
C***********************************************************************
C
      FUNCTION TPF(TPO,TDB,I)
```

```
      DATA SAO/2.2296E-4/,EL/3.7943E-2/,D/1.5558E-2/,DELT/0.25/,IPHR/4/
      J=I*IPHR
      TIME=(J-1)*DELT
      Z1=4.*SAO*TIME/EL**2
      Z2=4.*SAO*TIME/D**2
      P=-2.4606*Z1
      C=-5.7332*Z2
      IF(P.LT.-100) P=-10.
      IF(C.LT.-100) C=-10.
      P=EXP(P)*1.2665
      C=EXP(C)*1.5566
      IF(P.GE.1.) P=1.
      IF(C.GE.1.) C=1.
      TPF=(TPO-TDB)*P*C+TDB
      RETURN
      END
C
C*************************************************************************
C***     XMDOTF                                                         **
C*************************************************************************
C
C*************************************************************************
C***     RATE OF MOISTURE LOSS IS CALCULATED BASED ON TROEGER           **
C***     AND BUTLER'S (1979) EQUATIONS.                                 **
C*************************************************************************
C
C*************************************************************************
C***                                                                    **
C***           1. AMR = MOISTURE RATIO (DEC).                           **
C***                                                                    **
C***           2. T = DRY BULB TEMPERATURE (C).                         **
C***                                                                    **
C***           3. TDP = DEW POINT TEMPERATURE (C).                      **
C***                                                                    **
C***           4. AMO = DRY BASIS MOISTURE CONTENT OF PEANUTS AT THE    **
C***              PREVIOUS TIME INTERVAL (DEC).                         **
C***                                                                    **
C***           5. AME = DRY BASIS EQUILIBRIUM MOISTURE CONTENT (DEC).   **
C***                                                                    **
C***           6. AM = DRY BASIS MOISTURE CONTENT OF PEANUTS AT THE     **
C***              PRESENT TIME INTERVAL (DEC).                          **
C***                                                                    **
C***           7. A = DRYING EQUATION PARAMETER.                        **
C***                                                                    **
C***           8. B = DRYING EQUATION PARAMETER.                        **
C***                                                                    **
C***           9. XMDOTF = RATE OF MOISTURE LASS OR GAIN.               **
C***                                                                    **
C*************************************************************************
C
      FUNCTION XMDOTF(T,TDP,AMO,AME,AM,A,B)
      AMR=(AM-AME)/(AMO-AME)
      A1=0.02320+4.5E-4*T+6.3E-4*TDP+4.5E-4*TDP*AMO+8E-3*AMO
      B1=3.264-.025*T-.0162*TDP-.0342*TDP*AMO-.608*AMO
      A=A1
```

```
      B=B1
      IF(AMR.GE.0.40) GO TO 401
      IF(AMR.LE.0.12)GO TO 402
      A=A1*(2.40-AMO)
      B=B1*(0.88+0.20*AMO)
      GO TO 401
  402 A=A1*(2.4-AMO)**2
      B=B1*(0.88+0.2*AMO)**2
  401 CONTINUE
      XMDOTF=-A*(AMO-AME)*AMR**B
      RETURN
      END
C
C***********************************************************************
C***     AIR                                                          **
C***********************************************************************
C
C***********************************************************************
C***     STATIC PRESSURE MEASUREMENT USED TO CALCULATE AIRFLOW(M3/MIN)**
C***********************************************************************
C
C       FUNCTION AIR(P,A,B,C,D,E,S)
C            REAL*8 A,B,C,D,E
C            ARG=A+B*P+C*P**2
C            IF(ARG.GT.0.0) GO TO 10
C            WRITE(26,1) ARG
C    1       FORMAT(E20.4)
C            ARG=0.0
C   10       AIR=D*P+E+S*SQRT(ARG)
C       RETURN
C       END
C
C***********************************************************************
C***     REST                                                         **
C***********************************************************************
C
C***********************************************************************
C***     FUNCTION REST USES THE THERMISTER PROBE RESISTANCES AND      **
C***     CALCULATES THE TEMPERATURES (C)                              **
C***********************************************************************
C
       FUNCTION REST(R)
       REAL*8 A,B,C,D,E
       A=-2077.423
       B=4681.344
       C=498.4451
       D=21.7356
       E=100.1315
       S=-1.0
       ARG=A+B*R+C*R**2
       IF(ARG.GT.0.0) GO TO 10
       REST=100.0
       GO TO 20
   10  REST=D*R+E+S*SQRT(ARG)
   20  RETURN
```

```
      END
C***********************************************************************
C                    CORR
C***********************************************************************
C CORRECTION FOR THE MEASURED EXITING TEMPERATURE
C    THERMAL CONDUCTION AND FREE CONVECTION HEAT LOSS IS CALCULATED
C
      FUNCTION CORR(TDX1,TDA)
      REAL TDX1,TDA,ABS,TS,TS1,DT
      DO 600 II=1,18
       TS=TDX1
  601 DT=0.00742*((TS-TDA)**1.25)
      TS1=-9.8765*DT + TDX1
      IF (ABS(TS-TS1) .GE. 0.01) GO TO 602
        TDX1=TDX1 + DT
        GO TO 600
  602   TS = TS1
        GO TO 601
  600 CONTINUE
      CORR = TDX1
  603 RETURN
      END
C$ENTRY
/*
//GO.SYSIN DD *
 4 2 1986
 14 14  64 2 4
 4 07
 0.25  0.1295 20.0 248.88 0.76  54.65 301.3
2000 0.055
2400 0.055
0800 0.055
1200 0.055
1600 0.055
2000 0.055
2400 0.055
0800 0.055
1200 0.055
1600 0.055
2000 0.055
2400 0.055
0800 0.055
1200 0.050
2000 5.793 7.553 4.070 5.008 6.822
2400 6.561 8.053 3.462 4.980 6.660
0800 7.455 8.808 3.378 4.479 7.252
1200 6.497 8.229 3.485 4.102 6.891
1600 5.520 7.855 3.415 3.833 6.835
2000 5.832 7.998 3.440 3.928 6.969
2400 6.363 8.389 3.430 4.092 7.181
0800 8.259 9.159 3.450 4.408 7.057
1200 6.600 8.236 3.436 4.065 6.830
1600 5.934 8.170 3.435 3.831 6.800
2000 5.970 7.967 3.386 3.855 6.760
2400 6.127 8.088 3.518 3.917 6.814



0800 7.297 8.234 3.502 4.187 6.801
1200 7.208 8.198 3.616 4.276 6.812
/*
//
```

```
//A235PRO  JOB 50283,PROBM1,REGION=3500K
/*LONGKEY  AERSUX
/*ROUTE PRINT VPIVM1.PROBM1
/*PRIORITY IDLE
/*JOBPARM  LINES=15,CARDS=50000
//STEP1  EXEC FRTVCLGV
//FORT.SYSIN DD *
C***********************************************************************
C            ENERGY ... A HEAT BALANCE MODEL FOR ANALYSING DATA FROM
C                       THE PEANUT DRYING TESTS...
C***********************************************************************
C     DIMENSION TIME(25), SP(25)
      REAL N,SP
      INTEGER IHR
C***********************************************************************
C     ENERGY DATA:INTERVAL (HOURS), C1, C2, VOLT, QSS1
C***********************************************************************
      N=0.25
C INITIAL ENERGY STORED IN THE FAN, MJ
      QSS1=0.1037
C CONSTANTS FOR ENERGY TRANSDUCER
C       C1=57.15378905
C       C2=-0.31601435
C LINE VOLTAGE FOR THE ELEC. HEATERS., VOLTS
      VOLT=215
C***********************************************************************
C READ THE STATIC PRESSURE READINGS
C***********************************************************************
C
C     READ(05,6)NST
C     DO 4 K=1, NST
C     READ (05,3) TIME(K),SP(K)
C   4 CONTINUE
C***********************************************************************
C***INITIALIZE THE VARIABLES
C***********************************************************************
C
      SUMQX=0.0
      SUMQX1=0.0
      SUMQF=0.0
      SUMQSL=0.0
      SUMQSS=0.0
      SUMQE=0.0
C     MLOSS=0.0
C
C***********************************************************************
      READ(05,9)R1,R2,R3
      READ(05,9)T1,T2,T3
C***********************************************************************
C   THE PROGRAM CALCULATES ENERGY QUANTITIES AT EACH HOUR
C***********************************************************************
      DO 10 I=1,1000
        READ(05,1,END=20)IHR,SP,TDBA,TWBA,TDBI,TDBE,TWBE,V1,V2,V3,V4
        VDOT =(178.3836-6304.1415*(SP**2))*0.02832
        TDBA = TDBA + 273.16
```

```
        TDBE = TDBE + 273.16
        TWBA = TWBA + 273.16
        TWBE = TWBE + 273.16
         HR1 = FLOAT(IHR)
        IF(HR1.LE.T1)REC=R1
        IF(HR1.GT.T1.AND.HR1.LE.T2)REC=R2
        IF(HR1.GT.T2)REC=R3
        TR=TDBE
        TWBR=TWBE
   25   CALL ENTHAL(TDBA,TWBA,HA,HRA)
        SPV= SPVOL(TDBA,TWBA)
        AMB=1.0-REC
        CALL ENTHAL(TR,TWBR,HAR,HRAR)
C     WRITE(06,999)HA,HRA,HAR,HRAR
C 999 FORMAT(4F10.5)
        HA=HA*AMB + HAR*REC
        HRA=HRA*AMB + HRAR*REC
C     WRITE(06,998)HA,HRA
C 998 FORMAT(2F10.5)
C  30 CALL ENTHAL(TDBE,TWBE,HX,HRX)
        TDBA=TDBA-273.16
        TDBE=TDBE-273.16
        TWBA=TWBA-273.16
        TWBE=TWBE-273.16
        TR=TR-273.16
        TWBR=TWBR-273.16
C**********************************************************************
C**AMOUNT OF MOISTURE REMOVED******************************************
C**********************************************************************
C       DELML=MOIS(HRA,HRAR,VDOT,SPV,1)
C       MLOSS=MLOSS + DELML
C**********************************************************************
C**ENERGY LOST DURING DRYING****
C**********************************************************************
        QEXCH=QX(VDOT,TDBI,HAR,HRA,SPV,1)
C**********************************************************************
C SENSIBLE HEAT GAINED BY AIR
C**********************************************************************
        QSEN=QX1(VDOT,TDBI,HRA,HA,SPV,1)
C**********************************************************************
C**SUPPLEMENTAL HEAT ADDED TO AIR
C**********************************************************************
        QSUPP=QF(V1,VOLT,N) + QF(V2,VOLT,N)
     &       +QF(V3,VOLT,N) + QF(V4,VOLT,N)
C**********************************************************************
C**HEAT LOSS THROUGH THE COLUMN WALLS.
C**********************************************************************
        QHLOSS=QSL(TDBA,TDBI,TDBE)
C**********************************************************************
C***CHANGED IN THE STORED ENERGY
C**********************************************************************
        QSS2=QSS(TDBI)
        DELQSS=QSS2-QSS1
        QSS1=QSS2
C**********************************************************************
```

```
C*** ERROR TERM!
C**********************************************************************
        QE=QSUPP-(DELQSS+QHLOSS+QSEN)
C**********************************************************************
C***SUMMATION OF ENERGY TERMS
C**********************************************************************
        SUMQX=SUMQX+QEXCH
        SUMQX1=SUMQX1+QSEN
        SUMQF=SUMQF+QSUPP
        SUMQSL=SUMQSL+QHLOSS
        SUMQSS=SUMQSS+DELQSS
        SUMQE=SUMQE+QE
C**********************************************************************
C****OUTPUT
C**********************************************************************
        WRITE(06,2)QEXCH,QSEN,QSUPP,QHLOSS,DELQSS,QE
   10 CONTINUE
   20 WRITE(06,2)SUMQX,SUMQX1,SUMQF,SUMQSL,SUMQSS,SUMQE
    1 FORMAT(I2,F6.3,F6.2,F6.2,F6.2,F6.2,F6.2,F7.4,F7.4,F7.4,F7.4)
    2 FORMAT(F9.4,F9.4,F9.4,F9.4,F9.4,F9.4)
    3 FORMAT(F4.1,F8.4)
    5 FORMAT(3F5.1)
    6 FORMAT(I3)
    9 FORMAT(3F7.4)
      STOP
      END
C**********************************************************************
C**********************************************************************
C**********SUBPROGRAMS*************************************************
C**********************************************************************
C**********************************************************************
      FUNCTION QX(VDOT,TDBI,HAR,HRA,SPV,INT)
          HE=(1.006*TDBI+HRA*(2501+1.775*TDBI))*1000
         QX2=60.0*VDOT*(HE-HAR)/(1.E+06*SPV)
         QX =QX2*FLOAT(INT)
         RETURN
         END
      FUNCTION QX1(VDOT,TDBI,HRA,HA,SPV,INT)
          HE=(1.006*TDBI+HRA*(2501+1.775*TDBI))*1000
         QX1=60.0*VDOT*(HE-HA)*FLOAT(INT)/(SPV*1.E+06)
         RETURN
         END
C
      FUNCTION QF(VOUT,VOLT,N)
         REAL N
         AMP=0.025*VOUT*1000.0
         QF=(VOLT*AMP)*N*3600.*1.E-06
         RETURN
         END
      FUNCTION QSL(TDBA,TDBI,TDBE)
         DATA A1,A2,A4,A5,A6/2.48,6.13,16.78,0.233,7.02/
         DT1=TDBI-TDBA
         DT2=TDBI-TDBA
         DT4=0.0
         DT5=TDBE-TDBA
```

```
         DT6=0.0
         RVAL1=301.27
         Q1=(A1/RVAL1)*DT1
         Q2=(A2/RVAL1)*DT2
         Q4=(A4/RVAL1)*DT4
         Q5=(A5/RVAL1)*DT5
         Q6=(A6/RVAL1)*DT6
         QSL=(Q1+Q2+Q4+Q5+Q6)
         RETURN
         END
      FUNCTION QSS(TDBI)
         AMASS=9.979
         SPH=0.502
         QSS=AMASS*SPH*TDBI/1000.
         RETURN
         END
C***********************************************************************
C***** SUBROUTINE ENTHAL ***********************************************
C***********************************************************************
      SUBROUTINE ENTHAL(TDB,TWB,H,HRAT)
         PSWB=PS(TWB)
         HFGWB=LATENT(TWB)
         PV=WBLINE(HFGWB,PSWB,TWB,TDB)
         HRAT=HUMRAT(PV,TDB)
         TDP=SATUR(PV)
         HFGDP=LATENT(TDP)
         IF(255.38.LE.TDP.AND.TDP.LE.273.16)H=1006.9254*(TDB-273.16)
     &-HRAT*(333432.1+2030.5980*(273.16-TDP))+HFGDP*HRAT
     &+1875.6864*HRAT*(TDB-TDP)
         IF(273.16.LT.TDP.AND.TDP.LE.373.16)H=1006.9254*(TDB-273.16)+
     &4186.8*HRAT*(TDP-273.16)+HFGDP*HRAT+1875.6864*HRAT*(TDB-TDP)
         RETURN
         END
      FUNCTION HUMRAT(PV,T)
         PATM=101325.0
         IF(255.38.LE.T.AND.T.LE.533.16)HUMRAT=0.6219*PV/(PATM-PV)
         RETURN
         END
      FUNCTION WBLINE(HFGWB,PSWB,TWB,TDB)
         PATM=101325.
         DEPRES=TWB-TDB
         ARG1=(1006.9254*(PSWB-PATM)/(0.6294*HFGWB))*DEPRES
         ARG2=(ARG1*0.15577/PATM)*DEPRES
         WBLINE=(PSWB-ARG1)/(1.+ARG2)
         RETURN
         END
      FUNCTION PS(T)
         R=22105649.25
         A=-27405.526
         B=97.5413
         C=-0.146244
         D=0.125588E-03
         E=-0.480502E-07
         F=4.34903
         G=0.39381E-02
```

```
      PS=R*EXP((A+B*T+C*T**2+D*T**3+E*T**4)/(F*T-G*T**2))
      RETURN
      END
    FUNCTION LATENT(T)
      LATENT = 2502535.259-2385.76424*(T-273.16)
      RETURN
      END
    FUNCTION SATUR(PS)
      DIMENSION A(9)
      REAL ALOG
      DATA A/19.5322,13.6626,1.17678,-0.189693,0.087453,-0.0174053,
     & 0.00214768,-0.138343E-03,0.38E-05/
      SUM=0.
      DO 11 I=1,9
        J=I-1
      SUM=SUM+A(I)*(ALOG(0.00145*PS))**J
  11  CONTINUE
      SATUR=SUM+255.38
      RETURN
      END
    FUNCTION SPVOL(TDB,TWB)
      PATM=101325.
      PSWB=PS(TWB)
      HFGWB=LATENT(TWB)
      PV=WBLINE(HFGWB,PSWB,TWB,TDB)
      SPVOL=287.*TDB/(PATM-PV)
      RETURN
      END
/*
//GO.SYSIN DD *
00.2500 0.4000 0.6000
 0.000 24.00  48.00
 0 0.120 14.91 11.13 33.21 16.28 12.39 0.1542 0.1512 0.1409 0.1673
 1 0.120 15.50 11.25 33.42 17.43 13.45 0.1736 0.1698 0.1525 0.1516
 2 0.120 16.11 11.36 33.63 18.65 14.58 0.1469 0.1546 0.1433 0.1334
 3 0.120 16.74 11.48 33.85 19.96 15.77 0.1359 0.1278 0.1321 0.1357
 4 0.120 17.39 11.60 34.06 21.36 17.05 0.1394 0.1426 0.1294 0.1354
 5 0.120 17.77 11.85 34.04 21.80 17.16 0.1127 0.1137 0.0998 0.1074
 6 0.120 18.15 12.10 34.01 22.25 17.28 0.1201 0.1053 0.0918 0.0909
 7 0.120 18.55 12.36 33.99 22.72 17.39 0.1097 0.1172 0.1155 0.1237
 8 0.120 18.95 12.62 33.96 23.19 17.51 0.1281 0.1282 0.1295 0.1313
 9 0.120 19.38 12.72 33.78 23.27 17.44 0.1387 0.1401 0.1235 0.1148
10 0.120 19.81 12.81 33.59 23.36 17.37 0.1147 0.1135 0.1205 0.1224
11 0.120 20.26 12.91 33.41 23.44 17.30 0.1175 0.1193 0.1230 0.1230
12 0.120 20.71 13.00 33.22 23.53 17.23 0.1246 0.1258 0.1278 0.1306
13 0.120 19.66 12.73 33.33 23.53 17.23 0.1305 0.1348 0.1354 0.1369
14 0.120 18.66 12.46 33.44 23.54 17.23 0.1418 0.1415 0.1440 0.1433
15 0.120 17.72 12.20 33.55 23.54 17.23 0.1467 0.1486 0.1496 0.1537
16 0.120 16.81 11.94 33.66 23.55 17.24 0.1543 0.1552 0.1554 0.1578
17 0.119 16.73 11.74 33.54 23.66 17.06 0.1594 0.1586 0.1614 0.1595
18 0.118 16.65 11.55 33.42 23.76 16.88 0.1609 0.1630 0.1606 0.1627
19 0.117 16.57 11.36 33.30 23.87 16.71 0.1633 0.1637 0.1648 0.1647
20 0.116 16.49 11.18 33.18 23.98 16.53 0.1646 0.1654 0.1658 0.1696
21 0.115 16.42 10.99 33.06 24.09 16.36 0.1712 0.1706 0.1706 0.1722
22 0.114 16.34 10.80 32.94 24.20 16.19 0.1719 0.1775 0.1766 0.1769
```

```
C
C***********************************************************************
C***     AVERAGE MOISTURE CONTENT CALCULATIONS                        **
C***********************************************************************
C
C***********************************************************************
C***                                                                  **
C***          1. XMEM = WET BASIS EQUILIBRIUM MOISTURE CONTENT        **
C***             (ORIGINALLY WAS DRY BASIS -- CONVERTED BELOW).       **
C***                                                                  **
C***          2. XMWB = WET BASIS MOISTURE CONTENT AT PREVIOUS        **
C***             TIME INTERVAL.                                       **
C***                                                                  **
C***          3. XM1WB = WET BASIS MOISTURE CONTENT AT PRESENT        **
C***             TIME INTERVAL.                                       **
C***                                                                  **
C***          4. XMA = AVERAGE WET BASIS MOISTURE CONTENT OF ALL      **
C***             LAYERS.                                              **
C***                                                                  **
C***********************************************************************
C
      XMA=0
      DO 86 J=1,M
      XMA=XMA+XM1(J)
      XMEM(J)=XMEM(J)/(1.+XMEM(J))
      XMWB(J)=XM(J)/(1.+XM(J))
   86 XM1WB(J)=XM1(J)/(1.+XM1(J))
C     IF(J.EQ.13) GO TO 1000
C     GO TO 86
C1000 XM1WB(J)=XM1WB(J)*100.
C     WRITE(06,1001) TIMDRY,XM1WB(J)
C1001 FORMAT(2X,F6.2,2X,F6.2)
C     XM1WB(J)=XM1WB(J)/100.
C  86 CONTINUE
      XMA=XMA/FLOAT(M)
      XMA=XMA/(1.+XMA)
C     IF(XMA.GT..0598.AND.XMA.LT..0601) GO TO 1100
C     GO TO 100
C1100 XMA=XMA*100.
C     WRITE(06,1101) TIMDRY,XMA
C1101 FORMAT(5X,'IT TAKES',F6.2,' HOURS TO DRY THE PEANUTS TO AN AVERAGE
C    $ MOISTURE CONTENT OF ',F6.2,' PERCENT.')
C     XMA=XMA/100.
  100 CONTINUE
C
C***********************************************************************
C***     OUTPUT                                                       **
C***********************************************************************
C
      IF(IOUT.LT.IPRT) GO TO 310
      IOUT=0
      WRITE(06,400) TIMDRY
  400 FORMAT(/2X,'CONDITIONS EXITING EACH LAYER AT TIME=',F7.2,/)
      WRITE(06,401)
  401 FORMAT(2X,'LAYER NO.',2X,'MC(W.B.)(I-1)',2X,'MC(W.B.)(I)',2X,'  TX
```

```
23 0.113 16.26 10.62 32.82 24.32 16.02 0.1707 0.1638 0.1592 0.1576
24 0.112 16.18 10.44 32.70 24.43 15.85 0.1714 0.1562 0.2159 0.2108
25 0.111 16.10 10.26 32.59 24.54 15.69 0.2000 0.1914 0.1881 0.2025
26 0.110 16.02 10.08 32.47 24.65 15.52 0.1934 0.1874 0.1802 0.1708
27 0.112 16.16 10.31 32.78 25.42 15.66 0.1767 0.1721 0.1668 0.1596
28 0.113 16.29 10.53 33.09 26.22 15.80 0.1643 0.1686 0.1649 0.1572
29 0.115 17.59 11.23 33.32 27.10 16.21 0.1498 0.1380 0.1434 0.1419
30 0.117 18.98 11.96 33.55 28.01 16.62 0.1381 0.1217 0.0868 0.0706
31 0.118 20.47 12.71 33.78 28.97 17.04 0.0723 0.0740 0.0740 0.0748
32 0.120 22.10 13.50 34.01 29.98 17.47 0.0804 0.0781 0.0772 0.0805
33 0.120 21.50 13.30 33.93 29.64 17.25 0.0812 0.0824 0.0983 0.1037
34 0.120 20.92 13.11 33.85 29.31 17.04 0.0981 0.1081 0.1119 0.1186
35 0.120 20.36 12.91 33.77 28.99 16.83 0.1238 0.1246 0.1262 0.1306
36 0.120 19.81 12.72 33.69 28.66 16.62 0.1326 0.1350 0.1348 0.1366
37 0.120 19.29 12.43 33.72 28.26 16.29 0.1390 0.1385 0.1400 0.1432
38 0.120 18.78 12.15 33.75 27.87 15.97 0.1466 0.1522 0.1511 0.1529
39 0.120 18.28 11.88 33.79 27.48 15.66 0.1551 0.1552 0.1485 0.1569
40 0.120 17.79 11.60 33.82 27.11 15.35 0.1586 0.1602 0.1617 0.1600
41 0.120 17.28 11.34 33.90 27.17 15.27 0.1576 0.1642 0.1659 0.1694
42 0.120 16.78 11.08 33.98 27.24 15.20 0.1698 0.1748 0.1751 0.1766
43 0.120 16.29 10.82 34.05 27.30 15.13 0.1770 0.1788 0.1814 0.1826
44 0.120 15.81 10.57 34.13 27.37 15.05 0.1840 0.1852 0.1845 0.1844
45 0.120 15.35 10.32 34.22 27.43 14.98 0.1893 0.1890 0.1906 0.1939
46 0.120 14.90 10.07 34.30 27.50 14.91 0.1957 0.1943 0.1954 0.1949
47 0.120 14.45  9.83 34.38 27.57 14.84 0.1988 0.1970 0.1963 0.1939
48 0.120 14.02  9.58 34.46 27.63 14.76 0.1882 0.1952 0.1919 0.1886
49 0.120 15.71 10.39 34.17 28.16 15.10 0.1839 0.1761 0.1778 0.1667
50 0.120 17.55 11.24 33.89 28.69 15.43 0.1635 0.1539 0.1498 0.1454
51 0.120 19.60 12.12 33.61 29.25 15.78 0.1376 0.1325 0.1292 0.1178
52 0.120 21.89 13.05 33.33 29.81 16.13 0.0957 0.0814 0.0995 0.1012
53 0.120 22.30 13.39 33.56 30.49 16.45 0.0815 0.0725 0.0703 0.0678
54 0.120 22.72 13.74 33.80 31.19 16.78 0.0642 0.0646 0.0629 0.0643
55 0.120 23.14 14.09 34.03 31.91 17.12 0.0636 0.0650 0.0649 0.0653
56 0.120 23.58 14.46 34.27 32.66 17.46 0.0653 0.0666 0.0668 0.0687
57 0.120 22.67 14.14 34.08 31.92 17.32 0.0699 0.0742 0.0763 0.0797
58 0.120 21.80 13.82 33.89 31.20 17.17 0.0875 0.0939 0.1018 0.1092
59 0.120 20.96 13.52 33.70 30.51 17.03 0.1146 0.1152 0.1187 0.1214
60 0.120 20.17 13.21 33.52 29.85 16.89 0.1238 0.1274 0.1287 0.1315
61 0.120 19.39 12.80 33.70 29.56 16.51 0.1334 0.1356 0.1406 0.1416
62 0.120 18.65 12.40 33.89 29.27 16.14 0.1413 0.1447 0.1422 0.1492
63 0.120 17.93 12.01 34.08 28.99 15.78 0.1453 0.1474 0.1513 0.1529
64 0.120 17.24 11.63 34.27 28.71 15.42 0.1562 0.1580 0.1586 0.1637
65 0.120 16.86 11.39 33.85 28.41 15.21 0.1652 0.1671 0.1695 0.1712
66 0.120 16.48 11.15 33.45 28.11 15.00 0.1733 0.1733 0.1753 0.1745
67 0.120 16.11 10.91 33.05 27.82 14.79 0.1782 0.1812 0.1829 0.1836
68 0.120 15.75 10.68 32.65 27.54 14.59 0.1844 0.1866 0.1889 0.1890
69 0.120 15.40 10.45 32.27 27.26 14.38 0.1907 0.1929 0.1961 0.1963
70 0.120 15.05 10.22 31.89 26.98 14.18 0.1985 0.1987 0.1994 0.1989
71 0.120 14.71 10.00 31.52 26.70 13.99 0.2050 0.1825 0.1806 0.1759
72 0.120 14.38  9.77 31.15 26.43 13.79 0.1702 0.1626 0.1736 0,1678
/*
//
```

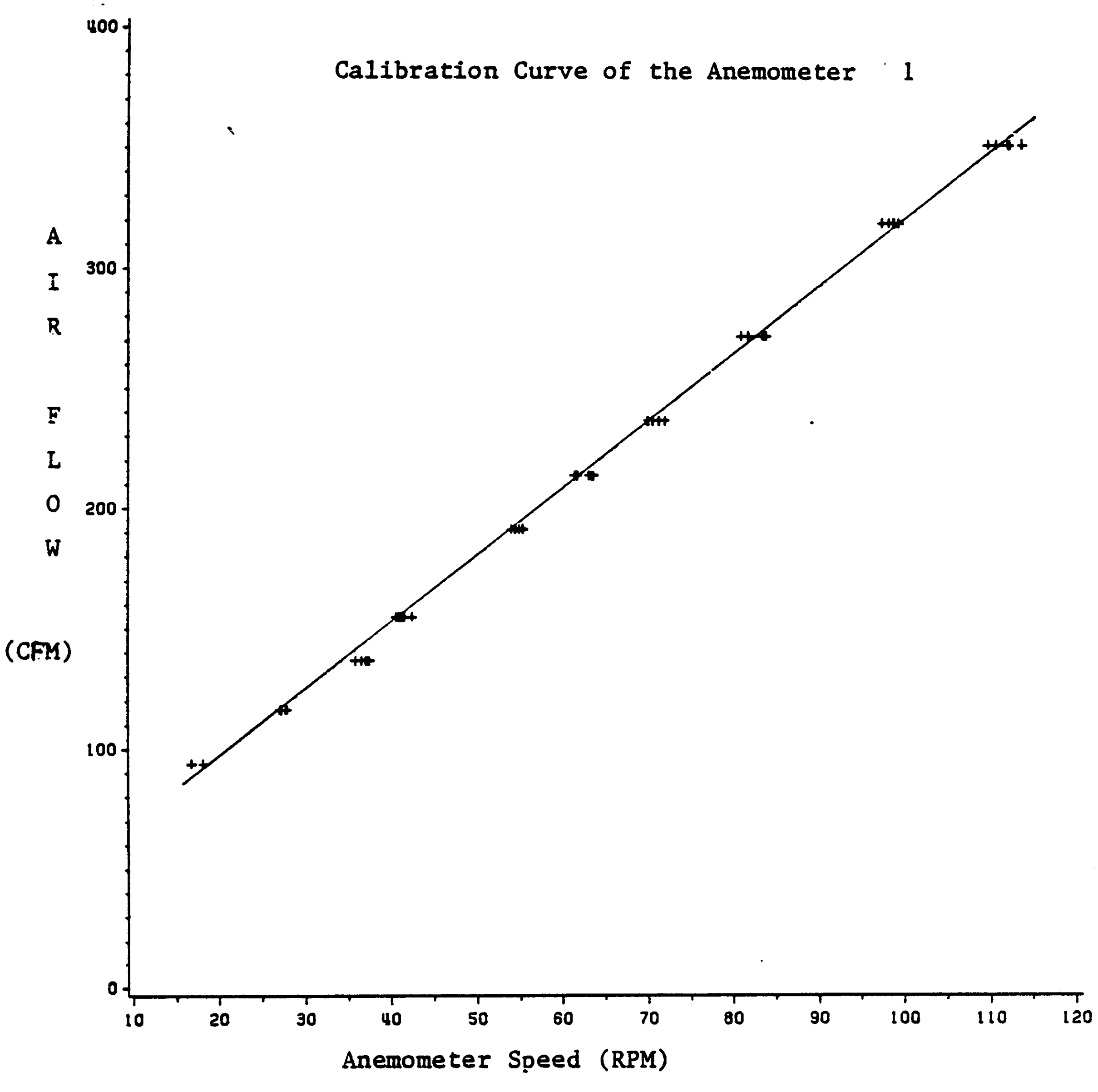
Appendix B

Calibration Curves for Anemometers

Statistical Results for the Calibration of the Anemometer # 1

```
                       GENERAL LINEAR MODELS PROCEDURE

DEPENDENT VARIABLE: FLOW

SOURCE                  DF        SUM OF SQUARES          MEAN SQUARE

MODEL                    1     333618.70964316      333618.70964316

ERROR                   48        720.70555684          15.01469910

CORRECTED TOTAL         49     334339.41520000

MODEL F =         22219.47                            PR > F = 0.0001

R-SQUARE              C.V.            ROOT MSE            FLOW MEAN

0.997844            1.8608          3.87488053         208.23400000

SOURCE                  DF         TYPE I SS    F VALUE      PR > F

RPM                      1   333618.70964316   22219.47      0.0001

SOURCE                  DF       TYPE III SS    F VALUE      PR > F

RPM                      1   333618.70964316   22219.47      0.0001

                                   T FOR H0:    PR > |T|   STD ERROR OF
PARAMETER             ESTIMATE    PARAMETER=0                 ESTIMATE

INTERCEPT          39.97789202          31.86     0.0001     1.25475371
RPM                 2.79158962         149.06     0.0001     0.01872771
```

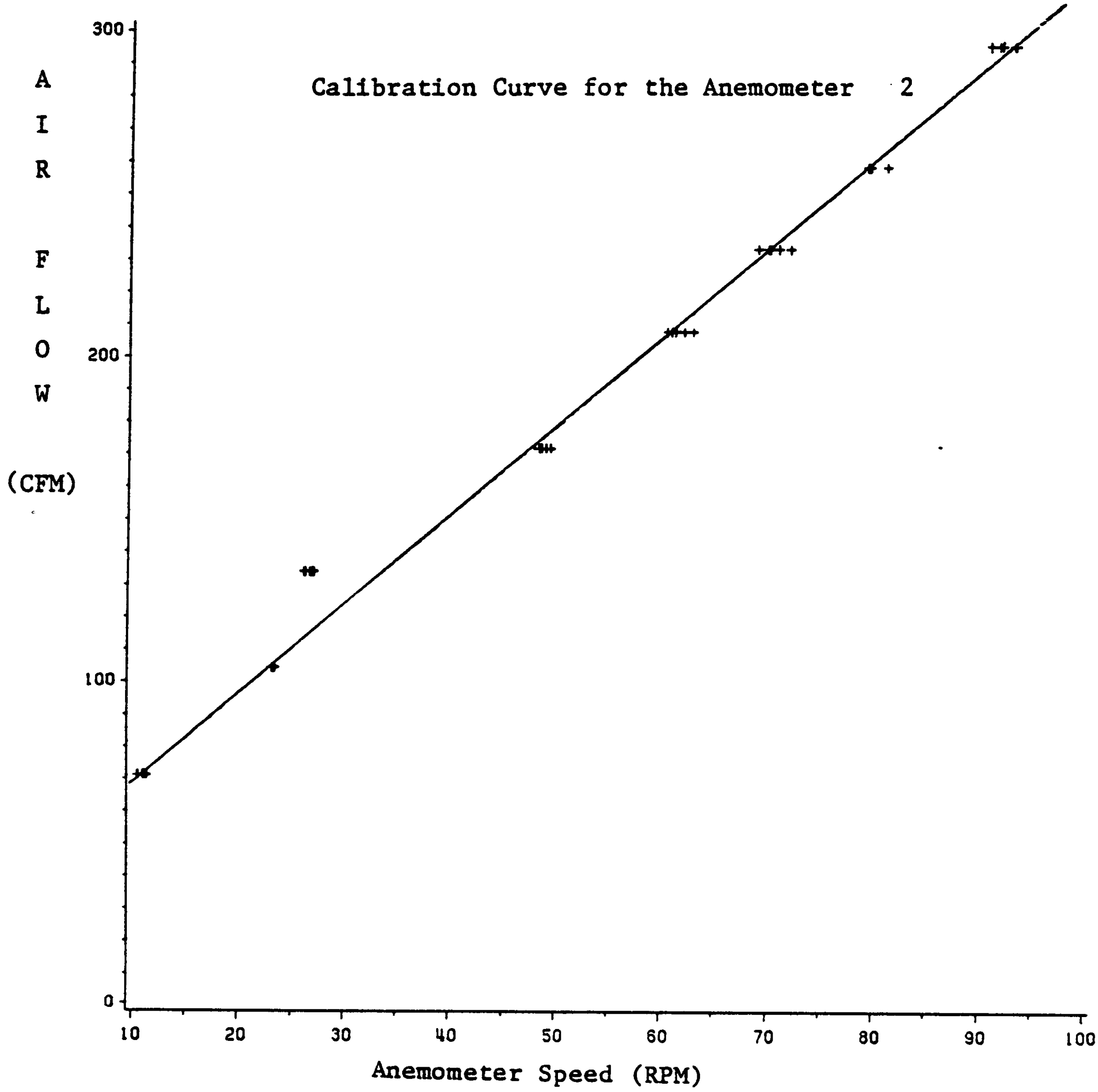
Curve: Flow(cfm) = 39.978 + 2.792*rpm


Calibration Curve of the Anemometer 1
A I R F L O W (CFM)
400
300
200
100
0
10
20
30
40
50
60
70
80
90
100
110
120
Anemometer Speed (RPM)

Statistical Results for the Calibration of the Anemometer 2

```
                          GENERAL LINEAR MODELS PROCEDURE
DEPENDENT VARIABLE: FLOW
SOURCE                 DF        SUM OF SQUARES             MEAN SQUARE
MODEL                   1    214065.62413501         214065.62413501
ERROR                  38      1883.74961499             49.57235829
CORRECTED TOTAL        39    215949.37375000

MODEL F =         4318.25                            PR > F = 0.0001

R-SQUARE             C.V.            ROOT MSE               FLOW MEAN
0.991277           3.8051          7.04076404            185.03250000

SOURCE                 DF          TYPE I SS     F VALUE     PR > F
RPM                     1    214065.62413501     4318.25     0.0001

SOURCE                 DF        TYPE III SS     F VALUE     PR > F
RPM                     1    214065.62413501     4318.25     0.0001

                                    T FOR H0:    PR > |T|    STD ERROR OF
PARAMETER            ESTIMATE     PARAMETER=0                  ESTIMATE
INTERCEPT         46.59645834           19.56      0.0001      2.38271835
RPM                2.68216807           65.71      0.0001      0.04081618
```

Curve: Flow(cfm) = 46.596 + 2.682*rpm


Calibration Curve for the Anemometer 2
AIR FLOW (CFM)
300
200
100
0
10
20
30
40
50
60
70
80
90
100
Anemometer Speed (RPM)

Appendix C

A Heat Transfer Model for Temperature Correction

The length of the polyvinylchloride (pvc) pipe from the dryer to the measuring point is approximately 1.8 m. This length is divided into 18 sections and temperature is corrected for each section. The conduction heat loss from the jth section of the pipe is given by the following equation:

$$Q_{cj} = 2\pi K \Delta x \frac{(T + \frac{\Delta T}{2} - T_s)}{\ln(\frac{r_2}{r_1})} \qquad [1]$$

where,

Q_{cj} = conduction heat loss from the jth section,

K = thermal conductivity of the rigid pvc,

Δx = length of the section,

T =temperature of entering air of the section,

ΔT= temperature change within the section,

T_s= average surface temperature of the pipe within the jth section,

r_2= outer radius of the pipe,

and

r_1= inner radius of the pipe.

The heat lost by the free convection is calculated from the following equation:

$$Q_{fcj} = h_f 2\pi r_2 \Delta x (T_s - T_a) \qquad [2]$$

where,

Q_{fcj}= free convection heat loss,

h_f = surface heat transfer coefficient, and

T_a = ambient air temperature.

Holman (1981) gave the following approximation for a free convection heat transfer coefficient of a horizontal cylinder. The free convection currents are assumed to be laminar.

$$h_f = 1.32[\frac{T_s - T_a}{2r_2}]^{0.25} \qquad [3]$$

The heat lost from air-water mixture can be calculated by

$$Q_{air} = \dot{m}C_p\Delta T \qquad [4]$$

where,

Q_{air} = heat lost by air,

$\dot{m}$ = mass flow rate of air,

and

C_p = specific heat of air.

But, from the heat balance for the section,

$$Q_{cj} = Q_{fcj} = Q_{air}. \qquad [4]$$

From these relationships the change in the temperature (ΔT) within the jth section can be calculated if T is known. If the calculation is started from the measuring point at which T is known, then the total temperature change can be calculated. For this purpose a computer program was written.