CONVECTIVE HEAT AND MASS TRANSFER IN THE SPOUTED BED OF A POROUS HYGROSCOPIC SOLID

By

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CHAPTER I

INTRODUCTION

Background

Scientists are continuously searching for a better way of curing farmer stock peanuts. As a result, the earlier concepts of curing such as stackpoling or windrowing are no longer considered essential requirements of the curing process. If the peanuts are harvested at a moisture content that permits the use of mechanical harvesters for separating pods from vines, artificial curing can prevent losses associated with field curing methods.

Thus artificial curing, termed hence forth "drying," has received wide attention from scientists and engineers in recent years. Conventionally the goal is to dry high moisture peanuts, 50 to 100 percent dry basis, to 10 percent dry basis moisture in a reasonable length of time. This is considered relatively safe for long storage and the market quality is preserved. The later is a point of great concern to the processor since without a high quality, peanuts fetch a lower return on the investment or no return at all.

Hence any drying process should result in good quality both from the standpoint of the processor and consumer. The consumer prefers peanuts with good aroma, flavor, taste, and palatability. The processor in addition to these characteristics looks for milling and shelling qualities such as fewer cracked or split kernels, unhardened outer layer, allowing uniform skin or testa slippage and facility for blanching (4, 5, 40, 41). Dried peanuts should also be free from aflatoxin and other toxic organisms (9, 14).

All these factors pose very stringent requirements on the acceptable drying systems (26, 33). A number of researchers have tried various drying methods ranging from field curing (33) to infrared drying (31). Quiescent bed drying has been by far the most common means whereby the conditioned air is forced from the bottom of a perforated bin for a period of 50 to 100 hours at a rate of 5 to 20 cfm/ft^3 of peanuts (4, 26, 36).

Recent trends in biomaterial curing have been to use (a) high temperature-short time process (dryeration), (b) cyclic or intermittent drying, (c) mixing and nonmixing continuous dryers, and (d) fluidized and spouted bed dryers to meet the heavy demand during the harvesting season (4, 5, 9, 11, 17, 21, 32, 38). These dryers have been successful in combating slow and non-uniform drying common to quiescent bed systems. Ease of loading and unloading the products, uniformly dried and clean products at higher drying efficiency are some of these advantages.

Importance and Scope of Study

During 1970 farmers in Oklahoma harvested 122 thousand acres of peanuts with an average yield of 1700 pounds per acre. This amounted to 93,000 tons of peanuts valued at 23.5 million dollars. Each year's crop must be dried to storage-level moisture before marketing. The spouted bed process appears very promising for a large scale drying plant capable of handling 2 to 3 tons of peanuts per hour. However, it has serious limitations in regard to heat efficiency, power requirements, equipment configurations, design dimensions and market value of the final product. Basically the process is a modification of a fluidized bed which finds its use mostly in powdered materials. Smaller biomaterials, like wheat and barley, have been dried successfully in the spouted bed. Peanuts are considerably larger in size, in excess of 2000 microns, and have stringent requirements on the final quality. Both of these factors complicate application of the spouted bed technique to peanut drying.

Preliminary investigations on spouted beds of peanuts (9, 14, 15, 29) have confirmed that the size does not in any way affect spouting performance, but it may have serious effects on final quality, both due to abrasion and impact. Germination ability and food value are two factors that would determine its acceptance as a successful dryer. Such a dryer should meet the following criteria:

1. Homogeneous drying with market quality (grade, taste, flavor, food value) preserved if not enhanced.
2. High drying efficiency with minimum air flow and heat requirements, ease of operation and handling of the product.
3. Low operating cost and minimum space requirements even though initial investment may be high.
4. Social acceptance with minimum noise, minimum air pollution and maximum operator comfort.

Statement of Objectives

Preceding background information indicates several areas that could be studied. The following objectives will help in answering some of the questions raised about the spouted bed drying technique.

1. To develop a prediction equation for drying efficiency of peanuts in the spouted bed.
2. To compare the drying efficiency of artificially reconstituted and field cured high moisture peanuts.
3. To compare drying efficiency of the spouted bed dryer with that of the quiescent bed and other drying systems.
4. To determine the grade and quality of peanuts dried in the spouted bed drying system.

CHAPTER II

REVIEW OF LITERATURE

The average annual production of peanuts for the world is nearly 16 million tons. The United States alone produces 6.53%, about 1.2 million tons valued at over $300 million (20). Peanuts are consumed in various forms such as peanut butter, oil, salted nuts and candy. The edible per capita consumption rate of peanuts for the current marketing year is estimated at about 8 pounds. The importance of determining the optimum conditions and the most efficient methods of artificial drying of peanuts is reflected by the above production statistics.

Fluidization of solids has proved to be a useful technique for vapor-solid contact. The reasons for its wide acceptance and application are certain unique characteristics which are inherent in the system; namely, ease of transferring solids to and from vessels, uniformity of conditions such as temperature within the bed, and high heat and mass transfer rates associated with the system. However, its application has been limited to relatively fine particles of such size that are generally not encountered in agricultural engineering applications. Coarse, uniformly sized particles above 200 microns are not amenable to fluidization.

It has been found possible, by use of either gases or liquids, to impart a regular cyclic motion to a bed of coarse particles in which the solids are rapidly carried upwards by the fluid in a central, well defined core within the bed. This technique, called the "spouted bed technique", is proved to be equally successful for coarse particles as is the fluidization for fine particles for drying purposes (Figure 1).

In this method the particles move uniformly downward in the annular space surrounding the core, thus providing dense phase counter current contact between the fluid and the solids. There are no walls separating the core from the annulus. Very recently particles as large as 300 microns like maize, peas, etc., have also been treated in the spouted bed. It is with this hope that the spouted bed of peanuts may also be successful for drying purposes.

Description of the Spouted Bed Technique

If coarse solid material is poured into a cone-bottomed column having a small central opening for air inlet at the base of the cone and subjected to an increasing upward air flow, the following steps will occur (23):

"At low air velocities the air will simply pass upward through the solids bed without disturbing the particles; however as the air velocity is increased a point will be reached when there is a noticeable adjustment of the particles (Figure 2). A further increase in air flow causes a stream of solids to rise rapidly as a central core, or spout within the bed. The solids in the spout, having reached somewhat above the bed level, fall back onto the annular space around the spout and travel downward uniformly as a packed bed. Thus a spouted bed is a composite of a central air spout carrying the solids upward and a downward moving annulus with a counter-current flow of air. A considerable crossflow of solids from the annulus into the spout takes place all

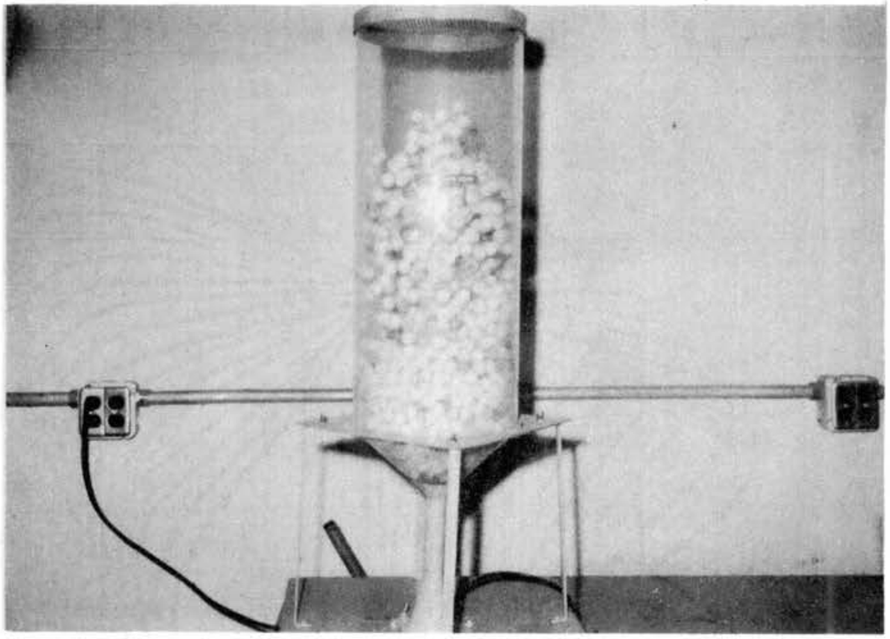

Figure 1. Model Spouted Bed (14)

along the bed height."

Conditions Necessary for Spouting

Mathur and Gishler (23) have shown that coarse particles, above 20 to 35 mesh, can be made to spout similar to a fluidized bed where due to vigorous mixing of particles very high heat and mass transfer rates are obtained. This technique of contacting gases for drying wheat and other biological and industrial materials has been successfully utilized at the National Research Council, Ottawa and the University of British Columbia, Canada. From the basic studies reported, it was concluded that the inlet pipe diameter, bed diameter, particle size and height of the bed are critical with respect to spouting pressure drop and total air flow requirement. For example, maximum bed depth which

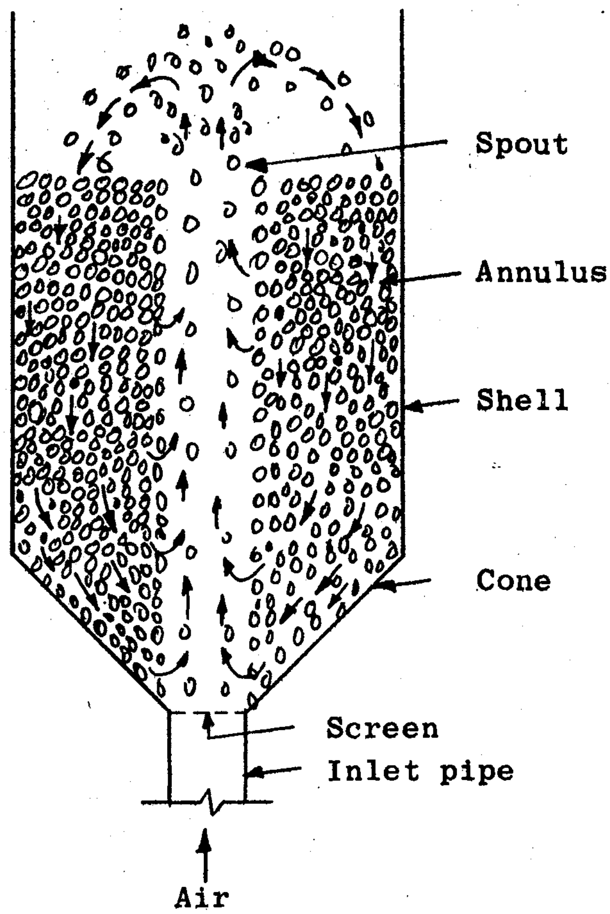

Figure 2. Spouted Bed Schematic (28)

can be made to spout depends upon the air inlet diameter, the bed diameter, and physical properties of the solids. Deeper beds can be spouted with the smaller inlet pipes and larger diameter beds since lower superficial velocities are needed for spouting in larger diameter beds. Air flow and pressure drop for spouting increases markedly with bed depth. Spouting was found to be more stable at steeper cone angles as well as smaller inlet pipe diameters and required considerably less air flow. Figure 3 is a schematic of a commercial spouted bed dryer (28).

Preliminary Investigations on Spouted Beds of Peanuts

Initial work on spouted beds of peanuts began in the spring of 1968. Gay and Nelson (14, 15, 29) studied the fluid and particle transport characteristics of the spouted bed and developed correlations for predicting (a) flow rates required for initiating and maintaining the spout, (b) pressure drop during initiating and maintaining stable spout, and (c) bed turn over times. Much of this information is required in selecting the fan size, bed diameter, bed depth and inlet pipe diameter. Table I gives the summary of equations they developed and Figure 4 shows a typical pressure drop vs. flow phenomenon in a spouted bed of peanuts.

Quiescent Bed Drying Experiments

Myklestad (26) dried peanuts from 31 percent to 12 percent mass concentration in a quiescent bed dryer using heated air at $100^{o}F$ and 14% relative humidity. He concluded that it took 24 hours to dry a volume of 40 ft^3 of peanuts at an air flow rate of 21 ft^3/min-ft^3. A larger dryer with 750 ft^3 capacity gave even better results.

Teter (36) conducted experiments on drying peanuts from 1952 through 1956 using air flow rates of 5 to 20 CFM/ft^3 of peanuts in square bins. The temperature of the air was raised $20^{o}F$ above ambient. It took from 30 to 130 hours to dry 20 to 32 inch depths of peanuts. The peanuts were dried to safe storage level from 20 to 40 percent mass concentration.

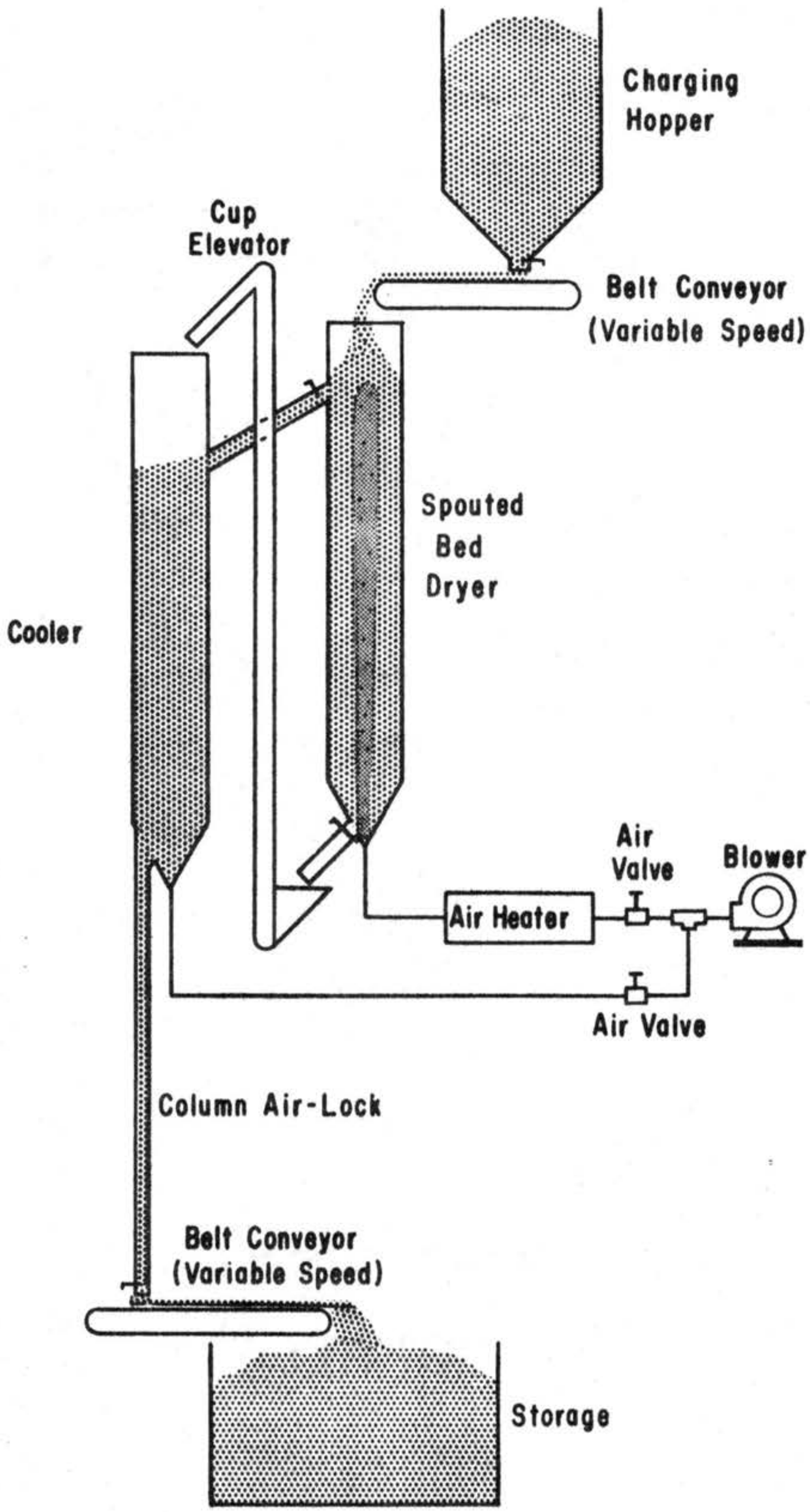

Figure 3. Spouted Bed Drying System (28)

TABLE I

PREDICTION EQUATIONS FOR PARTICLE AND FLUID TRANSPORT CHARACTERISTICS OF SPOUTED BEDS FOR WHOLE SPANISH PEANUTS

Air Flow for Quiescent Bed

$$\frac{\Delta P_1 \, D_c^2 \, D_{pe}^2}{\mu_a \, Q_{aq} \, H_b \sqrt{4 + G_r^2}} = 5471.7 \, D_r^{-1.193} \qquad (1)$$

Maximum Pressure Drop at Incipient Spout

$$\frac{\Delta P_2}{G \, \rho_b \, D_{pe}} = 755.6 \left[\frac{D_r}{S_f \, G_r} \right] \qquad (2)$$

Flow Rate at Incipient Spout

$$\frac{Q_{ai}^2 \, \rho_a \, N_e}{D_b^4 \, D_{pe} \, \rho_b \, G} = 1249.9 \times 10^4 \, D_r^{-3.964} \left[\frac{F_{rb}}{R_{eb}^2 \, S_f^3} \right]^{0.55}$$

$$\left[\frac{D_r}{G_r} \right]^{0.0919 D_r^{1.484}} \qquad (3)$$

Minimum Flow Rate at Spout Collapse

$$\frac{Q_{am}^2 \, \rho_a \, N_e}{D_b^4 \, D_{pe} \, \rho_b G} = 1255.7 \times 10^4 \, D_r^{-5.624} \left[\frac{F_{rb}}{R_{eb}^2 \, S_f^3} \right]^{0.503}$$

$$\left[\frac{D_r}{G_r} \right]^{0.1867 D_r^{1.378}} \qquad (4)$$

Pressure Drop and Air Flow During Stable Spouting

$$\frac{\Delta P_a}{D_{pe} \, \rho_b \, G} = 0.0372 \, F_{rb}^{0.373} \, R_{eb}^{0.733} \, D_r^{2.191} \, G_r^{-0.645} \qquad (5)$$

TABLE I (CONTINUED)

Wall Diameter, Bed Turnover Time

$$\frac{\Theta_w{}^2 G}{D_{pe}\ N_e} = 41.78 \times 10^4\ F_{rc}^{-8.325}\ R_{eb}^{-0.915}\ D_r^{17.029}\ G_r^{-6.284} \tag{6}$$

Median Diameter, Bed Turnover Time

$$\frac{\Theta_m{}^2 G}{D_{pe}\ N_e} = 158.3\ F_{rc}^{-3.955}\ D_r^{9.802}\ G_r^{-3.597} \tag{7}$$

Random Cycle, Bed Turnover Time

$$\frac{\Theta_r^2\ G}{D_{pe}\ N_e} = 1.092 \times 10^4\ F_{rc}^{-1.502}\ D_r^{4.204}\ G_r^{-2.747} \tag{8}$$

$$F_{rb} = \frac{Q_a^2\ N_e\ \rho_a}{D_b^4\ G\ D_{pe}\ \rho_b} \tag{9}$$

$$F_{rc} = \frac{Q_a^2\ N_e\ \rho_a}{D_c^4\ G\ D_{pe}\ \rho_b} \tag{10}$$

$$R_{eb} = \frac{Q_a\ N_e\ D_{pe}\ \rho_a}{D_b^2\ \mu_a} \tag{11}$$

$$R_{ec} = \frac{Q_a\ N_e\ D_{pe}\ \rho_a}{D_c^2\ \mu_a} \tag{12}$$

See Appendix E for definition of symbols.

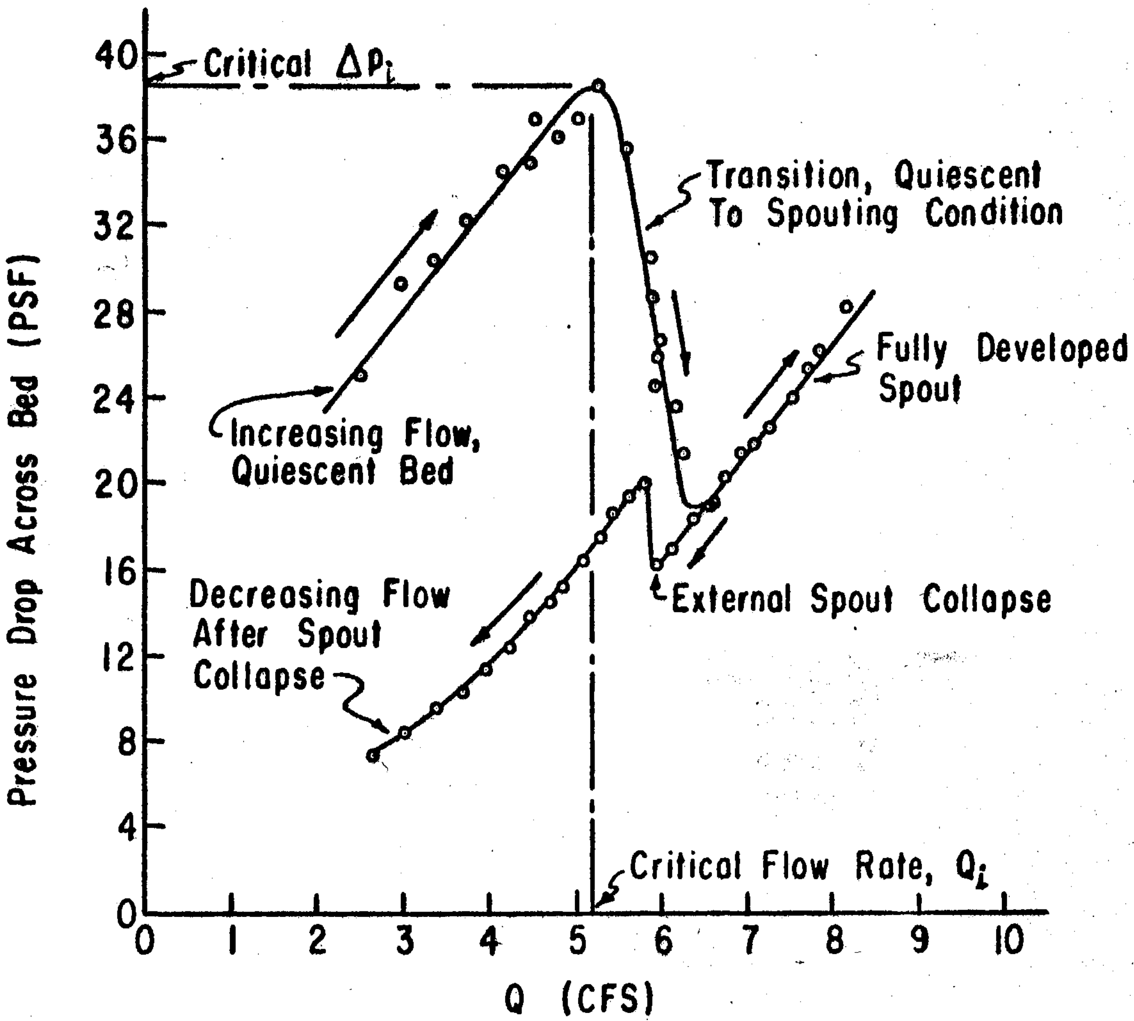

Figure 4. Typical Air Pressure Drop vs. Flow Phenomenon in a Spouted Bed of Peanuts. (H_b = 14.5", D_b = 18" and D_c = 3.5".)

Baker et al (4) studied a continuous column drying process for peanuts at 4 levels of mass concentration, temperature of drying air, relative humidity and air flow rates. They developed equations relating these variables and five other variables as follows:

$$y_1 = -468.363 + 3.35C + 1.96T + 3.07\phi + 0.323Q' \quad (13)$$

$$y_2 = -3.941 + 0.028C + 0.029T + 0.0013\phi + 0.013Q' \quad (14)$$

$$y_3 = -67.84 + 1.28C + 0.189T - 0.101\phi - 0.228Q' \quad (15)$$

$$y_4 = -77.467 + 1.23C + 0.168T + 0.365\phi - 0.228Q' \quad (16)$$

$$y_5 = 12.485 - 0.032C - 0.059T + 0.083\phi - 0.066Q' \quad (17)$$

Where:

y_1 = Thickness of drying layer in inches

y_2 = Rate of movement of trailing drying edge, inches per hour

y_3 = Time of departure of trailing drying edge, hours

y_4 = Time for entire mass of nuts to reach one half equilibrium, hours

y_5 = Final mass concentration of bottom layer, % dry basis

C = Mass concentration, percent

T = Temperature of drying air, ^{o}F

ϕ = Relative humidity, percent

Q' = Air flow rate, CFM/ft^2

Wright (41) studied forced convective drying of peanuts with and without a radio frequency field. He developed equations to describe the forced convective drying rate as,

$$\Pi_1 = 0.761(1.04)^{-\Pi_7} \Pi_2^{0.783} \Pi_3^{0.702}(1.0 - e^{-6.87 \times 10^{-5}\Pi_4}) \quad (18)$$

Where:

Π_1 = $(C_0 - C)$, moisture loss, percent dry basis

Π_2 = $(C_0 - C_e)$, available free potential, percent dry basis

C_0 = Initial mass concentration

C_e = Equilibrium mass concentration

C = Final mass concentration

Π_3 $\dfrac{(T - T_1)}{T}$, temperature potential

T_1 = Ideal exit air temperature following a wet bulb drying process, ^oF

Π_4 = $60'\Theta/D_{pe}$, air velocity time parameter

Θ = Drying time, hrs

D_{pe} = Characteristic length of peanut perpendicular to air flow direction, ft

Π_7 = H_b/D_{pe}, depth of sample parameter

H_b = Depth of peanuts in the direction of air flow, ft

Π_5 = $\Delta P\Theta/C_aT$, electrical power input parameter

ΔP = Power input to the peanuts from the radio frequency field minus the power input at the same field strength to dry peanuts, Btu/min-in^3

C_a = Volumetric specific heat of entering air, Btu/in^3-^oF

The drying rate, Π_1, increased as the moisture and temperature drying potentials, Π_2 and Π_3 increased. Drying rate was also found to increase asymptotically as the air-velocity-time parameter, Π_4, increased. However, it decreased ~~with the increase in~~ depth of the sample, Π_7. He found that an expression $(1.0 + 0.0224\ \Pi_5^{0.38})$, can be multiplied by the forced convective equation to express the effect of adding radio frequency energy to the sample. The drying rate was found to increase by the addition of electrical power.

Spouted Bed Drying Experiments

Malek (22) investigated bed to wall heat transfer in spouted beds, 3 and 6 in. diameter, using polyethylene, polystyrene, wheat, rice, millet, Timothy seed and Ottawa sand as the bed materials. Measurements indicated that the heat transfer coefficient, h, increased with increasing mass velocity of drying air up to the point of spouting. During spouting, h was independent of mass velocity, bed diameter and column diameter, but increased with increasing diameter and heat capacity of the particles, and decreased with increasing bed height. The value of h was found to vary from 10 to 24 Btu/(hr-ft^2-^{o}F).

Becker (6) developed a non-isochronal diffusion equation for the drying rate of wheat in spouted beds,

$$CR = 1.04\ X_r\ \mathrm{Exp}(-0.44\ X_r) \qquad (19)$$

Where:

CR = $(C_0 - C)/(C_0 - C_e)$, drying efficiency

X_r = $(S/V)\sqrt{(\alpha_{mp}\Theta)}$, (S/V) is the particle surface to volume ratio

α_{mp} = Diffusion coefficient for wheat

Θ = Weight average residence time in the drying bed.

The ratio of weight of particles in the bed to feed rate of particles was defined as Θ and X_r as the square root of the reduced weight average residence time. Diffusion coefficients calculated by this equation from data on drying wheat agreed closely with the Arrhenius equation,

$$\alpha_{mp} = 297 \operatorname{Exp}(-21960/RT_{ab}) \tag{20}$$

Where:

R = Gas constant 1.987 Btu/mole ^oR

T_{ab} = Absolute temperature, ^oR.

He developed a separate equation for critical temperature, T_c, above which the baking qualities of wheat were thermally injured as,

$$T_c = 189 - 115(C_0 + C) \tag{21}$$

Peterson (32) reproted the results of a commercial spouted bed dryer while drying peas, lentels and flax. He developed an empirical relationship between solids temperature and other variables as,

$$T_p + 2 = \frac{111\ T_a^{0.63}\ D_{pg}^{0.57}\ D_b^{0.38}}{F^{0.24}\ C_0^{0.29}} \tag{22}$$

Where:

T_p = Particle temperature, ^oF

T_a = Air temperature, ^oF

D_{pg} = Geometric particle diameter, in.

D_b = Bed diameter, ft.

F = Feed rate, lb_m/hr.

The reported results indicate that high drying capacity was achieved through the use of high air temperatures with the result that a two foot diameter spouted bed heater (plus cooler) dried almost two tons per hour of peas through an 8.8% moisture range. No damage was evident in the material dried.

Mather and Gishler (23), who reportedly invented the spouted bed, studied the wheat drying characteristics as a function of feed mass concentration, feed rate, bed depth and inlet air temperature. Two correlations were developed, one for the particle temperature,

$$T_p = \frac{26.4\ T_a^{0.53}}{F^{0.15}\ C_0^{0.3}} + 26.5 \qquad (23)$$

and the other for W_w', the amount of water removed from wheat particles in lb_m/hr,

$$W_w' = 0.25\ C\ T_a \qquad (24)$$

Thermal Conductivity

Contemporary theories have not advanced to the point of providing the means of independently calculating accurate values of thermal conductivity. Its experimental measurement is relatively difficult and fraught with many pitfalls. Experimental difficulties arise from the existence of competing mechanisms of heat and mass flow, from the necessity of measuring small temperature differences accurately and from satisfying rigid boundary conditions. In biomaterials this problem is further compounded due to the presence of water, pores, heteroginity of structure and anisotropic properties of constituent materials. In general it can be said that the thermal conductivity of biomaterials is a function of initial mass concentration, temperature, density and porosity.

The best known and most widely investigated method of thermal conductivity determination is the line heat source which has been used for ceramic materials, insulating materials, soils and many biomaterials such as rice, wheat, corn, and apples with excellent repeatability of results. The temperature rise at any point in an infinite solid containing a suddenly initiated, constant rate, line heat source is a function of spatial position, time, thermal properties of the solid and source strength. If at initial conditions temperature of the specimen is considered constant at any position, then the one-dimensional transient heat flow equation,

$$\frac{\partial T}{\partial \Theta} = \alpha_{hp}\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right) \tag{25}$$

can be solved for T,

$$T = \frac{Q}{2\pi K_p}\int_{\beta}^{\infty} \frac{Exp(-\gamma^2)}{\gamma}\, d\gamma \tag{26}$$

or in terms of the modified Bessels function,

$$T = \frac{Q}{2\pi\ K_p}\ I(\beta) \tag{27}$$

Where:

$$I = C - \ln(\beta) + \frac{\beta^2}{2} - \frac{\beta^4}{8} + \ldots \tag{28}$$

$$\beta = \frac{r}{2\sqrt{\alpha\Theta}}\ ,\ ft^{-1} \tag{29}$$

α_{hp} = $K_p/\rho_p C_{pp}$, thermal diffusivity, ft^2/hr

K_p = Thermal conductivity of particles, Btu/(hr-ft-^oF)

ρ_p = Mass density of particles, lb_m/ft^3

C_{pp} = Specific heat of particles at constant pressure, Btu/lb_m-^oF

Θ = Time, hrs

r = Distance from line heat source, ft

T = Temperature at distance r, ^oF

Q = Heat input, Btu/hr-ft

γ = Dummy variable of integration

C = Constant.

When $\beta < 0.16$ all the terms of the I series except the first two can be dropped (30).

$$I(\beta) = C - \ln(\beta) \tag{30}$$

hence

$$T = \frac{Q}{2\pi K_p}(C - \ln(\beta)) \tag{31}$$

The temperature change between two times Θ_1 and Θ_2 for a point close to the line source can be expressed with less than one percent error by

$$T_2 - T_1 = \frac{Q}{4\pi K_p}\ln(\Theta_2/\Theta_1) \tag{32}$$

Solving for K_p gives

$$K_p = \frac{3.415\ EI\ \ln(\Theta_2/\Theta_1)}{4\pi(T_2 - T_1)} \tag{33}$$

Where:

E = Electromotive force, volts

I = Current, amperes.

Equation 33 which no longer contains the thermal diffusivity or the distance, r, from the line source, is the equation normally used in determining the thermal conductivity (18, 30, 37).

Specific Heat

Several investigators have presented mathematical models for predicting the specific heat at constant pressure for peanut pods en masse. Wright and Porterfield (42) developed the following equations:

$$C_{pp} = 0.365 + 0.317\, T_p^{-0.996}\, MC^{0.652} \tag{34}$$

$$C_{pp} = 0.403 + 0.425\, MC^{0.881} \tag{35}$$

where,

C_{pp} = Specific heat of peanut pods, Btu/(lb$_m$ ^oF)

T_p = Temperature of peanuts, $^oF/100$

MC = Dry basis mass concentration, fraction

Equations 37 and 38 are applicable over the following range of variables.

$$65\ ^oF \leqq T_p \leqq 85\ ^oF$$

$$0.04 \leqq MC \leqq 0.65$$

Suter and Clary (35) developed a simple model for predicting the specific heat of peanut pods at constant pressure as,

$$C_{pp} = 0.749 - 1.501\, T_p + 6.936\, T_p^2 - 0.085\, MC + 0.143\, MC^2 - 0.128\, T_p\, MC \tag{36}$$

where,

T_p = Temperature of the peanut pods, $^oC/100$

The other variables are as defined earlier. Equation 39 is applicable over the following variable range

$$40\ ^oF \leq T_p \leq 103\ ^oF$$

$$0.43 \leq MC \leq 0.887$$

CHAPTER III

THEORETICAL CONSIDERATIONS

Since its development the spouted bed has been used to dry industrial and biomaterials successfully. Most of these materials were, however, below 2000 microns in size, while Spanish peanuts range from 2500 to 10,000 microns in diameter and up to 25,000 microns in length, Peanuts also represent a composite hygroscopic body consisting of a porous hull, air gap and kernels that have stringent requirements for market quality. It is therefore necessary that new investigations be made to develop a design criteria for such a dryer for peanuts. The results from other biomaterials may be used for initial equipment design.

A typical spouted bed consists of an inlet pipe, a cone and a cylindrical bed. Drying air is forced through the inlet pipe and causes a column of material called the 'spout' to break away and be pushed upward. The adjacent material called an 'annulus' travels down toward the inlet pipe and is transported to the top by incoming air. These steps form a continuous process of agitation and drying.

The inlet air while traveling through the bed diverges and removes some particles from the annulus. As these particles are lifted, their kinetic energy is overcome by gravitational forces, causing them to fall onto the surface of the annulus. Thus the spouted bed technique introduces complexities in applying the fundamental procedures for evaluating the convective heat and mass transfer rates during drying. This process of vigorously agitating the particles makes solution of the differential or integral equations of momentum mass and energy transfer very difficult if not impossible. Any attempt to simplify these equations, in order to describe the phenomenon of coupled heat and mass diffusion in the spouted bed introduces a high degree of uncertainity in reliability of the results. Moreover the effect of all variables cannot be taken into account. Therefore, dimensional analysis will be valuable in quantifying the effect of significant variables. A list of pertinent quantities, as used in this study, is given in Table II and their values are included in Appendix D.

A close examination of Table II reveals that only two of the three, solid density, ρ_p, bulk density, ρ_b, and porosity, δ_b, can be treated as independent quantities. By neglecting the effect of bed expansion on dryer performance, height of the quiescent bed, H_b, and the column height, H_c, become redundant quantities.

Evidence shows that bed expansion affects energy requirements for spouting until initiation of the spout. Application of the spouted bed technique to biomaterial drying, however, starts after the fully developed spout is sustained by the incoming air. Hence, effect of bed expansion on drying will be ignored and H_b, will be treated as an independent parameter.

Height of lift of column material, H_{cl}, depends upon air flow rate and bed depth. It was observed that peanuts would sustain heavy mechanical damage if H_{cl} was allowed to increase without bound. Also it resulted in high power requirements and a waste of heat energy in the exit air. All experiments will be carried out at controlled flow rates.

TABLE II

VARIABLES OF INTEREST IN THE STUDY OF CONVECTIVE HEAT AND MASS DIFFUSION IN A SPOUTED BED OF PEANUTS

No.	Symbol	Quantity and Description	Units
		Particle Characteristics	
1	C	Mass concentration at time Θ, to be measured	lb_m/lb_m
2	C_d	Drag Coefficient of peanut, a proportionality factor between the drag force and the force associated with fluid momentum	0
3	C_e	Equilibrium concentration	lb_m/lb_m
4	C_o	Initial concentration	lb_m/lb_m
5	C_{pp}	Specific heat of peanut en masse at constant pressure	$Btu/(lb_m {}^oF)$
6	D_{pe}	Characteristic dimension of peanut en masse	ft
7	K_p	Thermal conductivity of peanut en masse	$Btu/(hr\ {}^oF\ ft)$
8	P	Projected area of peanut en masse	ft^2
9	Q_{p1}	Latent heat of vaporization of water in peanut	$Btu/lb_m H_2O$
10	S	Surface area of peanut en masse	ft^2
11	T_p	Initial temperature of peanut en masse	^oF
12	V	Volume of peanut en masse	ft^3
13	α_{mp}	Mass diffusivity of water vapour through peanut	ft^2/hr
14	ρ_b	Bulk density of peanut en masse in the bed	lb_m/ft^3
15	ρ_p	Solid density of peanuts, lb_m bone dry peanuts ÷ volume of peanut	lb_m/ft^3
16	τ_{pp}	Particle-particle friction coefficient	0

TABLE II (Continued)

No.	Symbol	Quantity and Description	Units
17	τ_{pw}	Particle-wall friction coefficient	0
		Bed Characteristics	
18	D_c	Column diameter, same as inlet pipe diameter [if lateral expansion is neglected]	in
19	D_b	Diameter of bed above cone	in
20	H_c	Height of column	in
21	H_b	Height of quiescent bed material, same as height of column if bed expansion is ignored	in
22	H_{cl}	Height of lift of column material including H_b	in
23	λ	Cone angle	deg.
24	δ_b	Porosity of quiescent bed, ratio of volume of voids to total volume of bed	0
25	Θ	Elapsed drying time	hr
26	g_c	Gravitational conversion factor	lb_m-ft/(lb_f-sec^2)
27	G	Gravity field strength	lb_f/lb_m
		Drying Air Characteristics	
28	C_{Pa}	Specific heat of inlet air at constant pressure	Btu/lb_m-^oF
29	K_a	Thermal conductivity at inlet air	Btu/(hr-ft ^oF)
30	ΔP_a	Air pressure needed to maintain stable spout, measured at bed inlet. Can be regarded as fluid pressure drop, bed inlet to exhaust	lb_f/ft^2
31	Q_a	Air flow rate through column or inlet pipe during stable spouting	ft^3/sec

TABLE II (Continued)

No.	Symbol	Quantity and Description	Units
32	T_a	Dry bulb temperature of inlet air	^oF
33	α_{ma}	Mass diffusivity of water vapor through air at inlet	ft^2/hr
34	μ_a	Absolute viscosity of inlet air	lb_f-sec/ft^2
35	ρ_a	Mass density of inlet air	lb_m/ft^3
36	ϕ_a	Relative humidity of air at inlet	%

hence, H_{c1} will be a minimum and treated as a dependent quantity. It is assumed that the increased length of contact of material with the drying air due to an increase in H_{c1} will not affect the drying rate significantly, but will result in a poor quality product.

In the introductory chapter the scope of the study was limited to evaluation of drying efficiency of the spouted bed dryer for peanuts. This means only those factors that affect spouting performance, or drying rate, need be considered. It is apparent from the findings of previous research workers (14) that parameters like inlet pipe diameter, D_c, bed diameter, D_b, bed height, H_b, and particle size, D_{pe}, are critical with respect to spouting pressure drop, ΔPa, and total air flow rate requirements, Q_a. Since ΔPa and Q_a are redundant, only Q_a need be included in the dimensional analysis.

In order to define the characteristics of drying air fully three parameters are needed (3). The choice of inlet air pressure above atmospheric pressure, air temperature and relative humidity are preferred. Since the desorption isotherm of peanuts represents a relationship between equilibrium humidity and equilibrium mass concentration as a function of temperature, the effect of relative humidity on drying efficiency can be evaluated by the introduction of equilibrium mass concentration, C_e. This permits a suitable definition of drying efficiency, as the ratio of amount of water removed divided by the maximum amount of water that could have been removed at experimental conditions. Air properties, specific heat at constant pressure, Cp_a, thermal conductivity, K_a, mass density, ρ_a, and dynamic viscosity, μ_a, are essentially temperature dependent and α_{ma} is a function of both relative humidity, ϕ_a, and temperature, T_a.

Volume of bed can be computed knowing the diameter, height and cone angle of the bed floor (Appendix D). Peanut properties D_{pe}, V, P, S, C_d, τ_{pp}, τ_{pw}, ρ_b, and ρ_p are essentially concentration dependent and C_{pp}, Q_{P1}, K_p and α_{mp} depend upon both concentration and temperature. No reliable information is available, on any of these properties except the specific heat. Values presented in Appendix A are only estimates at normal laboratory conditions of 77°F, 50 percent humidity and one atmosphere pressure. It is assumed that their values do not vary markedly and their effect on measured concentration is not significant.

Thus, out of 36 quantities listed in Table II only 25 are independent quantities (Figure 5). In a physical system the number of dimensionless and independent ratios required to adequately describe the system are equal to the number of independent parameters minus the rank of the dimensional matrix of the independent variables. The rank of the matrix for 25 parameters is 6 treating mass, length, time, temperature, heat, and force (MLTΘHP) as independent dimensions. Therefore, 19 Pi terms will be required to describe the system adequately. A possible choice of dimensionless ratios is presented in Table III along with their physical significance in this study.

Preliminary investigation (9) showed that moisture removal is heavily dependent upon drying time or feed rate, air temperature, humidity, initial concentration and thermal properties of particles. Therefore, the influence of the Fourier number, F_0, temperature ratio, T_r, geometry ratio, G_r, diameter ratio, D_r, size factor, S_f, and initial concentration, I_c, should be investigated.

Values of the density ratio, W_r, Prandtl number, P_r, mass diffusivity index, M_a, Schmidt number, S_c, molecular diffusivity indicies, M_{01}

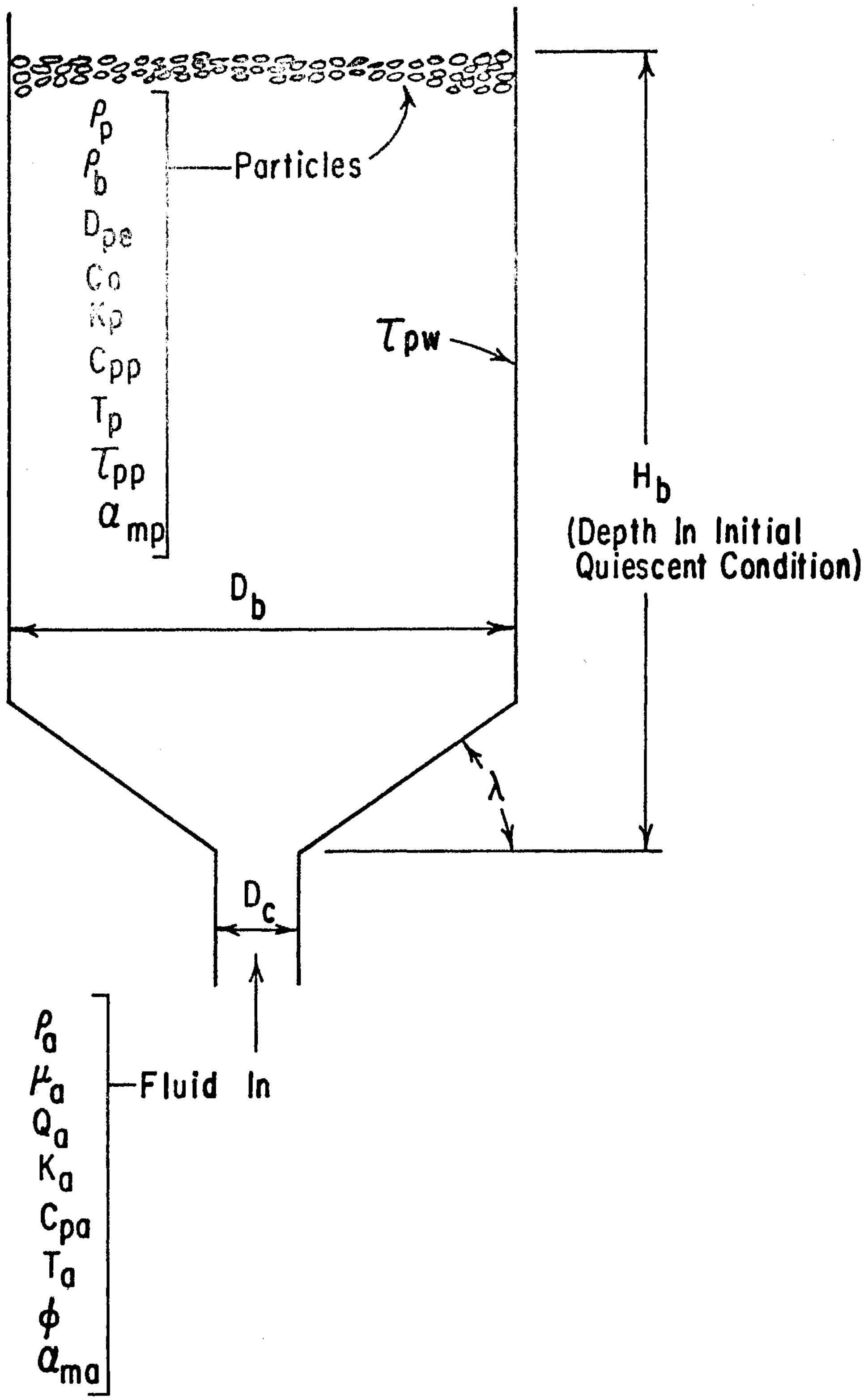

Figure 5. Pertinent Quantities for Mass Transfer Efficiency of a Spouted Bed

TABLE III

DIMENSIONLESS GROUPS AND THEIR INTERPRETATION

No.	Pi Term	Notation	Formula	Interpretation	Remark
1	Mass transfer efficiency	C_r	$\frac{C_0 - C}{C_0 - C_e}$	Amount of water removed ÷ total water that can be removed	Dependent
2	Reynolds number	R_e	$\frac{\rho_a D_{pe} Q_a}{\mu_a D_b^2 g_c}$	Inertia force ÷ viscous force of fluid in the bed or column	Variable
3	Fourier number	F_o	$\frac{K_p \Theta}{C_{pp} \rho_p D_{pe}^2}$	Rate of conduction of heat ÷ rate of storage of energy	Variable
4	Temperature ratio	T_r	$\frac{T_a}{T_p}$	Drying air temperature (final peanut temperature) ÷ initial peanut temperature	Variable
5	Geometry ratio	G_r	$\frac{D_b}{H_b}$	Diameter of bed ÷ height of bed	Variable
6	Diameter ratio	D_r	$\frac{D_b}{D_c}$	Diameter of bed ÷ diameter of column	Variable
7	Size factor	S_f	$\frac{D_b}{D_{Pe}}$	Diameter of bed ÷ equivalent diameter of peanut en masse	Variable
8	Initial concentration	I_c	C_o	Initial mass concentration	Variable

TABLE III (CONTINUED)

No.	Pi Term	Notation	Formula	Interpretation	Remark
9	Density ratio	W_r	$\frac{\rho_p}{\rho_b}$	Density of peanuts ÷ bulk density of peanuts in bed	Constant*
10	Prandtl number	P_r	$\frac{g_c \mu_a C_{pa}}{K_a}$	Diffusion of momentum ÷ diffusion of of heat	Constant*
11	Mass diffusivity index	M_a	$\frac{\alpha_{mp}}{\alpha_{ma}}$	Mass diffusivity of water in peanut : mass diffusivity of water in air	Constant*
12	Schmidt number	S_c	$\frac{g_c \mu_a}{\rho_a \alpha_{ma}}$	Diffusion of momentum ÷ diffusion of mass	Constant*
13	Molecular diffusivity index	M_{01}	$\frac{\alpha_{mp} \rho_p C_{pp}}{K_p}$	Mass diffusivity of peanut ÷ heat diffusivity of peanut	Constant*
14	Molecular diffusivity index	M_{02}	$\frac{\alpha_{ma} \rho_a C_{pa}}{K_a}$	Mass diffusivity of air : heat diffusivity of air	Constant*
15	Heat ratio	H_r	$\frac{C_{pp}}{C_{pa}}$	Specific heat of peanut ÷ specific heat of air	Constant*
16	Conductivity ratio	K_r	$\frac{K_p}{K_a}$	Thermal conductivity of peanuts ÷ thermal conductivity of air	Constant*
17	Floor angle	F_a	λ	Angle of the bed floor	Constant*
18	Particle friction	F_p	τ_{pp}	Particle-particle friction coefficient	Constant*

TABLE III (CONTINUED)

No.	Pi Term	Notation	Formula	Interpretation	Remark
19	Wall friction	F_w	τ_{pw}	Particle-wall friction coefficient	Constant*

*Will be treated constant.

and M_{02} heat ratio, H_r, conductivity ratio, K_r, floor angle, F_a, particle friction, F_p, and wall friction, F_w, will be held constant throughout the study and will not appear in the final prediction equation.

Experimental Design

From the previous analysis, it becomes clear that the drying efficiency, C_r, is a function of 7 independent and dimensionless ratios, or Pi terms,

$$Cr = F(R'_e, F_o, T_r, G_r, D_r, S_f, I_c) \tag{37}$$

In order to evaluate the effect of each of these parameters on C_r, experiments will be conducted by varying only one of these Pi terms and holding the others constant at predetermined values. The procedure of varying each of these Pi terms is presented in Table IV along with the values of the corresponding controlled variables. A total of 102 experiments will be performed under controlled conditions of temperature, humidity, air flow rate, bed depth, bed diameter, and column diameter.

TABLE IV

EXPERIMENTAL DESIGN FOR THE DRYING EFFICIENCY OF PEANUTS IN A SPOUTED BED

			Dimensionless Groups							Controlled Variables							
Exp. Series	Exp. No.	C	$R_e = \frac{\rho_a Q_a D_{pe}}{g_c \mu_a D_b^2} \times 10^{-2}$	$F_o = \frac{k_p \theta}{C_{pp} \rho_p D_{pe}^2}$	$T_r = T_a/T_p$	$G_r = D_b/H_b$	$D_r = D_b/D_c$	$S_f = D_b/D_{pe}$	$I_c = C_o$	H in. (oil)	θ hr.	T_a °F	D_b in.	H_b in.	D_c in.	T_d °F	Rep.
	211		5.36							4.0							
	221		7.36							8.0							
200	231	Measure	9.17	2.48	1.11	1.28	6.0	32.2	0.30	12.0	1.5	100.0	18.0	14.0	3.0	44.0	3
	241		10.69							16.0							
	311			0.83							0.5						
	321			1.66							1.0						
300	331	Measure	7.0	2.49	1.11	1.28	6.0	32.2	0.30	7.0	2.0	100.0	18.0	14.0	3.0	44.0	3
	341			3.32							2.5						
	351			4.98							3.0						
	411				1.09							90.0				35.0	
	421				1.11							100.0				44.0	
400	431	Measure	7.0	2.48	1.13	1.28	6.0	32.2	0.30	7.0	1.5	110.0	18.0	14.0	3.0	52.0	3
	441				1.15							120.0				61.0	
	451				1.17							130.0				70.0	
	511					2.57								7.0			
	521					1.80								10.0			
500	531	Measure	7.0	2.48	1.11	1.28	6.0	32.2	0.30	7.0	1.5	100.0	18.0	14.0	3.0	44.0	3
	541					1.00								18.0			
	551					0.86								21.0			
	611						9.0								2.0		
	621						7.2								2.5		
600	631	Measure	7.0	2.48	1.11	1.28	6.0	32.2	0.30	7.0	1.5	100.0	18.0	14.0	3.0	44.0	3
	641						5.2								3.5		
	651						3.6								5.0		
	711							21.50		3.0			12.0	9.4	2.0		
	721							26.78		4.9			15.0	11.7	2.5		
700	731	Measure	7.0	2.48	1.11	1.28	6.0	32.20	0.30	7.0	1.5	100.0	18.0	14.0	3.0	44.0	3
	741							37.50		9.5			21.0	16.4	3.5		
	751							42.80		12.4			24.0	18.7	4.0		
	811								0.20								
	821								0.25								
800	831	Measure	7.0	2.48	1.11	1.28	6.0	32.2	0.30	7.0	1.5	100.0	18.0	14.0	3.0	44.0	3
	841								0.35								
	851								0.40								

See Appendix E for definition of symbols.

CHAPTER IV

EXPERIMENTAL APPARATUS AND PROCEDURES

Primary units of the experimental apparatus used in this investigation were developed by Gay (14) in the evaluation of particle and fluid transport characteristics of spanish peanuts. For the study of drying characteristic a 21 kilowatt heater with a silicon controller was added which resulted in substantial pressure drop. It was compensated by adding a 1000 CFM, 4 oz/in^2 pressure, propeller fan in series with the existing 800 CFM, 7.5 oz/in^2 pressure turbo compressor. This combination led to a total capacity of 500 CFM at a maximum of 24 inches of water pressure after accounting for pressure drop through the orifice and heater housing.

Figure 6 is a composite view of the spouted bed drying apparatus consisting of a humidifier in combination with a water cooler, spray nozzles and high pressure pump; two fans; air pipe; heater and bed. Figures 7 through 13 show details of various elements of the apparatus. The air flow was measured with an orifice meter. Downstream and upstream pressures across the orifice were measured with a U-tube manometer. Dew point and dry bulb temperature downstream were measured using a Honeywell dew point probe, a nickle resistance thermometer and a multipoint strip chart recording potentiometer. The detailed procedure for air flow rate determination is given in Appendix B.

The heater was capable of raising air temperature to 180 ^{o}F with a

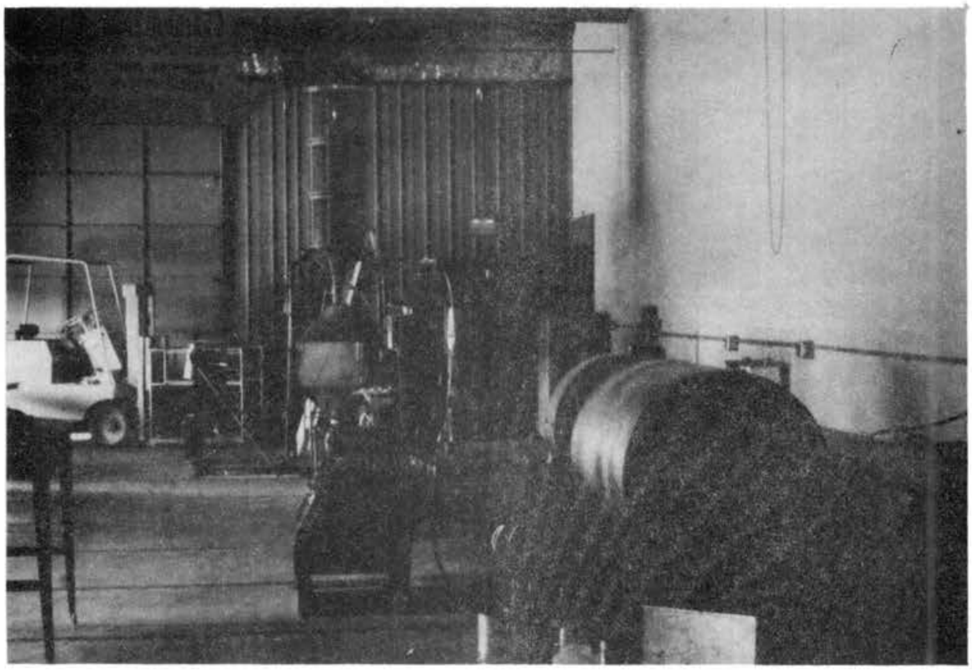

Figure 6. Composite View of the Spouted Bed Drying Apparatus

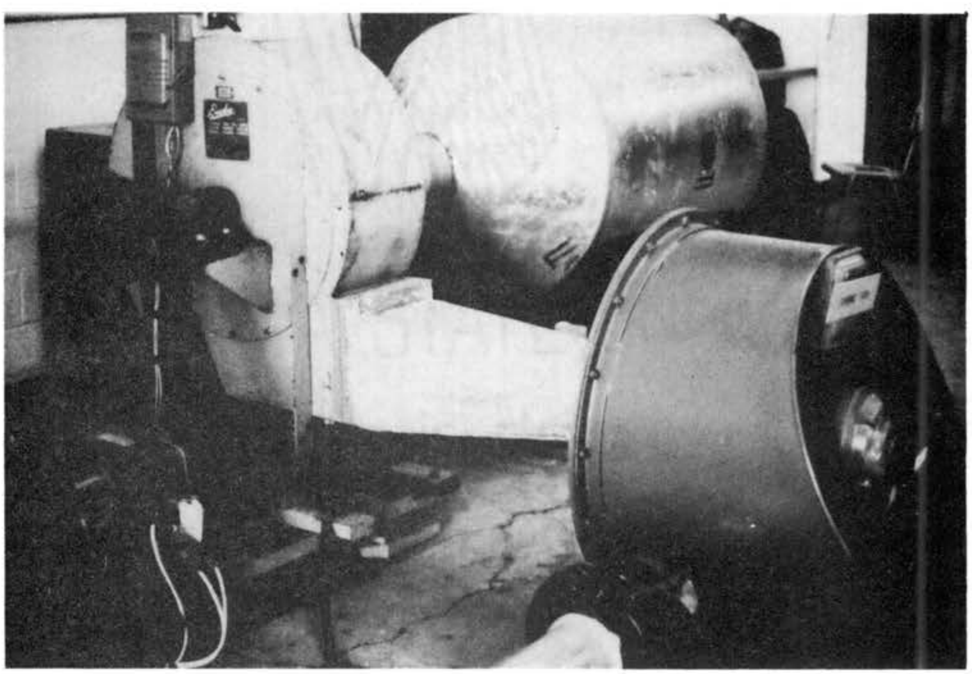

Figure 7. Close-up of Fans and Humidifier

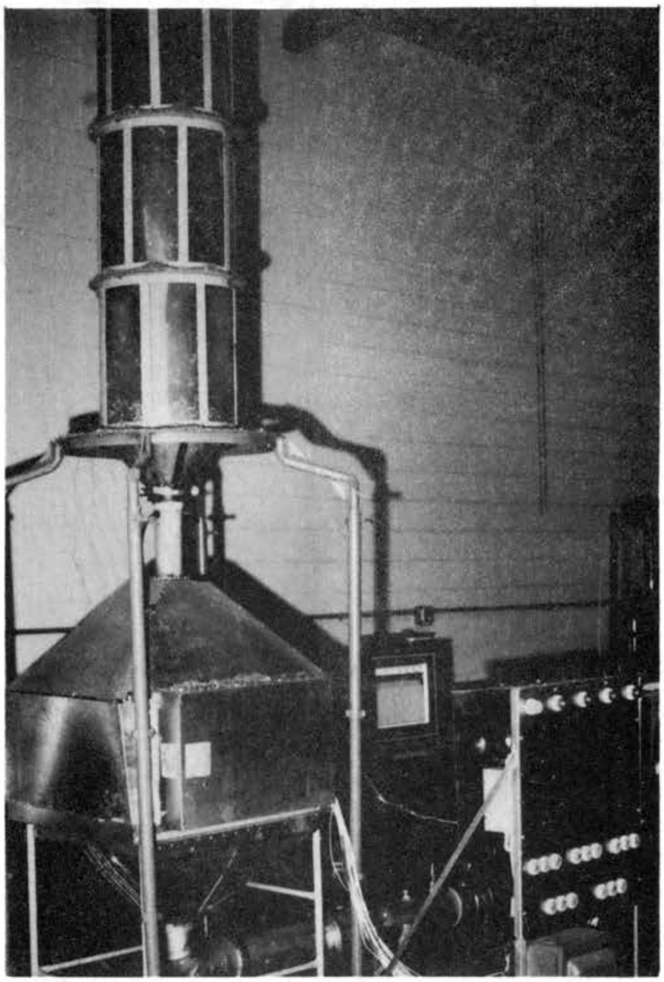

Figure 8. Close-up of Heater, Heater Controller and Bed

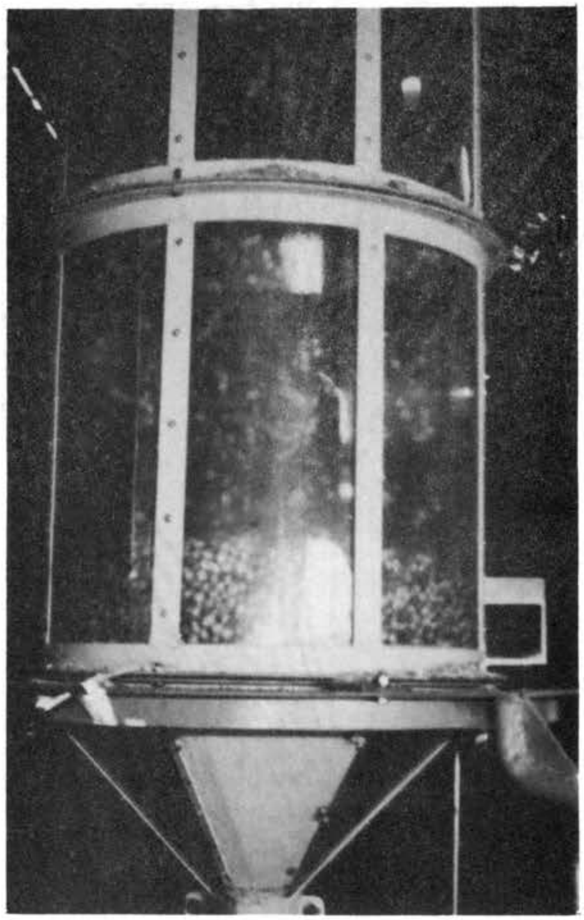

Figure 9. Inlet Pipe, Cone, Gate and Bed Arrangement

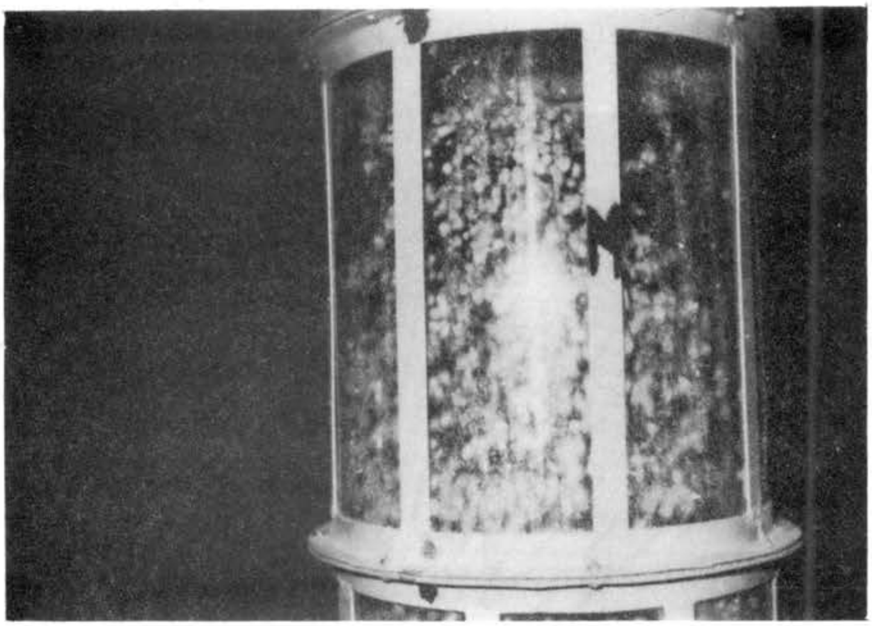

Figure 10. Spout of Peanut in Action (Side View)(14)

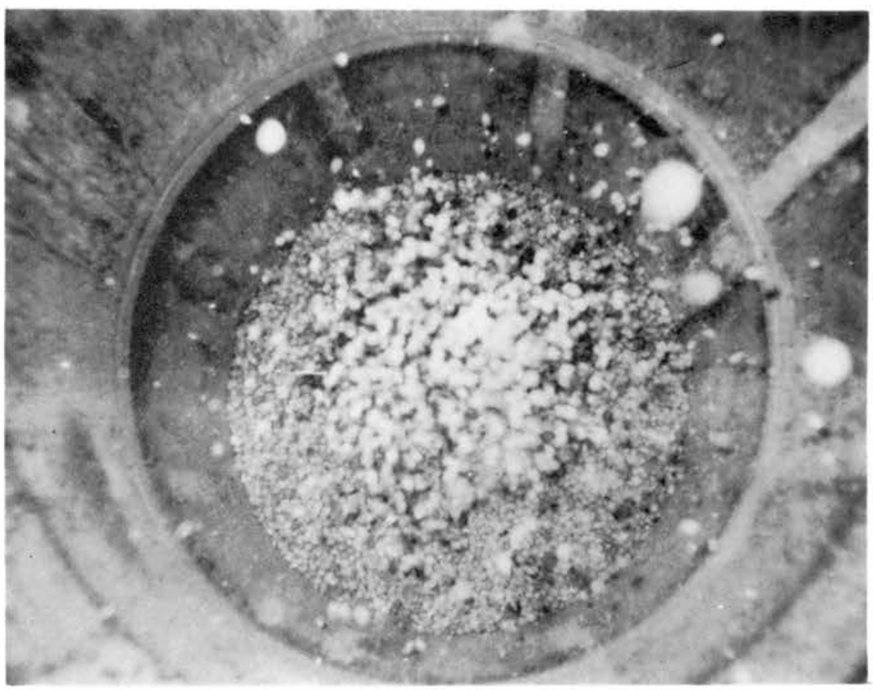

Figure 11. Spout of Peanut in Action (Top View) (14)

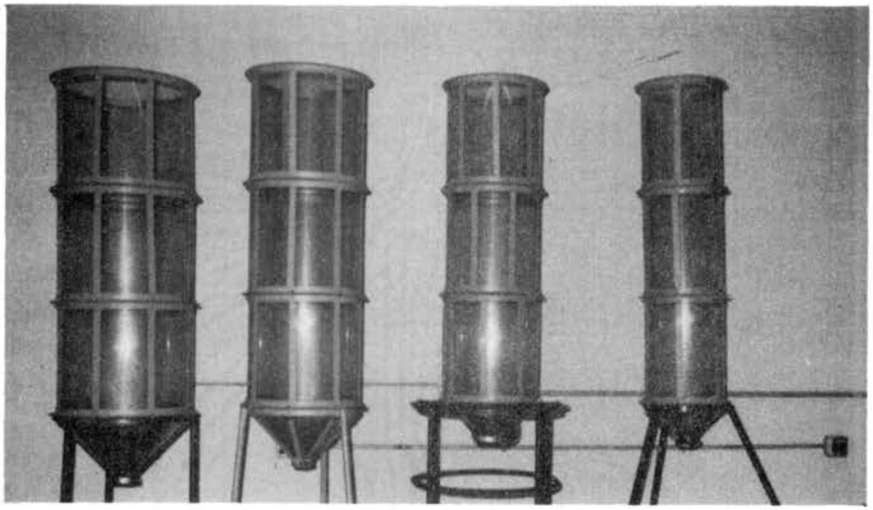

Figure 12. Combination of Bed Sizes Used (24", 21", 18" and 15")(14)

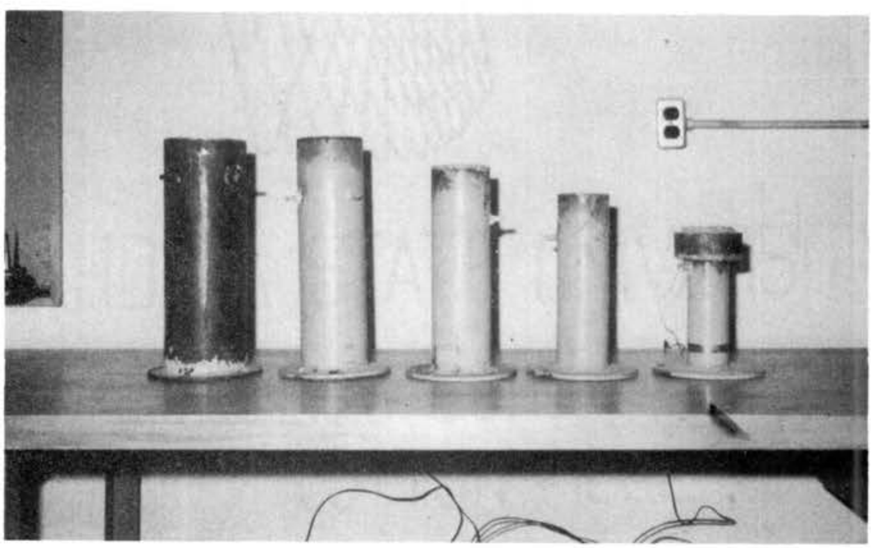

Figure 13. Inlet Pipes of Different Diameter Used (5", 4", 3.5", 3", and 2.5") (14)

tolerance of ± 1 ^{o}F. The flow rate was controlled by gate valve located at the exit of the turbine compressor. The humidifier consisted of four aspen pads 4 to 6 inches thick, that were kept wet with spray water. Temperature of spray water was controlled below ambient such that the combination of dew point temperature and bed inlet temperature resulted in a constant relative humidity of the bed inlet air. In general relative humidity varied between 12 and 18 percent in all tests. Exit air of the humidifier was saturated to 95 percent at all times. The conditions of air at the inlet to the bed and orifice are given in Appendix C.

The Particulate Material

Naturally Cured Peanut Samples

Reconstituted and naturally cured peanuts were dried in the spouted bed during the Fall of 1969 and Fall of 1970. In both years partially field cured farmers stock peanuts were obtained from the Oklahoma State University Experimental Farm, Fort Cobb, and contained moisture in excess of 50 percent dry basis. Since the volume of particulate material to be handled in each test varied from 1.5 to 3 ft^3 (30 to 75 lb_m wet) it was not feasible to remove all foreign material from each sample. However, samples were passed through a mechanical cleaner to remove soil, shelled kernels and stems. Fresh peanuts were spread on the floor under normal laboratory conditions for 24 to 48 hours, depending upon initial concentration, to remove excess moisture. These were stored in bags in a cooling chamber at 40 ^{o}F to 45 ^{o}F until used. Two days prior to testing, small 100 gm samples were drawn for mass concentration determination and kept in the oven at 266 ^{o}F for one hour. If the concentration was found in excess of the desired limit, peanuts were again spread on the floor in the laboratory, concentration rechecked at regular intervals until it reached within ± 2% of the concentration required in a particular experimental series. These peanuts were replaced in the cooling chamber until the following day's test time.

Reconstituted Peanut Samples

During the Fall of 1969 and 1970 some peanuts were dried to approximately 8% dry basis for prolonged storage. These peanuts were reconstituted to the desired concentration by adding water and gently tumbling for 15 minutes during each 3 hour period. The tumbler speed was designed to mix the peanuts uniformly and to cause minimum abrasion damage to the pods. The reconstituting was done at 45 ^{o}F temperature and required 24 hours. Amount of water needed to raise the concentration to the desired value was computed from the formula;

$$W_w = W_o\left[\frac{C}{100} - \frac{C_o}{100 + C_o}\left(1 + \frac{C}{100}\right)\right] \qquad (38)$$

where,

W_w = Weight of water added, lb_m

W_o = Initial weight of peanuts, lb_m

C = Desired concentration, percent

C_o = Initial concentration, percent

Mass Concentration Determination

In all the experimental series, for naturally cured and reconstituted peanuts mass concentration was determined by an air oven operated at 180 ^{o}F for 24 hours. It is assumed that this method reduced the peanut pods to zero moisture content since no change in the sample mass was apparent. However, it may have resulted in evaporation of some low volatile oils. Information on a specified method for producing a bone dry sample is still lacking. There is no universal method accepted and used by all investigators for determining the moisture content of peanut pods.

Equilibrium Mass Concentration

Equilibrium mass concentration of Southeastern runner spanish peanuts was obtained from Karon and Hillery's data as reported in reference (1). The value for test conditions was obtained by linear interpolation from their tabulated data. A separate equation relating the mass concentration, C_o, saturation vapor pressure of water and relative humidity was developed from the data of Beasley (5) in the range of 50 to 90 ^{o}F (1).

$$\phi = 100 \, Exp[4.215 \, MC^{-1.672} \, (ln(P_s) - 1.0) + 0.119] \quad (39)$$

where:

ϕ = Relative humidity, percent

MC = Mass concentration, percent wet basis

P_s = Saturation vapor pressure of water at the test temperature, K_{gf}/cm^2

Drag Coefficient

Drag coefficient, C_d, of peanut pods and kernels was computed using equation 40 which is derived from the force balance on a freely falling particle in a stationary fluid medium.

$$C_d = 2\, g_c[-m \frac{d^2y}{dt^2} N_e + m\, G - m\, (\rho_f/\rho_s)G]/\rho_f\, P(\frac{dy}{dt})^2 \tag{40}$$

Where:

$\frac{dy}{dt}$ = Velocity of particles, ft/sec

$\frac{d^2y}{dt^2}$ = Acceleration of particles, ft/sec^2

m = Mass of particles, lb_m

P = Projected area of particles, ft^2

ρ_s = Mass desnity of particles, lb_m/ft^3

ρ_f = Mass density of fluid, lb_m/ft^3

G = Gravity field strength, lb_f/lb_m

N_e = Reciprocal of Newton's second law coefficient, g_c, lb_f - sec^2/lb_m - ft

Peanuts were allowed to fall in a clear acrylic tube 3.65 inches inside diameter and 6 feet long. The tube was graduated at one inch intervals to facilitate measurement of the time-distance relationship. The fluids were selected so that a velocity of approximately 0.25 ft/sec was obtained for kernels and whole pods. Water at three temperatures and gasoline were selected, as stationary fluid mediums in this study.

Drag coefficient of peanut pods was found to be a function of mass concentration, Reynolds number, and surface conditions. The value for peanut pods reported in Appendix D is extrapolated from reference (2) to include the range of test Reynolds number and normal laboratory conditions (NLC) of 77°F and 50% relative humidity. The drag coefficient is constant beyond Re = 10,000 based on equivalent diameter of peanut pods.

Thermal Conductivity

Thermal conductivity of peanut en masse, initially at normal laboratory conditions, was determined by 'column method' using a line heating source (Figure 14). The line heat source was constructed, according to the procedure given by Hopper and Lepper (18) and Tye (37), from a 26 gage constantan heating element 1 ft long with a resistance of 0.98 ohms/foot. A 36 gage copper - constantan thermocouple was silver soldered to the center of the heating element. Copper leads were connected at both ends of the heating element. The line heat source was mounted in an aluminum cylinder, 1' long and 6" diameter, with insulated ends. Current was supplied by a 6 volt battery through a combination of two 50 ohm variable resistors. Neither the voltage nor current changed more than 1% from preset values during the tests. Temperature of the thermocouple was recorded by a potentiometer with a tolerance of 1 °F.

Peanuts at normal laboratory conditions were placed in the cylinder at a bulk density of 18.3 lb_m/ft^3. In the line heat source method values of voltage, current, and temperature at two different times are essential to determine thermal conductivity. Several preliminary tests revealed that after applying heat, the wire temperature reached steady state after 6 minutes. This time and another arbitrary time of 30 minutes, that yields a value of $\frac{r}{2}\frac{1}{\sqrt{\alpha\theta}}$ approximately equal to 0.01, were chosen for calculation of thermal conductivity. The thermal conductivity was calculated from the formula,

$$K = \frac{3.415\ EI\ \ln\ (\theta_2/\theta_1)}{4\pi\ (T_2 - T_1)} \tag{33}$$

where,

K = Thermal conductivity of peanut, en masse, Btu/(hr ft °F)

Q = Heat input, watts

θ = Time, hrs

T = Temperature of heating element, °F

Results from a typical test are presented below.

Initial temperature of peanuts	= 70.5 °F
Voltmeter reading	= 1.5 volts
Ammeter reading	= 1.4 amps
Temperature at 6 minutes	= 176 °F
Temperature at 30 minutes	= 190 °F

$$K = \frac{3.415 \times 1.5 \times 1.4 \times \ln(30/6)}{4\pi\ (190-176)} = 0.0656\ \text{Btu/(hr ft}\ ^{o}\text{F)}$$

The value of K presented in Appendix D represents an average of six such test values.

Friction Coefficient

Particle-particle friction of peanut pods, τ_{pp}, was assumed to be the same as the angle of repose. The later was determined by pouring peanuts on the floor and measuring the angle of the pile with horizontal surface. Particle-wall friction, τ_{pw}, was measured in laboratory using an Instron Universal Testing machine (Figure 15). Two materials, steel and plastic, were used in construction of the spouted bed, hence the friction coefficient of peanut pods on both materials was determined at normal laboratory conditions (Appendix D).

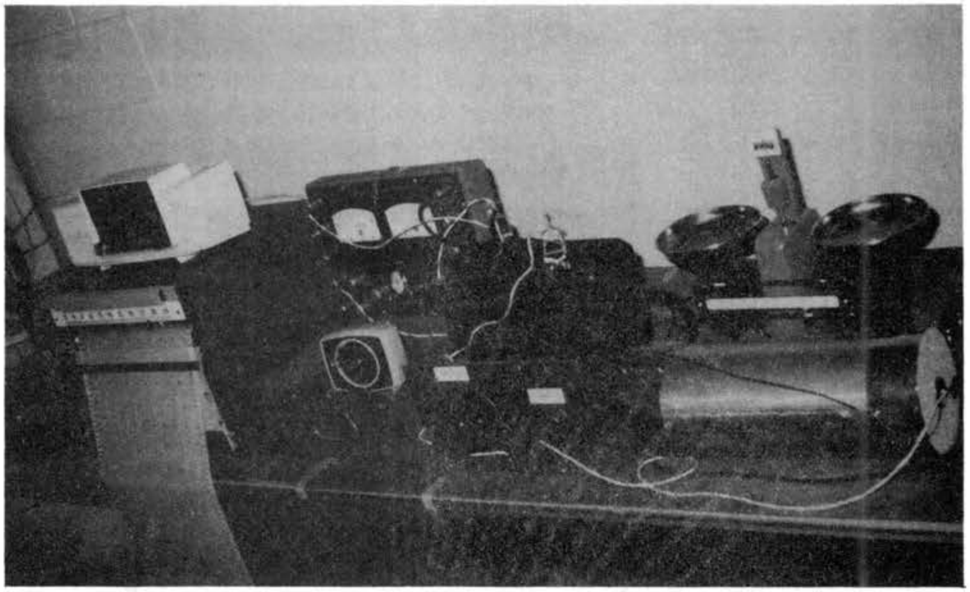

Figure 14. Thermal Conductivity Apparatus--Line Heat Source

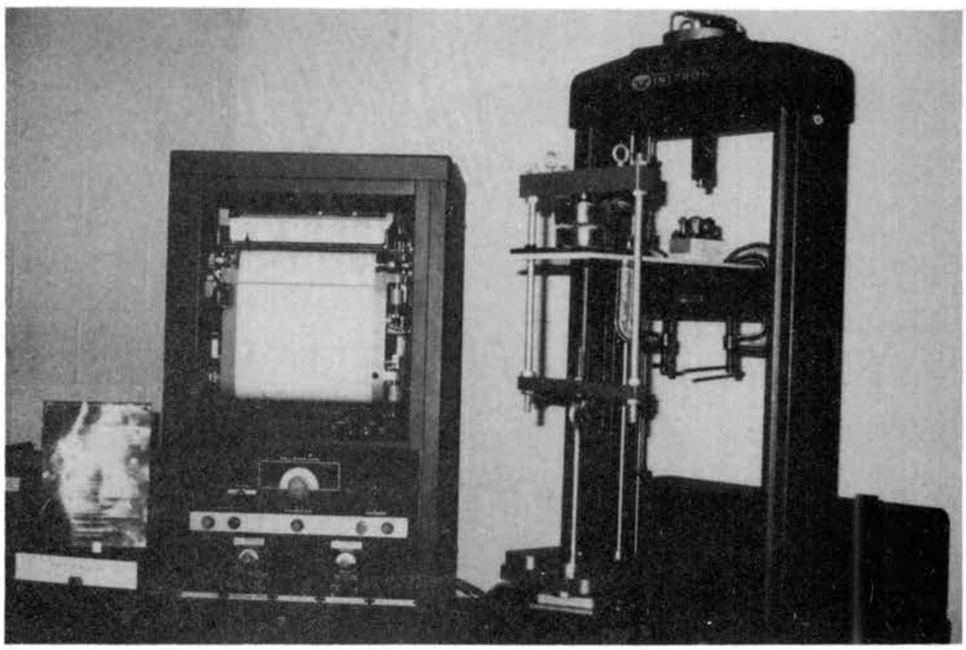

Figure 15. Instron Universal Testing Machine as Used for Coefficient of Friction Determination

Both τ_{pp} and τ_{pw} vary during drying process due to pod abrasion, temperature rise and loss in moisture content. No attempt was made to investigate changes in the reported values since both of these parameters are assumed to have no effect on drying rates.

Characteristic Dimension

It has been shown that diameter of a sphere having a volume equal to the volume of a peanut pod is adequate for estimating Reynolds number when predicting drag coefficient (2). In order to calculate the diameter of an equivolume sphere, an estimate of volume of a representative peanut pod is essential. This is done by summing the partial volumes of each of the four peanut types described in Appendix A. They are defined as single kernel ellipsoids, cassinoids, paired ellipsoids, and two kernel ellipsoids (Figures 16 through 20) respectively. This volume is assumed to be the volume of an equivolume sphere.

$$VxW = \sum_{i=1}^{4} Vi \times Wi \qquad (41)$$

$$= 0.0608 \times 0.1678 + 0.1092 \times 0.4166 + 0.0865 \times 0.1978 + 0.088 \times 0.1322$$

$$V = 0.0844/0.9144$$

$$= 0.092 \text{ in}^3$$

where,

V = Total volume of peanut en masse

W = Weight fraction of four peanut types

Vi = Partial volume of each peanut type

Wi = Partial weight fraction of each peanut type

Therefore, equivalent diameter of a representative peanut pod is,

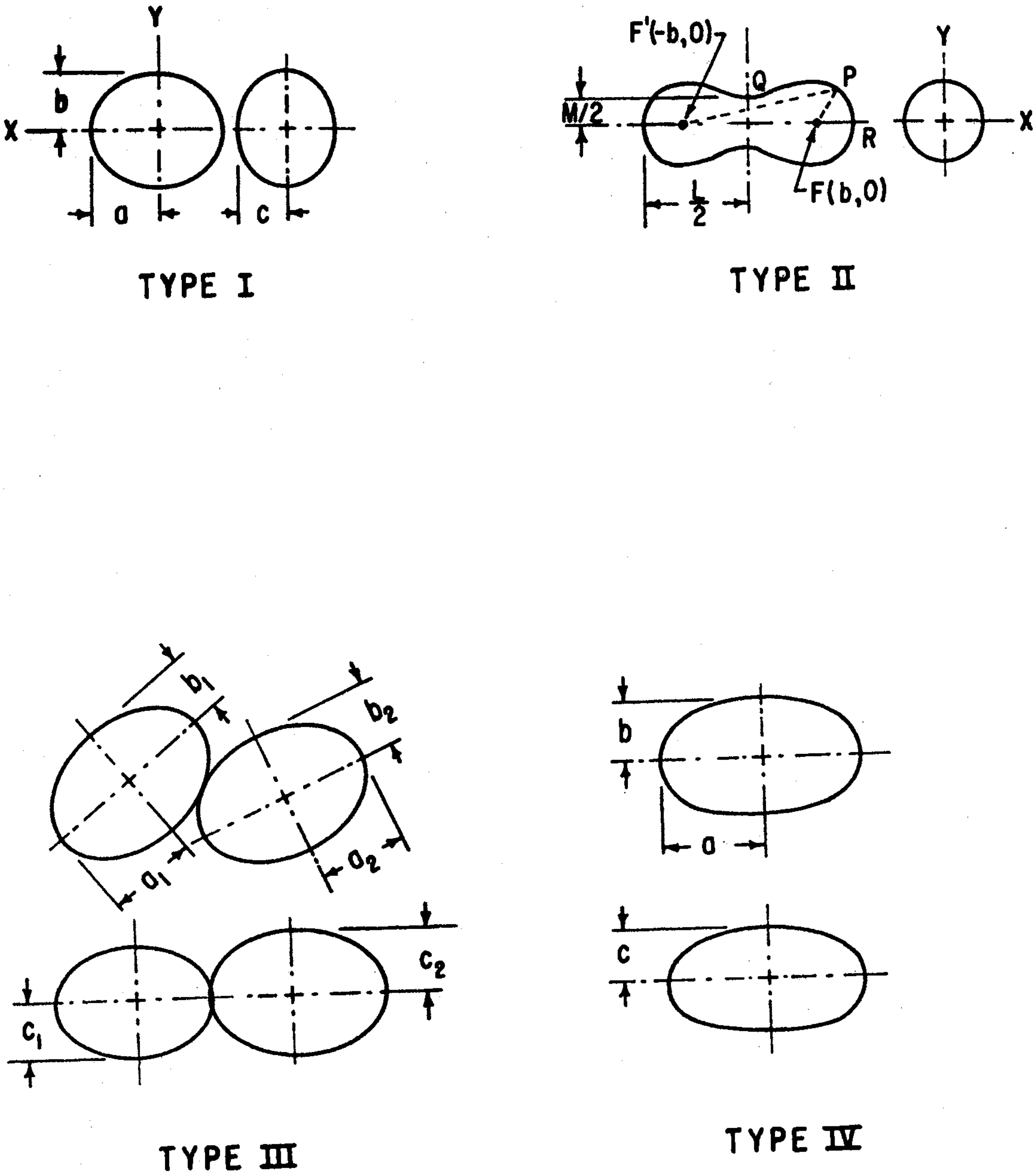

Figure 16. Schematic of Peanut Types en masse. Type I (single kernel ellipsoid), Type II (cassinoid), Type III (paired ellipsoid), Type IV (two kernel ellipsoid)

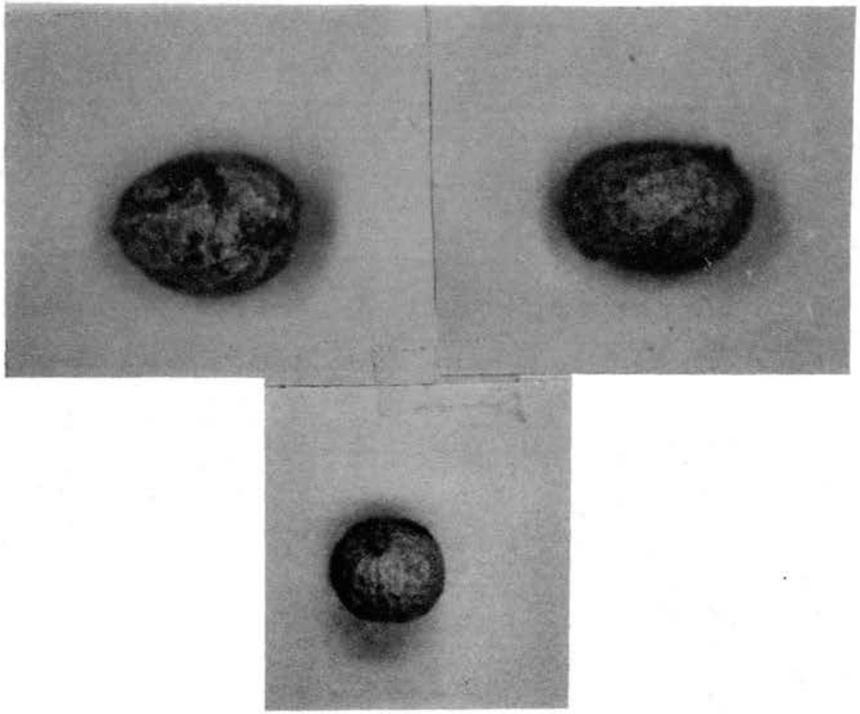

Figure 17. Peanut Type I, Single Kernel Ellipsoid

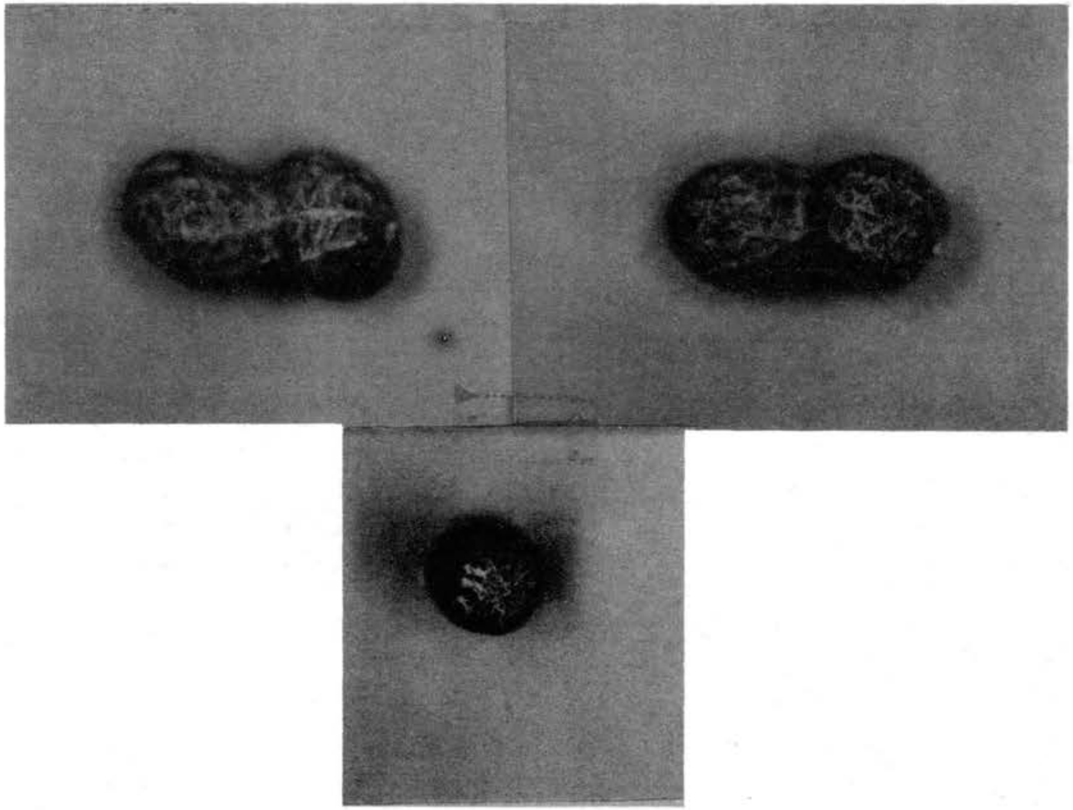

Figure 18. Peanut Type II, Cassinoid

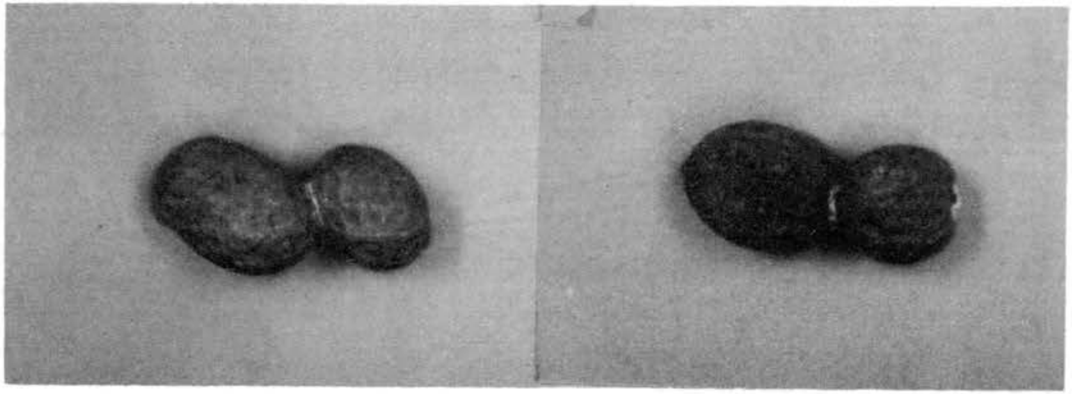

Figure 19. Peanut Type III, Paird Ellipsoid

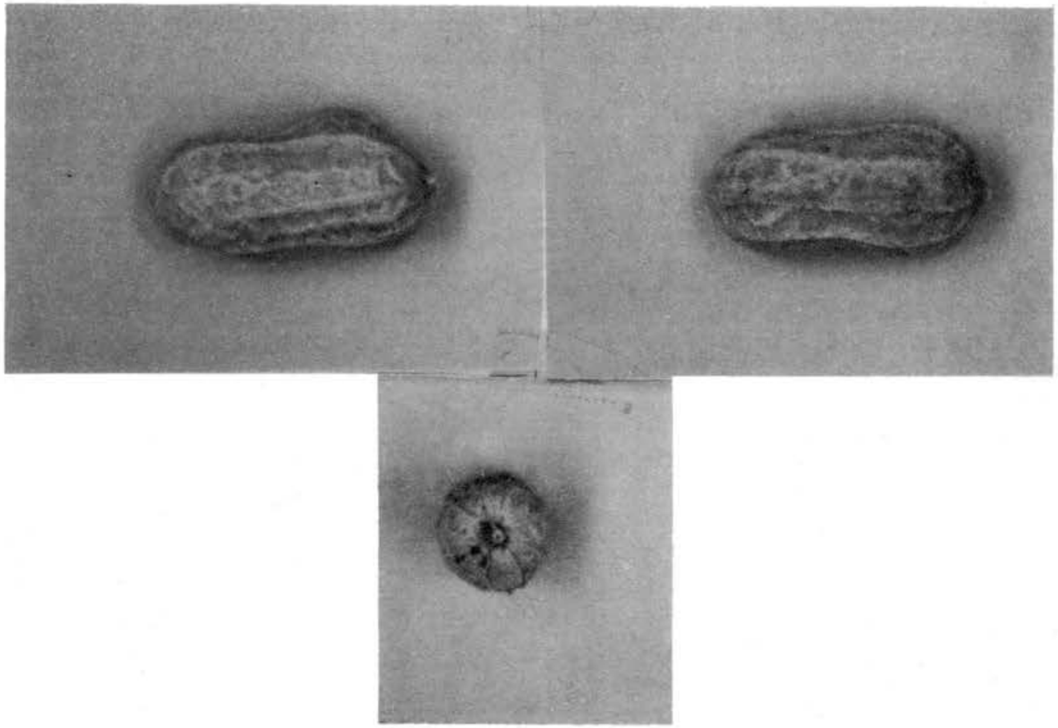

Figure 20. Peanut Type IV, Two Kernel Ellipsoid

$$D_{pe} = 3\sqrt{6V/\pi}$$

$$= 3\sqrt{6 \times 0.092/\pi} \qquad (42)$$

$$= 0.56 \text{ in}$$

This diameter was used to calculate the projected area, P, and surface area, S, of representative peanuts en masse.

Mass Density

Bulk density and absolute density of spanish peanut pods as used in tests were determined in laboratory. A container of known volume was filled with pods and its weight recorded. Ratio of pod mass to container volume was regarded as bulk density of peanut en masse at normal laboratory conditions. Absolute density was determined from measurements of mass and volume of individual pods. A Mettler balance graduated to nearest 0.0001 gram was used for mass determination and volume was measured using Archemedes principle. Pods were submerged in water using weights of known volume. Adsorption of water by the pod during this period was small and neglected (Appendix A).

Porosity

Porosity of the bed, ρ_b, was determined during the bulk density tests by pouring water in a cylinder filled with peanuts. It was assumed that the entire entrapped air will be evacuated and all the pore volume will be occupied by water. Volume of water needed to fill the cylinder divided by its volume is reported as the porosity. The relation between porosity, solid density and bulk density of particles is given by

$$\rho_s = \frac{\rho_b}{(1-\delta_b)} . \qquad (43)$$

The values of ρ_s, ρ_b and δ_b agreed to the specified tolerance in Appendix D as determined by the methods of porosity and density measurement.

Heat of Vaporization

Heat required to vaporize moisture from peanuts varies with mass concentration. Up to 5% mass concentration it has been reported to be 81.95 Btu per pound of water (41). Above this concentration it is either greater than or equal to that of the free water. At normal laboratory conditions ratio of latent heat of vaporization of water in peanut pod to free water is 1.1334 (1). Latent heat of free water at 77^oF is 1050.1 Btu/lb_m.

Composite Drying Efficiency

Peanut Quality Determination

As stated in Chapter I a commercial dryer must perform three vital functions; namely, have high efficiency, be economical and preserve quality. Based upon these three factors a convenient index called "Composite Drying Efficiency" can be formed to compare the performance of existing peanut dryers. Such an index should include indices of heat efficiency, mass transfer efficiency, quality and economics. In general high heat and mass transfer efficiencies are indicators of low operating cost which is a major factor in economical considerations. Product quality is judged differently by the producer, processor, and consumer. Since product quality is very vulnerable, it may be changed at several other stages before it reaches the consumer, hence consumer quality will be considered beyond the scope of this study. As stated before, the producer is mainly interested in the market value while the processor is concerned with market and processing qualities. From the producer's point of view indices of heat and mass transfer efficiencies will be more important to compare while from the processer's viewpoint indices of quality need be considered. As far as the product output from a dryer is concerned these indices can be characterized with such features as, a) uniformity of mass concentration in the entire product, b) fewer damaged pods and broken kernels, c) good taste, flavor and aroma, and d) freedom from toxic substances.

Lack of mixing and prolonged drying time in quiescent dryers result in nonuniform mass concentration and growth of toxic substances. It has been noted that the nature of the spouted bed completely eliminates these problems due to vigorous mixing and use of higher temperatures to achieve high drying rates. However, peanuts can be damaged so that odor and flavor are impared.

Factors to be considered in evaluating peanut, flavor and aroma are varied and sensitive. No reliable quantative scientific procedure is so far available. Taste panel studies are very subjective in nature. No attempt will be made to use such a procedure in this study.

Peanut damage can be quantified rather accurately by following the scheme outlined in Figure 21. A large sample of peanuts, before and after drying efficiency tests, was divided into several subsamples until a working sample of about 100 gms was obtained. It was passed through an 'USDA grading screen' to separate sound mature pods from split kernels, immature pods and trash. Each component of the original working sample

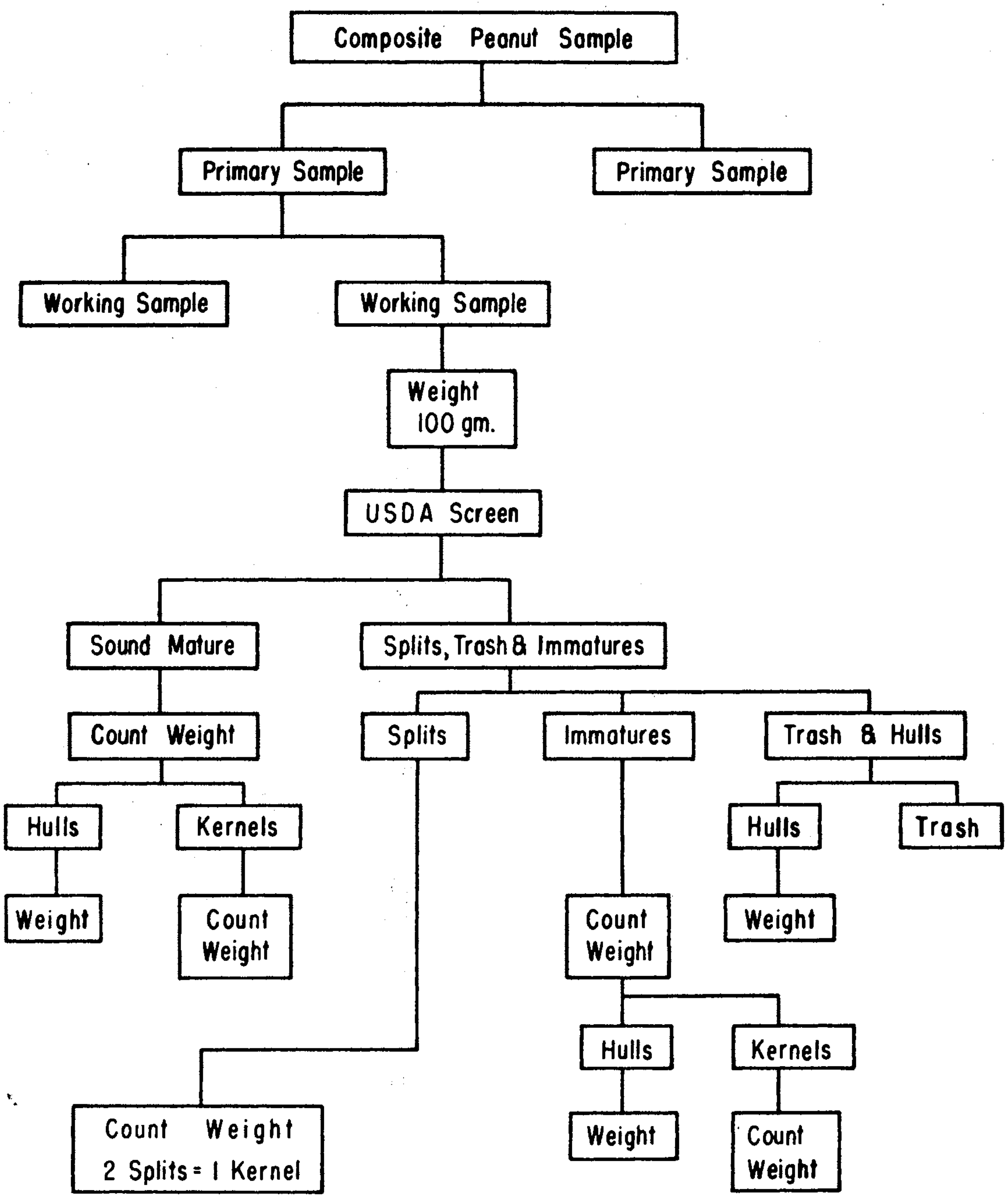

Figure 21. Method of Analysis of Peanut Samples for Quality Determination

was further separated into kernels and hulls and quantified by weight and count.

CHAPTER V

PRESENTATION OF DATA AND RESULTS

Mass Transfer Efficiency Tests

Component Equations

Dimensional analysis allows evaluation of drying efficiency of the spouted bed by relating the effect of individual dimensionless group in the form of component equations and then combining these equations to form a single prediction equation.

Recall that the mass transfer efficiency was defined to be the ratio of the water removed, (C_o-C), to the total water that can be removed, (C_o-C_e). Since C_e depends upon the relative humidity and temperature of the drying air, it denotes the lower limit of particle mass concentration. Similarly specific heat, C_{pp}, and thermal conductivity, K_p, vary with temperature and initial mass concentration. Density, ρ_p, and equivalent particle diameter, D_{pe}, are functions of initial concentration only. All these parameters appear in four Pi terms C_r, R_e, F_o, and S_f in equation 44.

$$C_r = f(R_e, F_o, T_r, G_r, D_r, S_f, I_c) \tag{44}$$

Observed values of C_r, in equation 44 are presented in Appendix C and are plotted in Figures 22 through 30. The straight line plotted in each figure is the linear regression line obtained by the method of least

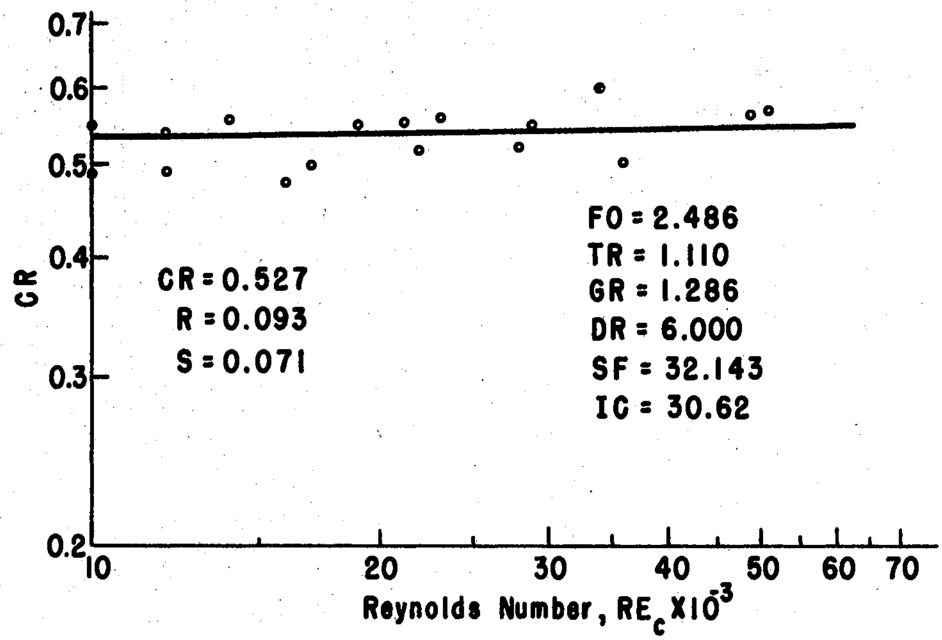

Figure 22. Component Curves--Log Log of Drying Efficiency vs. Reynolds Number Based on Velocity of Air in Column and Particle Diameter

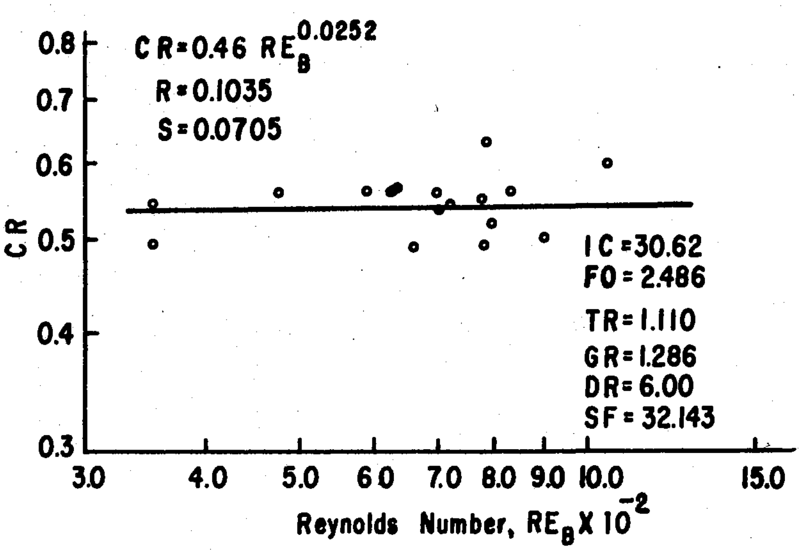

Figure 23. Component Curves--Log Log of Drying Efficiency vs. Reynolds Number Based on Superficial Velocity of Air in Bed and Particle Diameter

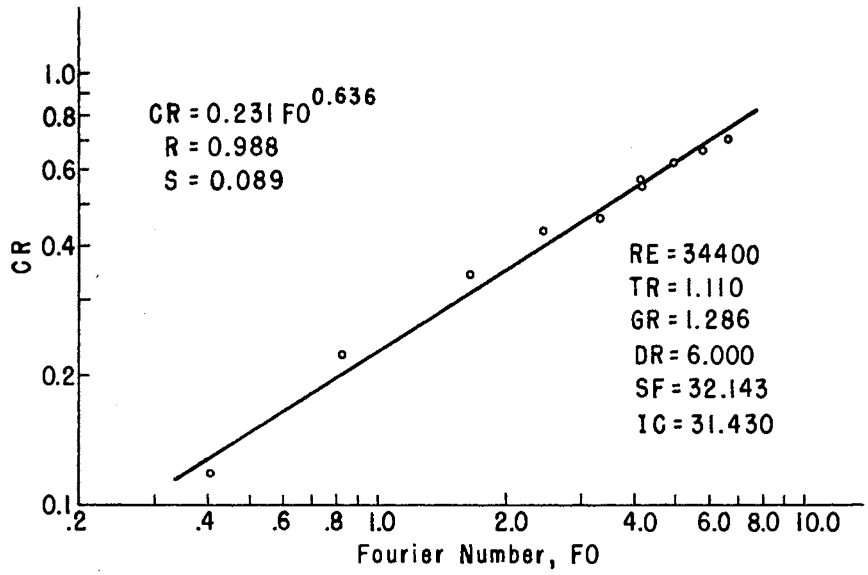

Figure 24. Component Curves--Log Log of Drying Efficiency vs. Fourier Number

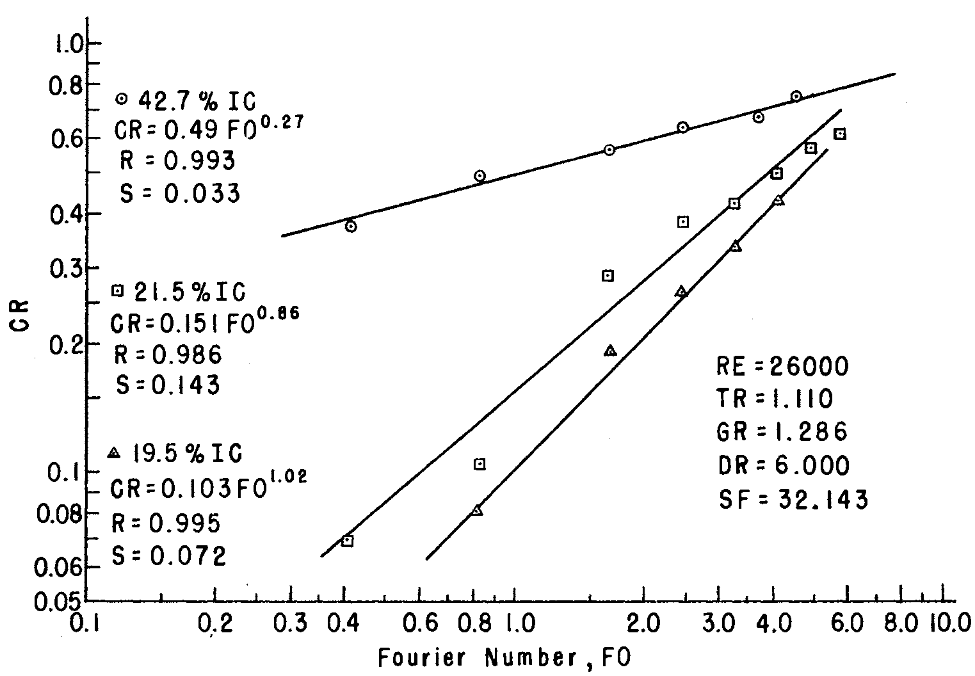

Figure 25. Variation of Drying Efficiency With Initial Mass Concentration, I_c

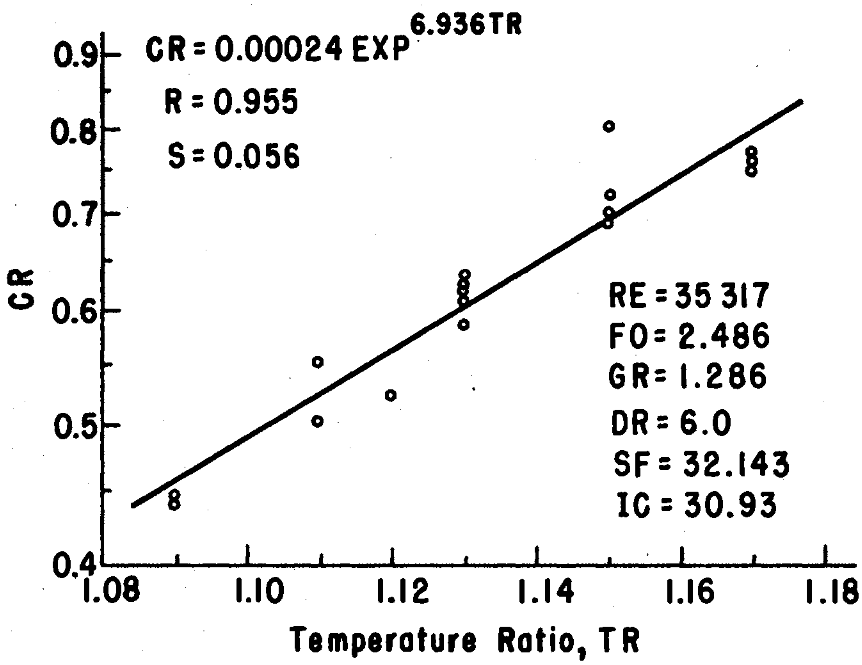

Figure 26. Component Curves--Log of Drying Efficiency vs. Temperature Ratio, T_a/T_p

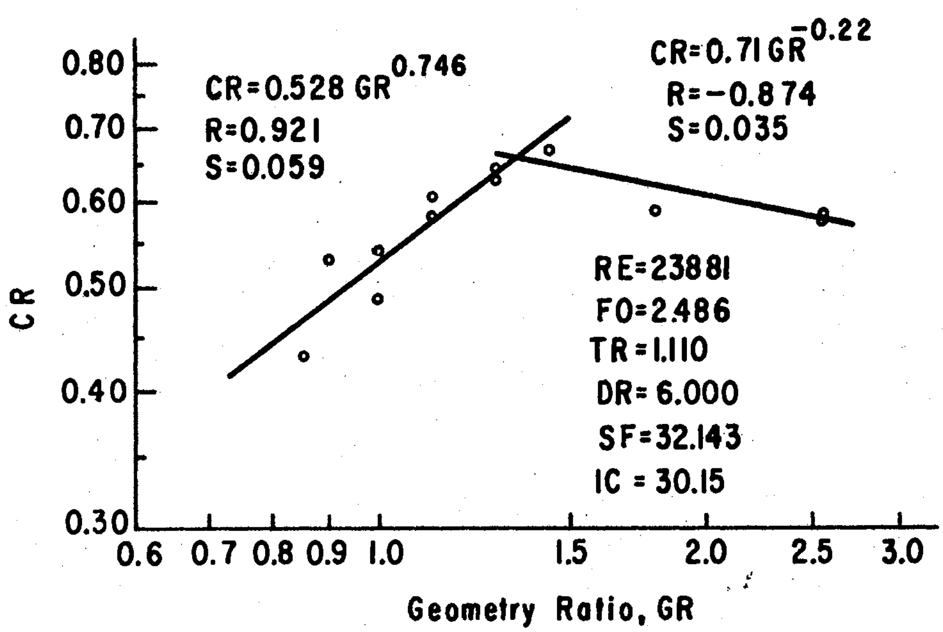

Figure 27. Component Curves--Log Log of Drying Efficiency vs. Geometry Ratio, D_b/H_c

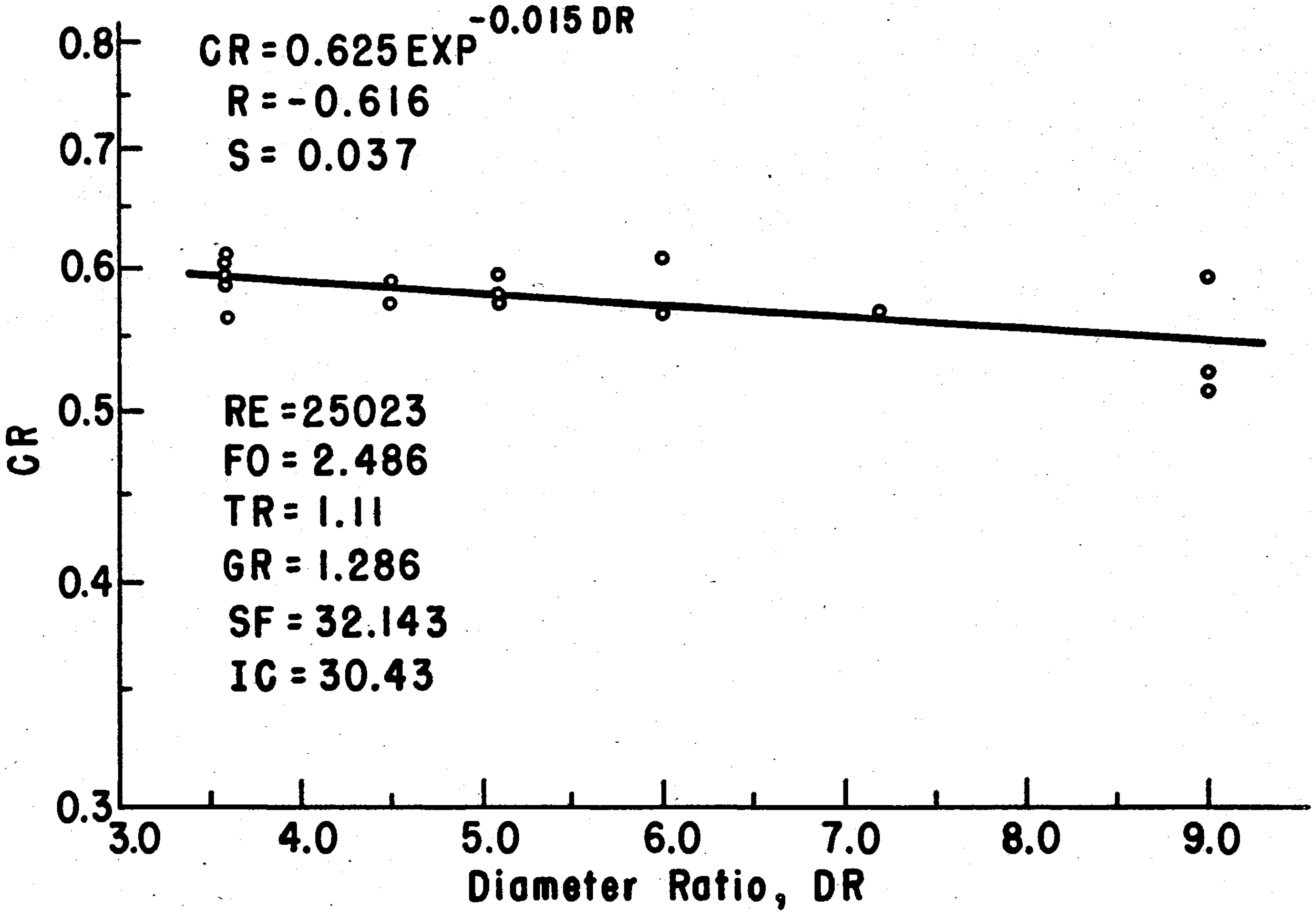

Figure 28. Component Curves--Log of Drying Efficiency vs. Diameter Ratio, D_b/D_c

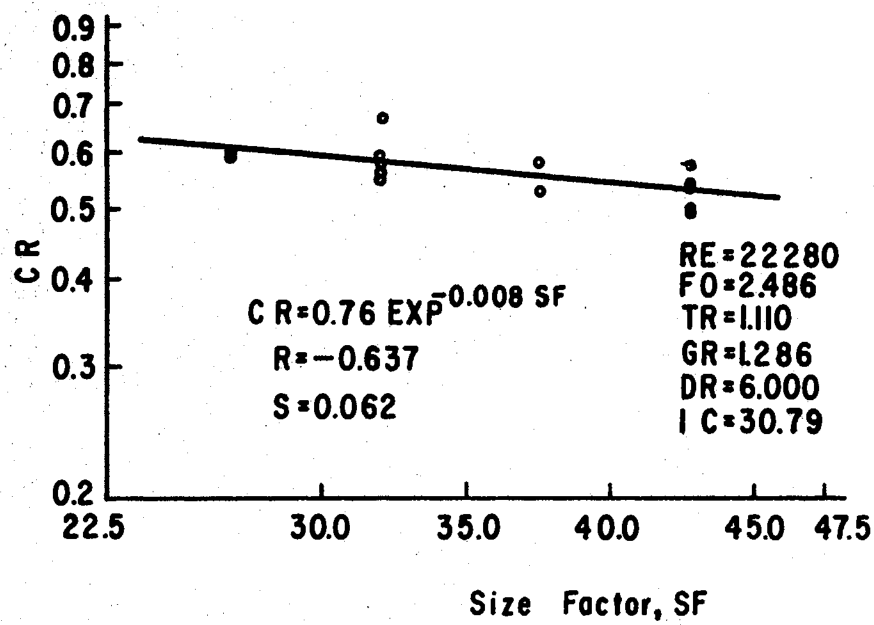

Figure 29. Component Curves--Log of Drying Efficiency vs. Size Factor, D_b/D_{Pe}

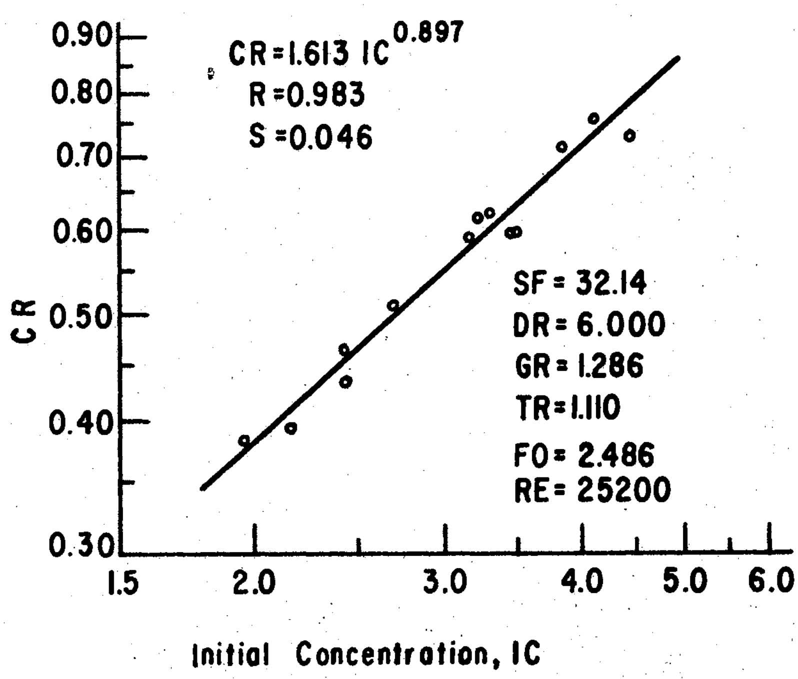

Figure 30. Component Curves--Log Log of Drying Efficiency vs. Initial Concentration

squares (7). The equation of the regression line, regression correlation coefficient, R, and sample standard deviation of regression, S, are included in each figure. A summary of component equations is presented in Table V along with the values of standard deviation of regression coefficient, S_b, and calculated values of t distribution. The lowest values of R was 0.093 and highest 0.988 for the test series. Series 500 and 500a represent two parts of the C_r vs. G_r curve.

Figures 22 and 23 are plots of drying efficiency, C_r, and Reynolds number based on particle diameter and air velocity in the inlet pipe, R_{ec}, and velocity in the bed, R_{eb} respectively. There is no evidence that the Reynolds number or for that matter air flow rate affects drying efficiency. Air velocities required to initiate the spout are in excess, 10 to 20 times, of those used in quiescent bed and continuous drying systems (4,20). Most workers have limited the flow rate between 5 to 20 $ft^3/min\text{-}ft^3$. Wright (41), however, has used 300 to 400 $ft^3/min\text{-}ft^3$, of flow rate in radio frequency energy drying system as compared to 125 to 250 $ft^3/min\text{-}ft^3$ in the spouted bed. He did not attempt to evaluate the effect of flow rate on drying efficiency directly. Preliminary investigations on the spouted bed (9) led to the conclusion that the effect of air flow rate on drying rate was insignificant. The spouted bed is characterized as a well mixed isothermal bed, with the drying rate controlled by mass diffusion within the particles. Any resistance to mass transfer may be neglected (α_{mp}/α_{ma}) in comparison to the internal mass transfer resistance. According to an estimate by Becker (6) the effect of flow rate on drying becomes negligible for $R_{ec} > 900$. Relationships between the Fourier number, F_o, and drying efficiency C_r, (Figures 24 and 25) illustrate that two factors controlling the efficiency are drying

TABLE V

SUMMARY OF THE COMPONENT EQUATIONS

Experiment Series	Average R_{ec}	F_o	T_r	G_r	D_r	S_f	Average I_c	Component Equations	Regression Correlation Coefficient R	Standard Deviations S	Standard Deviations S_b	Calculated t	Degrees of Freedom DF	Equation No.
200	R_{eb}	2.486	1.11	1.286	6.0	32.143	30.62	$C_r = 0.459\ R_e^{0.0252}$	0.1030	0.0705	0.0570	0.441	18	45
200a	R_{ec}	2.486	1.11	1.286	6.0	32.143	30.62	$C_r = 0.5274$	0.0931	0.0706	0.0572	0.000	18	46
300	34400	-----	1.11	1.286	6.0	32.143	31.43	$C_r = 0.231\ F_o^{0.6363}$	0.9880	0.0890	0.0325	19.594	9	47
400	35317	2.486	----	1.286	6.0	32.143	30.93	$C_r = 0.00024\ \mathrm{Exp}^{6.936T_r}$	0.9551	0.0562	0.5558	12.479	15	48
500	23881	2.486	1.11	-----	6.0	32.143	30.15	$C_r = 0.5284\ G_r^{0.7463}$	0.9208	0.0588	0.1195	6.248	7	49
500a	23863	2.486	1.11	-----	6.0	32.143	30.65	$C_r = 0.7062\ G_r^{-0.2184}$	-0.8736	0.0355	0.7020	- 3.109	3	50
600	25023	2.486	1.11	1.286	---	32.143	30.43	$C_r = 0.6255\ \mathrm{Exp}^{-0.0145D_r}$	-0.6161	0.0373	0.0046	- 3.129	16	51
700	22280	2.486	1.11	1.286	6.0	------	30.79	$C_r = 0.7603\ \mathrm{Exp}^{-0.0079S_f}$	-0.6367	0.0616	0.0027	- 2.977	13	52
800	25200	2.486	1.11	1.286	6.0	32.143	-----	$C_r = 1.6134\ I_c^{0.8969}$	0.9826	0.0460	0.0488	18.358	12	53

S = Sample Standard Deviation from Regression line.
S_b = Standard Deviation of the Regression Coefficient.
See Appendix E for definition of other symbols.

time, θ, and initial concentration, C_o. The fact that the mass diffusion coefficient, α_{mp}, is concentration dependent has been well established (6,39). Whitaker and Young's data (39) indicate that α_{mp}, is not constant in the range of 50 to 70% concentration for peanuts. Becker (6) established that α_{mp}, is independent of C_o between 15 to 25% concentration for wheat. Hence variation of C_r in the range of test values of C_o is justified in Figures 25 and 30. Mass transfer efficiency varied exponentially with the temperature ratio T_r (Figure 26). This is due to the temperature dependence of the mass diffusion coefficient, α_{mp}. During the spouted bed drying tests, an estimate of time required to heat the peanuts from an initial 45° F temperature to an air temperature of 100° F, was obtained by inserting a 36 gage Copper-Constantan thermocouple. Individual peanuts attained air temperature within 15 minutes. In other tests for thermal conductivity where a heating element was inserted in individual peanuts, it took 6 to 10 minutes (depending upon the heat applied) for the entire surface to reach an equilibrium temperature above ambient temperature. This reveals that variation of C_r, exponentially with T_r, is mainly due to an increase in the mass diffusion coefficient.

Effect of the size factor, S_f, and diameter ratio, D_r, on drying efficiency is small (Figures 28 and 29). Any change in D_r or S_f results in changing flow conditions and a change in the Reynolds number. A larger S_f means a larger bed diameter or lower bed superficial velocity and a larger volume of material to be dried. Due to an increase in bed volume, the efficiency is expected to decrease as is evidenced by Figure 29. Since the diameter ratio, D_r, was varied by changing the column diameter, D_c, bed volume remained constant while R_{ec}, varied. These relationships are similar to the one for C_r vs. R_e where a horizontal straight line resulted.

Effect of the geometry ratio, G_r, on the drying efficiency, C_r, (Figure 27) is shown by two straight lines intersecting at $G_r = 1.35$. At higher bed depths magnitude of G_r is small and a larger G_r infers small bed depth. Beyond $G_r = 1.35$ or $H_b \sim 13.5$ inches, performance of the dryer is severely affected due to impact damage to the final product. Cracked kernels, number of splits, and hull abrasion increased markedly. Some hulls were also blown off the dryer along with the finer particles. Net result of these changes in product condition was seen in the samples drawn for mass concentration determination. A higher value of concentration resulted essentially due to the fact that peanut kernels, that constituted the bulk of the sample, contained more water per pound of dry matter than did the hulls. Thus the magnitude of $(C_o - C)$ divided by $(C_o - C_e)$ became small resulting in an apparent lower efficiency. Hence the line with a negative slope in Figure 27 or equation 50 will not be included in the prediction equation. Use of higher bed depths, above 13.5 inches, is therefore desirable for the bed configurations used.

Prediction Equations for Mass Transfer Efficiency

According to Murphy (25) component equations that form straight lines on log-log coordinates, can be combined as,

$$C_r = \frac{F_1(R_e, \bar{F}_o \ldots\ldots\ldots \bar{I}_c) \ldots\ldots F_7(\bar{R}_e, \bar{F}_o, \bar{G}_r \ldots\ldots I_c)}{[F_8(\bar{R}_e, \bar{F}_o \ldots\ldots \bar{I}_c)^{s-2}} \qquad (54)$$

where:

s = Total number of independent and dimensionless groups

The bar over each group indicates that it was held constant during the indicated experimental series.

The component equations and constant values of dimensionless groups are tabulated in Table V. In order that component equations be combined by multiplication equations 48, 51 and 52 should be transformed from semi-log space to log-log space. For the same slope and intercept an equation of the form,

$$Y = A \, \text{Exp}(B\,X) \tag{55}$$

will transform to,

$$Y = A \, (\text{Exp}(X))^{B} \tag{56}$$

The fact that values of the regression coefficient for models of C_r vs. R_{eb} and R_{ec} are small (0.0252 and 0.0) leads to the doubt that the slope of the lines in Figures 22 and 23 may be negligible. A t test on the slope of the line in Figures 22 and 23 at 90 percent significance level confirms that the slope is not different from zero. Hence the overall effect of R_e on C_r can be regarded to be negligible and component equations 45 and 46 need not be included in the prediction equation. This leaves 7 Pi terms and 6 component equations to be combined.

The denominator of equation 54 can be evaluated as follows:

$$F_8(\bar{F}_o, \bar{T}_r \ldots \bar{I}_c) = \frac{[F_8(\bar{F}_o, \ldots . \bar{I}_c)]_2 + \ldots + [F_8(\bar{F}_o, \ldots . \bar{I}_c)]_7}{6} \tag{57}$$

$$[F_8(\bar{F}_o . . \bar{I}_c)]_2 = 0.231 (F_o)^{0.6393} = 0.4123 \tag{58}$$

$$[F_8(\bar{F}_o . . \bar{I}_c)]_3 = 0.00024 \, \text{Exp}(6.936 \, T_r) = 0.5294 \tag{59}$$

$$[F_8(\bar{F}_o . . \bar{I}_c)]_4 = 0.5284 \, G_r^{0.7463} = 0.6374 \tag{60}$$

$$[F_8(\bar{F}_o..\bar{I}_c)]_5 = 0.6255 \, Exp(-0.0145 \, D_r) = 0.5734 \tag{61}$$

$$[F_8(\bar{F}_o..\bar{I}_c)]_6 = 0.7603 \, Exp(-0.0079 \, S_f) = 0.5898 \tag{62}$$

$$[F_8(\bar{F}_o..\bar{I}_c)]_7 = 1.6134 \, I_c^{0.8969} = 0.5480 \tag{63}$$

Therefore,

$$[F_8(\bar{F}_o..\bar{I}_c)]_{av.} = 0.5484$$

After eliminating R_e

$$s = 7 - 2 = 5$$

Multiplying all the constants in equations 47, 48, 49, 51, 52, and 53 yields, $K = 0.225 \times 10^{-4}$. The equation for predicting drying efficiency in the spouted bed becomes,

$$C_r = 0.225 \times 10^{-4} \{F_o^{0.63} [Exp(T_r)]^{6.93} G_r^{0.75} [Exp(D_r)]^{-0.014} [Exp(S_f)]^{-0.008} I_c^{0.9}\}/(0.5484)^5 \tag{64}$$

$$= 4.53 \times 10^{-4} \{F_o^{0.63} G_r^{0.75} I_c^{0.90} [Exp(T_r)]^{6.93} [Exp(D_r)]^{-0.014} [Exp(S_f)]^{-0.008}\} \tag{65}$$

Range of Pi Terms

Equation 67 was developed from experimental data with the following limits placed on each dimensionless group.

$$0.829 \leq F_o \leq 5.629$$

$$1.09 \leq T_r \leq 1.17$$

$$0.857 \le G_r \le 1.35$$

$$3.6 \le D_r \le 9.0$$

$$26.78 \le S_f \le 42.85$$

$$0.195 \le I_c \le 0.445$$

the Reynolds number range during the tests was,

$$350 \le R_{eb} \le 1100$$

$$10{,}000 \le R_{ec} \le 50{,}000$$

rapolation beyond this limit may lead to erroneous results.

Close observation of Figures 28 and 29 reveals that the pe of straight lines represented by Equations 51 and 52 may too small (-0.0145 and -0.0079) to be of any significance this study. Applying the t statistic as a test criterion null hypothesis of the regression coefficient it is found t the null hypothesis is accepted at the 99.9% significance el for both component equations, but at the 99% significe level the null hypothesis is accepted only for component ation 52. Therefore the effect of both D_r and S_f on C_r be neglected at the 99.9% significance level (Equation 66) only the effect of S_f can be neglected at the 99% sigicance level (Equation 67).

This change leads to two additional equations: one for s transfer efficiency as a function of F_o, T_r, G_r, and I_c another as function of F_o, T_r, G_r, D_r, and I_c at the indied probability levels.

The equations are,

$$C_r = 3.14 \times 10^{-4} \{F_o^{0.63}\, G_r^{0.75}\, I_c^{0.90}\, [\mathrm{Exp}(T_r)]^{6.93}\} \quad (66)$$

$$C_r = 3.47 \times 10^{-4}\{F_o^{0.63}\ G_r^{0.75}\ I_c^{0.90}\ [\mathrm{Exp}(T_r)]^{6.93}\ [\mathrm{Exp}(D_r)]^{-0.014}\} \quad (67)$$

Strong dependence of drying efficiency on drying time, drying air temperature, bed depth, initial concentration and bed diameter is well known in quiescent bed drying systems (17,21). In a drying process both bed diameter and bed depth influence the total mass of material being dried. Stringent specification must be placed on the geometry ratio of the spouted bed since for a given bed depth several combinations of bed diameters and volumes can be obtained. It was seen that G_r greater than 1.35 resulted in a poor quality product.

Predicted Versus Observed Results

Predicted versus observed results for each equation 65 and 67, are shown in Figures 31 and 32. The observed mass transfer efficiency data were those used to develop the prediction equations. Both of these plots serve to indicate that the component equations have been combined satisfactorily. Data from tests on naturally cured peanuts are also plotted. These plots serve to confirm that there was no significant variation in drying rates of both naturally cured and reconstituted peanuts.

Composite Drying Efficiency

From the previous chapter major factors of concern in evaluating the composite drying efficiency can be summarized as a) index of drying rate, b) heat spent during drying, c) extent of kernel and pod damage and d) odor and flavor characteristics. Since no attempt was made to determine the odor and flavor aspect of quality before and after the tests, the other three indices will be used in determining the composite

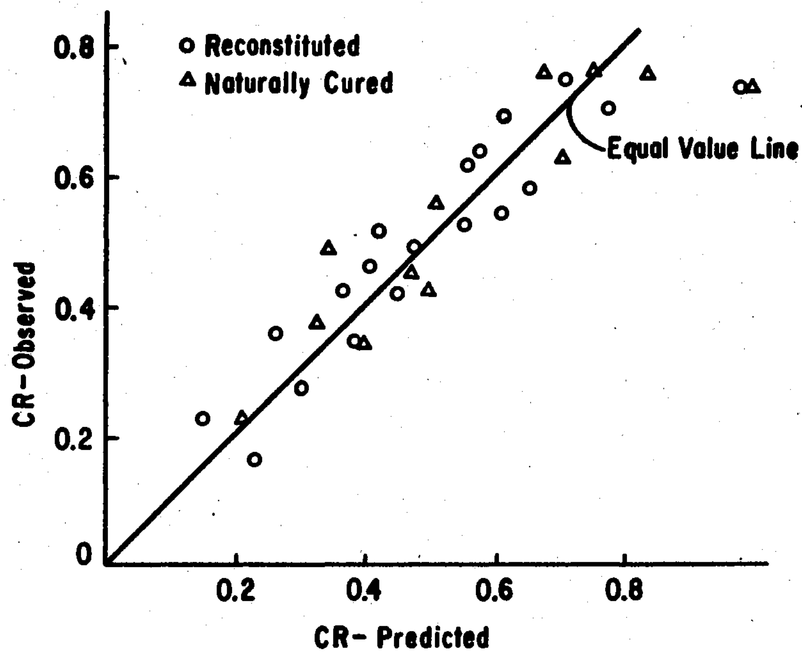

Figure 31. Observed vs. Predicted Drying Efficiency as Affected by All the Variables

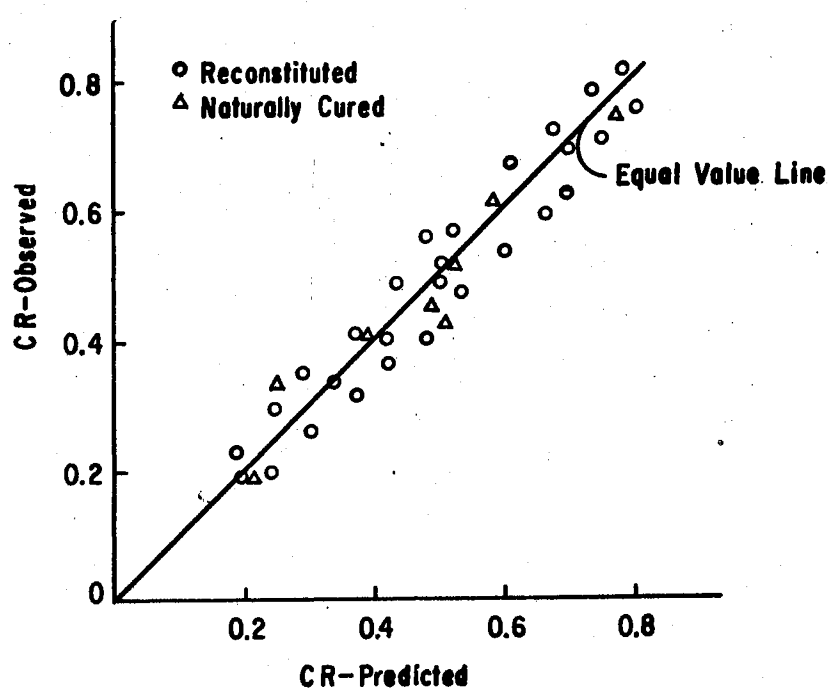

Figure 32. Observed Vs. Predicted Drying Efficiency as Affected by Major Variables

drying efficiency.

Heat Requirements

Two indicators of overall heat efficiency of a dryer are the amount of heat required to dry one cubic foot of product, H_v, and per pound mass of water evaporated, H_w. Neither of the two alone, however, is sufficient to compare the performance of drying systems. Table VI was prepared from the data of several workers who dried peanuts under different conditions. Teter (36) does not report the exact conditions of entering air and Baker (4) gives the final mass concentration of the bottom layer which is generally much lower than the rest of the product in a deep bed dryer. These lead to low values of H_w in Table VI. Examination of this table indicates that the spouted bed dryer requires the same amount of heat as the quiescent bed dryers. Data of Wright (41) on radio frequency energy is not directly compatible since he used a small volume and very high air flow rates, in excess of those used in the spouted bed dryer.

Drying Rate

Table VI also summarizes the values of initial and final mass concentrations and indices of drying rate for various drying systems. It is evident from this table that the spouted bed dryer has a somewhat lower rate than the other dryers at the same drying efficiency. Amount of water removed per hour was of the order of 1.5 lb_m/hr as compared to 0.15 to 4.0 lb_m/hr for other systems. The output of dried peanuts varied from 18-33 lb_m/hr as compared to 10-60 lb_m/hr for heated air drying systems. A commercial unit will perhaps show even a higher drying rate

TABLE VI

SUMMARY OF DRYING RATES AND HEAT REQUIREMENTS OF VARIOUS DRYERS

C_o %	C %	C_r %	T ^oF	W lb_m/lb_m	θ hrs	Q" CFM/ft^3	V_b ft^3	W_w lb_m	W'_w lb_m/hr	F lb_m/hr	H_v Btu/cft	H_w Btu/lbm	Remarks
28.2	19.21	0.44	100	0.0060	1.5	136.0	2.5	2.6	1.73	33.33	26660	25267	Experimental Spouted bed dryer
31.0	17.58	0.57	100	0.0060	1.5	243.0	1.4	2.2	1.47	18.67	47636	31000	
35.0	8.00	0.98	74	0.0090	115.0	5.0	4.4	13.2	0.12	0.76	67718	22573	Quiescent bed natural air dryer, Teter (36)
35.0	8.00	0.98	74	0.0090	87.0	10.0	4.4	13.2	0.15	1.01	102461	34154	
35.0	8.00	0.98	74	0.0090	58.0	20.0	4.4	13.2	0.23	1.52	136614	45538	
31.0	19.15	0.51	100	0.0060	13.5	21.0	40.0	54.0	4.0	59.26	37050	27305	Quiescent bed heated air dryer, Myklestad(26)
31.0	12.00	0.81	100	0.0060	24.0	21.0	40.0	87.0	3.62	33.33	65866	30276	
54.0	8.50	0.50	96	0.0158	17.5	4.5	8.75	39.0	2.22	10.00	13600	3068	Continuous column heated air dryer, Baker (4)
54.1	9.30	0.50	115	0.0170	10.3	9.0	8.75	38.0	3.68	17.00	18334	4204	
62.8	5.90	0.50	90	0.0114	16.0	18.2	8.75	46.0	2.87	10.94	42490	8105	
63.0	6.50	0.50	80	0.0083	15.5	13.6	8.75	45.0	2.90	11.29	25474	4899	

since higher bed depths can be spouted by eliminating the pressure drop at the accessories.

Kernel and Pod Damage

In order to evaluate peanut quality as affected by temperature, air flow rate, inlet pipe diameter and bed depth, samples from the final and initial products were analyzed. A preliminary investigation revealed that a high air flow rate could destroy the market value of peanuts. In all quality tests an air flow was selected that would initiate and maintain a stable spout. A summary of 9 tests is presented in Table VII. Two parameters, percent abrasion and percent split kernels, are important from the market quality point of view. In all tests peanuts suffered some abrasion. Both types of peanuts, reconstituted, and naturally cured, were cleaned during drying (Figures 33, 34, 35 and 36). Peanuts at the lowest bed depth suffered highest abrasion and least abrasion resulted with the greatest inlet pipe size. In general abrasion was found to increase with temperature.

Percent weight and number of split kernels increased directly with temperature and inversely with bed depth. Smaller bed depths resulted in lower drying efficiency and a reduction in quality. Hence further tests were discontinued. From this analysis it becomes clear that the spouted bed dryer should be operated at the highest bed depth commensurate with lowest air flow rate, inlet pipe diameter and air temperature. Air temperatures in excess of 100°F did not seem to affect the general appearance during 1.5 hours of drying. A rigorous taste panel study may be required, however, to confirm these observations. General appearance of pods improved up to 15% abrasion, beyond which the shells were found

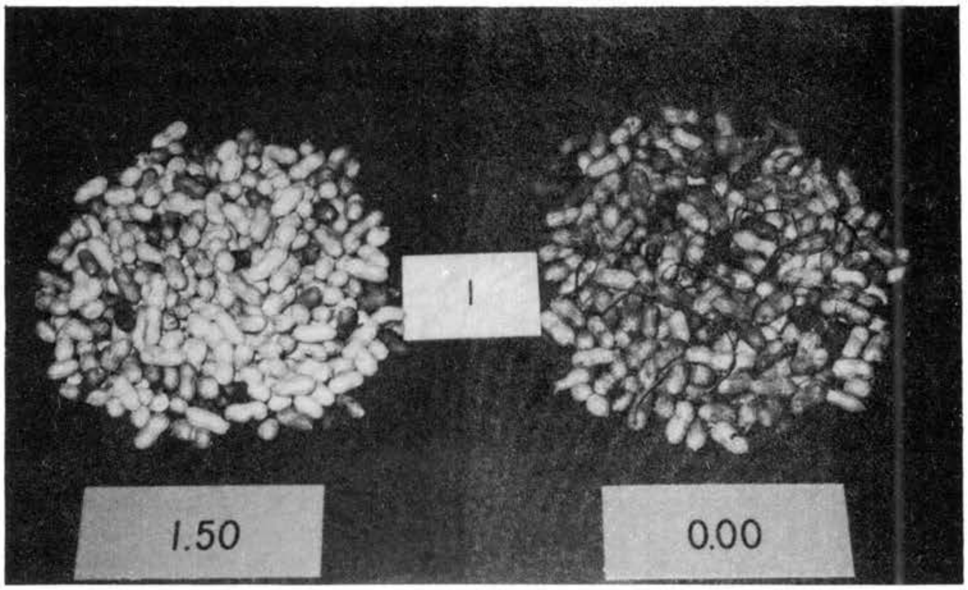

Figure 33. Reconstituted Peanuts at the Beginning and End of Test (0-1.5 hrs, 100°F, 3"D_c, 18"D_b, and 14"H_c)

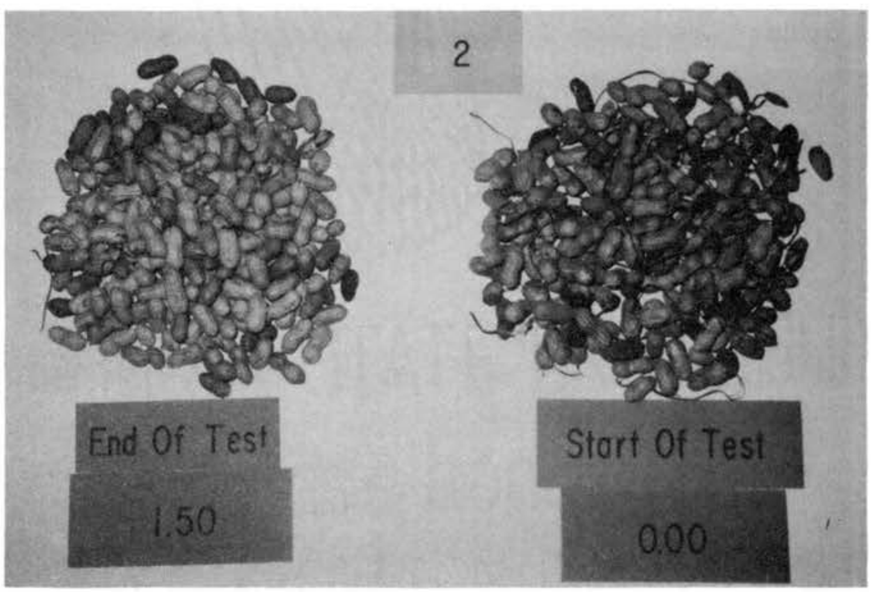

Figure 34. Reconstituted Peanuts at the Beginning and End of Test (0-1.5 hrs, 130°F, 3"D_c, 18"D_b and 14"H_c)

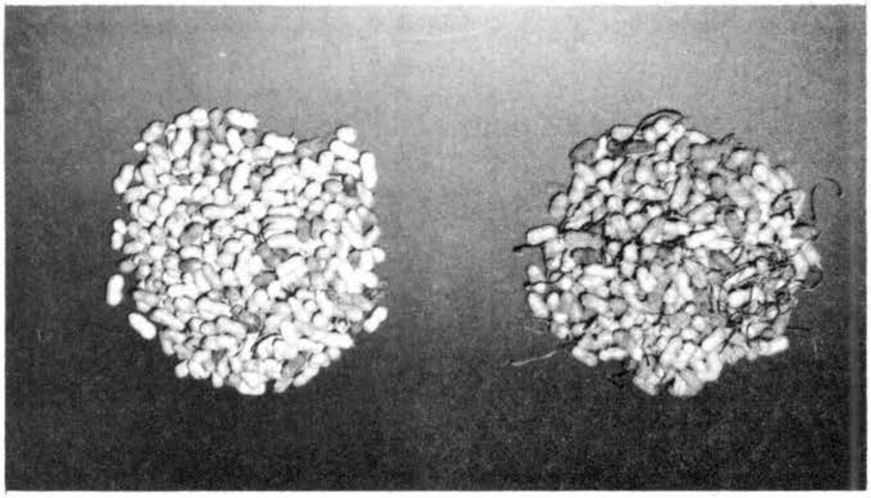

Figure 35. Naturally Cured Peanuts at the Beginning and End of Test. (1.5 hrs, 100^oF, $3''D_c$, $18''D_b$, $14''H_c$.)

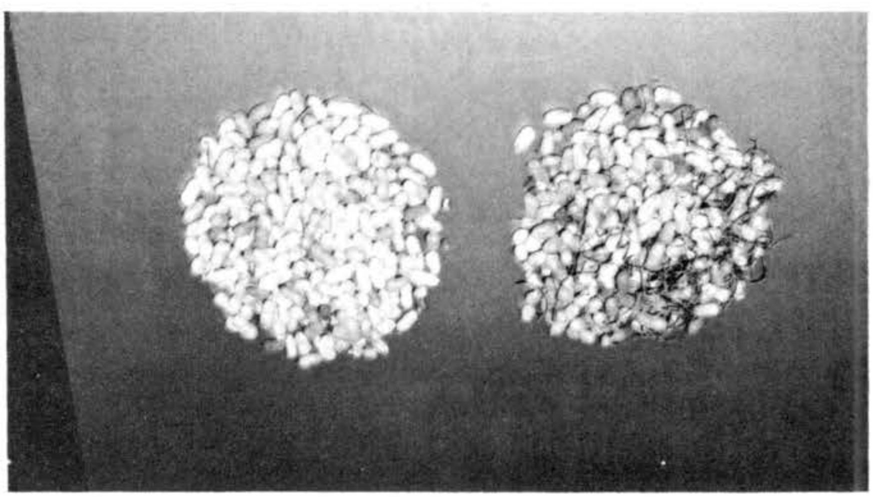

Figure 36. Naturally Cured Peanuts at the Beginning and End of Test (1.5 hrs, 130^oF, $3''D_c$, $18''D_b$, $14''H_c$)

TABLE VII

SUMMARY OF TESTS FOR QUALITY DETERMINATION

Exp. Series	Test No.	% wt. Mature	% wt. Immature	% wt. Kernels	% wt. Shells	% Abrasion	% wt. Splits	% No. Splits	% wt. Trash	H_b	D_b	D_c	T_a
					Temperature Effect								
	-	88.65	9.52	77.49	20.68	0.00	0.00	0.00	1.83	--	--	---	---
400	1	87.59	6.55	80.77	18.50	10.50	5.13	5.40	0.73	14	18	3	110
	2	82.82	4.79	81.55	18.22	11.90	12.06	6.90	0.23	14	18	3	120
	3	82.37	5.42	81.85	18.00	13.00	12.83	8.60	0.15	14	18	3	130
					Bed Depth Effect								
	-	73.01	13.79	69.97	23.79	0.00	6.96	18.90	6.24	--	--	---	---
500	4	79.35	13.69	73.84	21.20	10.90	5.89	17.00	0.07	21	18	3	100
	5	71.00	3.61	79.78	18.25	23.30	23.43	30.12	1.97	7	18	3	100
					Column Diameter Effect								
	-	92.06	6.53	77.40	21.19	0.00	0.00	0.00	1.41	--	--	---	---
	6	85.51	8.25	72.66	21.10	0.40	0.00	0.00	6.24	14	18	5	100
	7	86.39	7.09	73.64	19.84	6.40	0.00	0.00	6.52	14	18	5	130
600	8	90.91	6.68	77.00	20.59	2.83	0.00	0.00	2.41	14	18	4	100
	-	84.88	12.81	76.77	20.92	0.00	0.00	0.00	2.31	--	--	---	---
	9	83.49	10.67	78.55	19.26	7.90	3.85	8.90	2.19	14	18	3.5	100

weak and eroded. Figure 37 shows peanut shells from test 5 in Table VII at a 7 inch bed depth and 100°F air temperature.

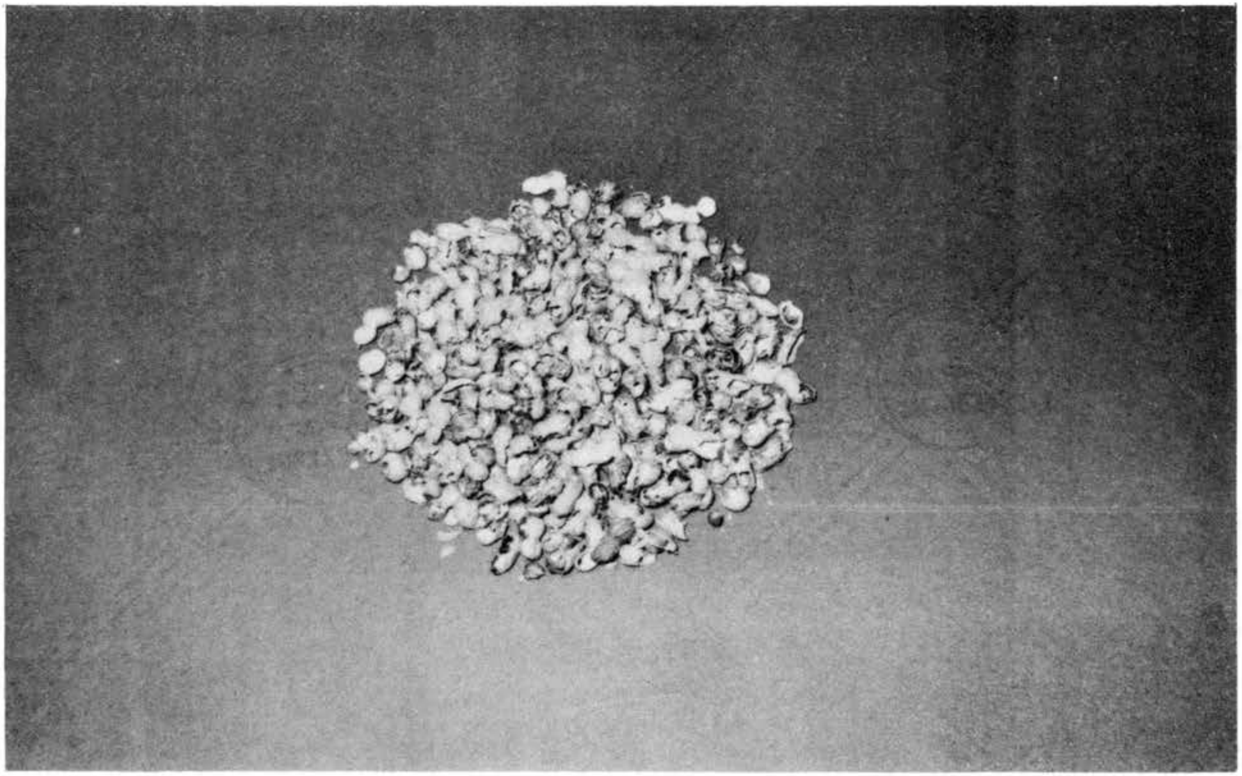

Figure 37. Reconstituted Damaged Peanut Hulls at the End of Test (1.5 hrs., $100^{o}F$, $3''D_c$, $18''D_b$ and $7''H_c$)

CHAPTER VI

SUMMARY AND CONCLUSIONS

The primary objectives of this study were a) to develop a method whereby the average mass transfer efficiency of spanish peanut en masse in a spouted bed can be predicted and b) to compare the composite drying efficiency of various dryers. The prediction equation for the mass transfer efficiency is of the form

$$C_r = f(R_e, F_o, T_r, G_r, D_r, S_f, I_c, W_r, P_r, M_a, S_c, M_{o1}, M_{o2}, H_r, K_r, F_a, F_p, F_w) \quad (68)$$

For this study the density ratio, W_r, Prandtl number, P_r, mass diffusivity index, M_a, Schmidt number, S_c, molecular diffusivity indices, M_{o1} and M_{o2}, heat ratio, H_r, conductivity ratio, K_r, floor angle, F_a, particle-particle friction, F_p and particle-wall friction, F_w were all treated as constants so that they do not enter into the prediction equation. Equation 68 reduces to

$$C_r = F(R_e, F_o, T_r, G_r, D_r, S_f, I_c) \quad (44)$$

Employing the method of similitude, component equations were developed that fitted as straight lines on logarithmic and semi-logarithmic coordinates. Component equations that yielded straight lines on semi-logarithmic space were transformed to log log space and combined by multiplication. This resulted in equation 65 for predicting the average mass transfer efficiency from spanish peanut pods in a spouted bed dryer.

as

$$C_r = 4.53 \times 10^{-4} \{F_o^{0.63} G_r^{0.75} I_c^{0.90} [Exp(T_r)]^{6.93} [Exp(D_r)]^{-0.014}$$

$$[Exp(S_f)]^{-0.008}\} \quad (65)$$

This experimental correlation was developed over the following range of independent dimensionless groups.

$$350 \leq R_{eb} \leq 1100$$

$$0.829 \leq F_o \leq 5.629$$

$$1.09 \leq T_r \leq 1.17$$

$$0.857 \leq G_r \leq 1.35$$

$$3.6 \leq D_r \leq 9.0$$

$$26.78 \leq S_f \leq 42.85$$

$$0.195 \leq I_c \leq 0.445$$

Using the t statistic as the criterion for determining the significance of each Pi term it was found that effect of the size factor, S_f, on drying efficiency, C_r, was not significant. This reduced eqution 65 to,

$$C_r = 3.47 \times 10^{-4} \{F_o^{0.63} G_r^{0.75} I_c^{0.90} [Exp(T_r)]^{6.93} [Exp(D_r)]^{-0.014}\} \quad (67)$$

An index of composite drying efficiency was developed considering drying rate, heat spent during drying, and indices of quality of dried peanuts, at a certain mass transfer efficiency.

Conclusions

The following conclusions were drawn from the experimental data:

1. The methods and procedures described in this report are adequate for evaluating the mass transfer efficiency and composite drying efficiency of a porous hygroscopic solid en masse in a spouted bed dryer.

2. Peanut en masse can be equally divided into two geometries, cassinoid and ellipsoid, for predicting the physical properties.

3. The magnitude of predicted and measured mass transfer efficiency described herein falls within the limiting values of the dimensionless groups.

4. Percent abrasion of hulls and percent split kernels increased directly with temperature and inversely with bed depth. Dried peanuts were found clean and the general appearance of pod improved up to 15% hull abrasion. Beyond this value hulls disintegrated allowing kernel damage. The single major factor responsible for most hull abrasion was shallow bed depth. Abrasion due to temperature at 130°F was found to be 13 percent.

5. Heat spent during drying per cubic feet of peanuts dried and per pound of water removed was not excessive when compared to other drying systems. The spouted bed dryer required 27,000 - 47,000 Btu/ft^3 and 25,000 - 31,000 Btu/lb$_m$ of heat as compared to 13,000 - 65,000 Btu/ft^3 and 27,000 - 45,000 Btu/lb$_m$ for other dryers at the same mass transfer efficiency.

6. Drying rate of peanuts in the spouted bed was not significantly

lower when compared with conventional large scale drying plants. Moisture loss varied from 1.4 - 1.7 lb_m/hr as compared to 2-4 lb_m/hr and the output of dried peanuts ranged from 18 - 33 lb_m/hr as against 10 - 60 lb_m/hr for heated air drying systems. This slight reduction in drying rate was mainly attributed to nature of the experiments resulting in considerable pressure loss in the accessoreis. The drop in pressure led to a limiting value of maximum spoutable bed depth of 21 inches.

7. Air flow rates required to initiate and maintain stable spouting were found to be excessive, 15 - 20 times that of quiescent bed dryers. Reynolds number and size factor (ratio of bed diameter to particle diameter) did not affect mass transfer efficiency.

8. Mass transfer efficiency increased directly with Fourier number, temperature ratio and initial concentration. It also increased directly with geometry ratio up to a value of 1.35. A lower limit of bed depth, 13.5 inches, therefore was established below which efficiency will decrease. Efficiency was found to be inversely proportional to the diameter ratio indicating that either larger bed diameter or smaller inlet pipe diameters will result in reduced efficiency. From the considerations of all these independent variables it was concluded that the spouted bed dryer must be operated at the highest spoutable bed depth commensurate with lowest air flow rate, drying air temperature, particle mass concentration and bed configurate for greatest efficiency.

9. The difference between mass transfer efficiencies of naturally cured and artificial cured peanut pods was insignificant.

10. Composite drying efficiency of spouted bed dryer compare very favorably with other types of dryers. Pod damage due to abrasion and breakage was not significant. Based upon the results from this investi-

gation it should be possible to design a prototype dryer for a large scale drying plant.

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APPENDIX A

A MATHEMATICAL MODEL OF PEANUT POD GEOMETRY

Introduction

In many engineering operations such as machine sizing and grading, air conveying and separation, and thermal treatment and conditioning, it is essential to have an accurate estimate of shape, size, projected area, surface area, and volume of agricultural products (19). This report is intended to mathematically define peanut pod geometry, permitting determination of these properties.

Background

Spanish peanut pods generally have one or two kernels. A careful analysis of a sample of peanut pods reveals that there are essentially six groups into which the entire sample can be divided (See Figures 38 through 43). They are:

1. Broken, shrivelled, cracked and immature peanuts--single or double kernel.
2. Single kernel pods that are ellipsoidal or spheroidal in shape. The spheriod can be either prolate or oblate.
3. Two kernel pods similar in shape to cassinoids where a cassinoid is a solid of revolution of the ovals of cassini (8).
4. Two kernel pods that appear to have two ellipsoids or spheroids paired to form a single pod.

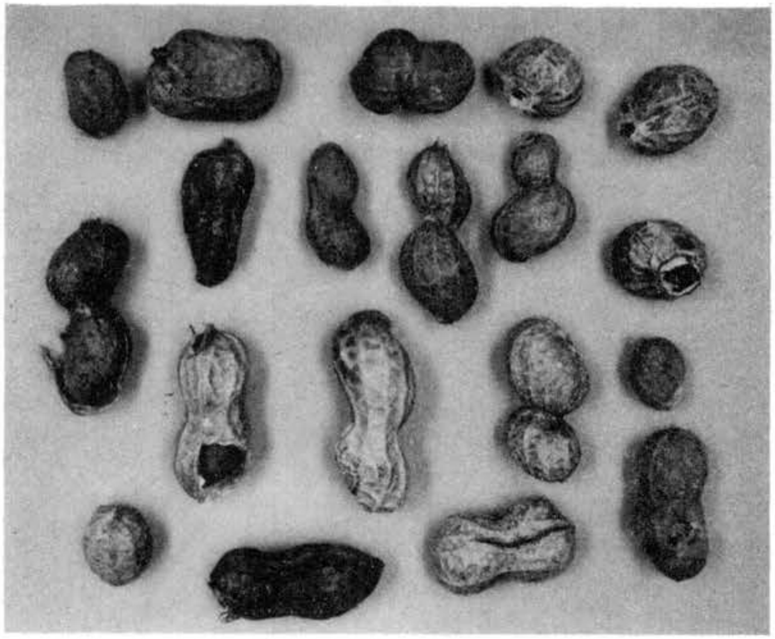


Figure 38. Analysis of Peanut Samples--
Damaged or Immature Pods

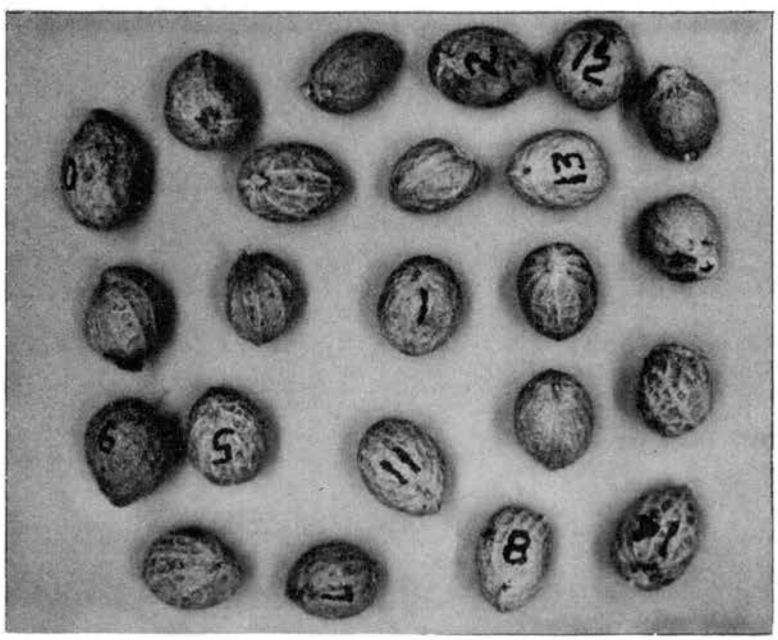


Figure 39. Analysis of Peanut Samples--
Single Kernel Ellipsoids

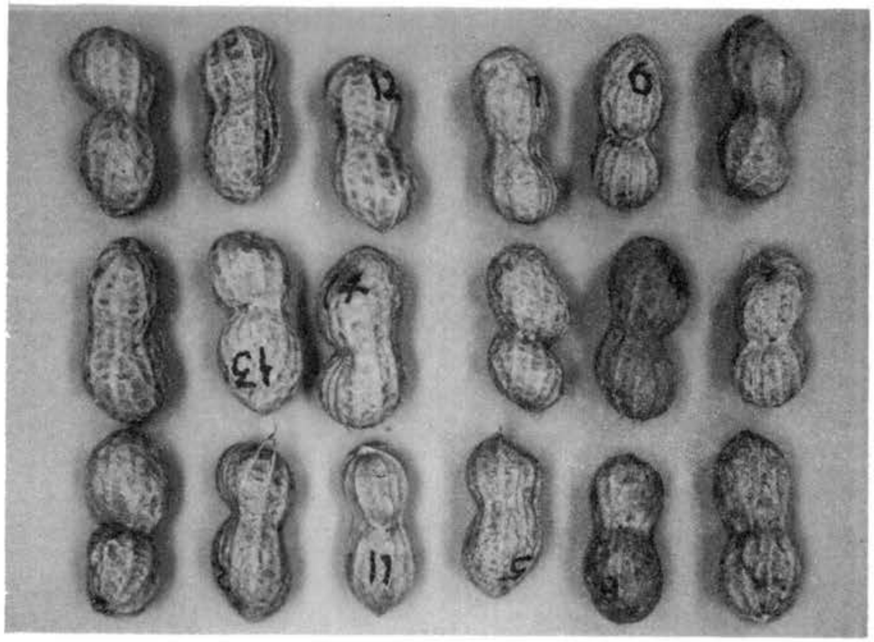


Figure 40. Analysis of Peanut Samples--
Cassinoids

Figure 41. Analysis of Peanut Samples--
Paired Ellipsoids

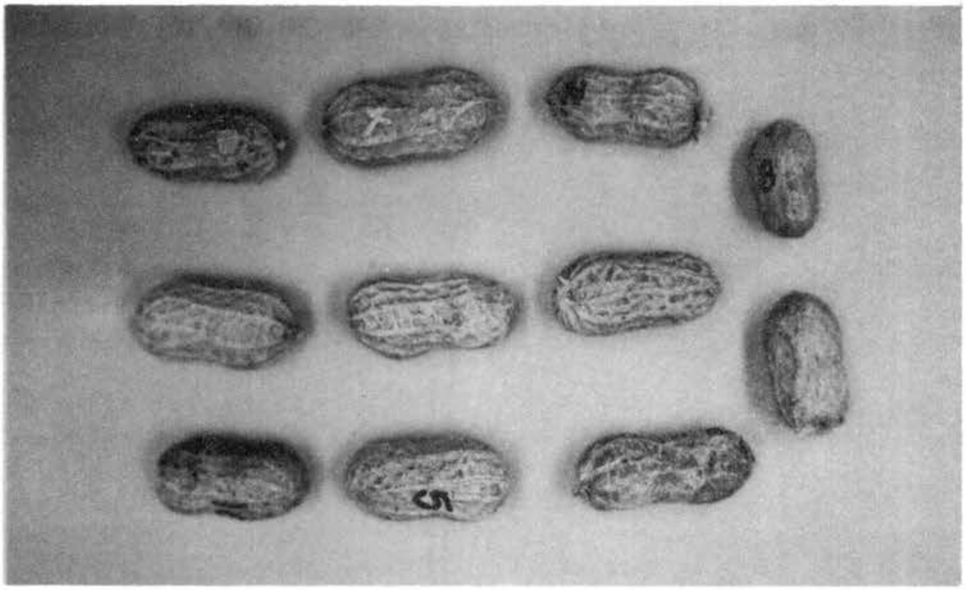


Figure 42. Analysis of Peanut Samples--
Two Kernel Ellipsoids

Figure 43. Analysis of Peanut Samples--
Undefined Pods

5. Two kernel pods resembling an ellipsoid or a finite cylinder with spherical ends.
6. Two kernel pods that cannot be defined explicitly by any of the groups 3, 4 or 5.

The pods in group 1 vary in shape, depending upon their maturity level or mechanical damage during harvest. These are similar to shapes described in group No. 2, 3, 4 or 5. The geometry of peanut pods in group 6 is difficult to define because they do not clearly represent a particular shape.

It is possible to form four separate classes of geometries (Figure 16) that will predict physical properties such as cross-sectional area, projected area, surface area and volume. They are:

Type I - Spheroid - prolate or oblate

Type II - Cassinoids

Type III - Paired ellipsoids

Type IV - Ellipsoids

Before we can test this hypothesis it is necessary to form criteria for identifying a particular class of pods among undefined ones. This is done by measuring pertinent dimensions and testing the calculated properties against measured values. The percent deviation between these values will determine which class each of these pods will fit.

Theoretical Considerations

General Ellipsoid

A general ellipsoid has three pertinent dimensions: a, the semi-major axis; b, semi-minor axis; c, semi-transverse axis, as represented by the equation (69):

$$(\frac{x}{a})^2 + (\frac{y}{b})^2 + (\frac{z}{c})^2 = 1 \quad (69)$$

When an ellipse in the x-y plane is rotated about its major axis an ellipsoid of revolution called a prolate spheriod results with dimension b equal to c. Its cross-sectional area, A, surface area, S, and volume, V, are given by the following equations:

$$A = \pi ab \quad (70)$$

$$S = 2\pi b\left(b + a(\arcsin)/e\right) \quad (71)$$

Where, the eccentricity, e, is given by

$$e^2 = 1 - (\frac{b}{a})^2 \quad (72)$$

and,

$$V = \frac{4}{3} \pi ab^2 \quad (73)$$

If the same ellipse is rotated about its minor axis then an oblate spheriod is generated with dimension a equal to c. Its surface area and volume are given by the explicit relation:

$$S = 2\pi a^2 + \pi \frac{b^2}{e} \ln[\frac{1 + e}{1 - e}] \quad (74)$$

$$V = \frac{4}{3} \pi a^2 b \quad (75)$$

If in a general ellipsoidal equation a, b and c are equal, a sphere of radius a, results which has well defined properties in terms of its radius.

The projected area of a general ellipsoid is given by equation 70 The surface area of an arbitrary solid is defined by,

$$S = \int_R \int \sqrt{1 + \left(\frac{\partial z}{\partial x} \right)^2 + \left(\frac{\partial z}{\partial y} \right)^2} \, dAxy \tag{76}$$

The region of integration in the case of a general ellipsoid is from $-a$ to a for the x coordinate and $-b\sqrt{1 - \left(\frac{x}{a} \right)^2}$ to $b\sqrt{1 - \left(\frac{x}{a} \right)^2}$ for the y coordinate. Equation 76 takes the form,

$$S = 2 \int_{-a}^{a} \int_{-B}^{B} \sqrt{1 + \left(\frac{\partial z}{\partial x} \right)^2 + \left(\frac{\partial z}{\partial y} \right)^2} \, dx \, dx \tag{77}$$

Where:

$$B = b\sqrt{1 - \left(\frac{x}{a} \right)^2}$$

In general this integral could be evaluated by solving equation 69 for z and substituting for the indicated partial derivatives. But in order to attain accuracy and speed it will be desirable to transform equation 69 as follows:

Let $\frac{x}{a} = X$; $\frac{y}{b} = Y$ and $\frac{z}{c} = Z$

The equation for the general ellipsoid becomes

$$X^2 + Y^2 + Z^2 = 1 \tag{78}$$

from which, considering the positive value of Z only,

$$Z = \sqrt{1 - X^2 - Y^2} \tag{79}$$

Now,

$$\left(\frac{\partial Z}{\partial X} \right)^2 = \frac{X^2}{1 - X^2 - Y^2} = \frac{a^2}{c^2} \left(\frac{\partial z}{\partial x} \right)^2 \tag{80}$$

and,

$$\left(\frac{\partial Z}{\partial Y} \right)^2 = \frac{Y^2}{1 - X^2 - Y^2} = \frac{b^2}{c^2}\left(\frac{\partial z}{\partial y} \right)^2 \tag{81}$$

Substituting equations 80 and 81 into equation 77 we get,

$$S = 2\int_{-1}^{1} dX \int_{-C}^{C} \frac{\sqrt{1 + (\frac{c^2}{a^2} - 1)X^2 + (\frac{c^2}{b^2} - 1)Y^2}}{\sqrt{1 - X^2 - Y^2}} dY \tag{82}$$

Where:

$$C = \sqrt{1 - X^2}$$

The integral in equation 82 requires special procedures for numerical solution due to the variable limits. It must be transformed to a definite integral by the transformation,

$$u = \frac{Y}{\sqrt{1 - X^2}} \tag{83}$$

$$du = \frac{dY}{\sqrt{1 - X^2}} \tag{84}$$

Substituting in equation 82 and simplifying we get,

$$S = 2ab \int_{-1}^{1} dX \int_{-1}^{1} \frac{\sqrt{1 - A_b X^2 - A_c u^2 (1 - X^2)}}{\sqrt{1 - u^2}} du \tag{85}$$

Where:

$$A_b = 1 - c^2/a^2 \tag{86}$$

$$A_c = 1 - c^2/b^2 \tag{87}$$

At a known value of x the second integral is of the form (27):

$$\int_{-1}^{1} \frac{f(u)}{\sqrt{1 - u^2}} du \tag{88}$$

which can be easily identified as an equivalent form of the Gauss-Chebyschev integral of the first kind. The first integral having smooth behavior can be evaluated by a Gauss-Legendre Scheme (27). Thus the double integral of equation 85 reduces to

$$S = 2ab \sum_{j=1}^{10} U(2,J)W(2,J)\left[\sum_{k=1}^{10} F(U(1,K),U(2,J))W(1,K)\right] \tag{89}$$

Where $U,_s$ and $W,_s$ are abscissas and weights of appropriate Gaussian integration schemes.

The volume of the general ellipsoid is given by

$$V = \frac{4}{3}\pi abc \tag{90}$$

Cassinoids

The general equation of the ovals of cassini in cartesian coordinates is given by (8)

$$(x^2 + y^2 + b^2)^2 - 4b^2x^2 = k^4 \tag{91}$$

Where b and k are constants such that (see Figure 16)

$$F'P \times FP = k^2 \tag{92}$$

$$b < k \tag{93}$$

The constants b and k can be determined by knowing the length, L, and minimum distance, M, and solving equation 92 at points Q and R.

Thus,

$$k = \pm \sqrt{\frac{(L/2)^2 + (M/2)^2}{2}} \quad (94)$$

$$b = \pm \sqrt{k^2 - (M/2)^2} \quad (95)$$

The projected area of the ovals of cassini is given by

$$A = \int_{-x}^{x} y \; dx \quad (96)$$

where the positive value of y can be found from equation 91 as

$$y = \sqrt{\sqrt{k^4 + 4b^2x^2} - (x^2 + b^2)} \quad (97)$$

Thus, the projected area A can be given by four times the area represented by the top right hand quadrant of the ovals of cassini cross-section.

$$A = 4 \int_{0}^{x} \sqrt{\sqrt{k^4 + 4b^2x^2} - (x^2 + b^2)} \quad (98)$$

If the top half of the ovals of cassini is revolved around the x-axis a solid of revolution called a cassinoid will result. According to Pappus' theorem the surface area and volume of the solid of revolution can be represented as

$$S = 2\pi \int_{-x}^{x} y \sqrt{1 + (\frac{dy}{dx})^2} \, dx \quad (99)$$

Substituting for y and dy/dx and simplifying we get

$$S = 4\pi \int_{0}^{x} \sqrt{\sqrt{N} - b^2 + \frac{4b^2x^2}{\sqrt{N}} \left(\frac{b^2 - 1}{\sqrt{N}}\right)} \; dx \quad (100)$$

Where:

$$N = k^4 + 4b^2x^2 \tag{101}$$

The volume of the cassinoids is given by

$$V = \pi \int_{-x}^{x} y^2 dx \tag{102}$$

Substituting for y^2 we get,

$$V = 2\pi \int_0^x [\sqrt{N} - (x^2 + b^2)] \, dx \tag{103}$$

Equations 98, 100, and 103 can easily be integrated numerically by an appropriate integration scheme. Equation 103 can also be solved explicitly between the limits 0 and L/2 to yield,

$$V = 2\pi b \left[xR + \left(\frac{k^2}{2b} \right)^2 \ln(x + R) \right]_0^{L/2} - \left[\frac{2\pi}{3} x^3 + 2\pi b^2 x \right]_0^{L/2} \tag{104}$$

Where:

$$R = \sqrt{x^2 + \left(\frac{k^2}{2b} \right)^2} \tag{105}$$

The volume determined by equation 104 will serve as a good check on the integration procedure.

Materials and Methods

Sample Analysis

A random lot of Spanish peanut pods was divided into 3 samples of approximately 140 gms each. Each of these samples were separated into components defined by groups 1 through 6. Table VIII gives the average values of the component weights and percent weight fraction as compared to the original sample size.

TABLE VIII

AVERAGE ANALYSIS OF PEANUT SAMPLES

No.	Group	Weight (gm)	Weight Fraction %	Remarks
1	Rejects	12.0	8.6	
2	Single kernel spheroids	23.5	16.8	
3	Cassinoids	45.5	32.5	Sample wt. 140 gms.
4	Paired ellipsoids	25.0	17.8	
5	Two kernel ellipsoids	11.0	7.9	
6	Undefined	23.0	16.4	

A criterian for selection was set up for those peanuts that could not be classified explicitly in a particular class. Most of the peanuts in the undefined class were two kernel pods. Generally a two kernel peanut pod has its smallest dimension, c, at the center point, a smaller diameter, b, at one end and a larger diameter, a, at the other end. The ratios of smallest dimensions were computed with respect to the length, smaller diameter, and larger diameter for well defined and undefined peanuts. The range of these ratios is given in Table IX for paired ellipsoids, cassinoids and ellipsoids. If at least two ratios of an undefined peanut were found to lie in the range of a particular class then it was considered to represent that class. This criteria was used uniformly to classify all the undefined peanuts. Table X gives the typical dimensions and computed ratios for undefined peanuts. Notice how effectively each peanut can be classified

TABLE IX

CRITERION FOR CLASSIFYING THE UNDEFINED PEANUTS

Peanut Types	c/L	c/a	c/b
Paired ellipsoids	0.15 - 0.29	0.32 - 0.60	0.35 - 0.67
Cassinoids	0.29 - 0.38	0.60 - 0.80	0.67 - 0.84
Ellipsoids	0.38 - 0.60	0.80 - 0.96	0.84 - 0.99

TABLE X

FINAL ANALYSIS OF THE SPANISH PEANUT SAMPLES

No.	Group	Weight (gm)	Weight Fraction %	Remarks
1	Immature and broken	12.0	8.56	Rejects
2	One kernel ellipsoid	23.5	16.78	Type I
3	Cassinoids	58.3	41.66	Type II
4	Paired ellipsoids	27.7	19.78	Type III
5	Two kernel ellipsoid	18.5	13.22	Type IV

into the appropriate class.

The components of peanut samples were reweighed and a new weight fraction computed (Table XI). Each class was closely re-examined. It was found that Type I pods should be renamed as one kernel ellipsoids instead of spheriods since two lateral dimensions a, and b, were not exactly equal. The representative views of each of these classes are shown in Figures 17 through 20.

Projected Area

Ten peanut pods from each Type were photographed with a 4 x 5 Polaroid Graflex view land camera (f/4.6; 135 mm) in an orientation that will give the maximum projected area. These pictures were magnified up to 3 times. The scale of magnification was determined by the base graph paper and a steel ball of known diameter placed on the graph paper. Theoretical cross-sectional areas and projected areas measured with a compensating polar planimeter were found identical for the ball and base graph. No attempt was made to correct the readings for parallax.

Linear dimensions of the peanuts were measured with scales, calipers, and micrometers to compute the projected area using equations 70 and 98. The required dimensions are shown in Figure 16 and projected areas in Table XII. Notice that the percent deviations from the measured values are small.

Surface Area

Equations 89 and 100 were solved numerically using the Gaussian integration procedure (7, 27) and Romberg's algorithm in combination

TABLE XI

TYPICAL DIMENSIONS AND THEIR RATIOS FOR UNDEFINED PEANUTS

No.	Dimensions				Ratios		
	L(in)	a(in)	b(in)	c(in)	c/L	c/a	c/b
1	0.950	0.477	0.430	0.376	0.396	0.788	0.874
2	1.020	0.440	0.485	0.322	0.315	0.732	0.664
3	1.102	0.448	0.444	0.380	0.345	0.848	0.856
4	0.982	0.430	0.382	0.314	0.320	0.730	0.822
5	0.859	0.379	0.325	0.289	0.336	0.760	0.889
6	0.899	0.470	0.424	0.379	0.421	0.806	0.894
7	0.897	0.493	0.451	0.399	0.445	0.809	0.885
8	0.960	0.478	0.369	0.338	0.352	0.707	0.916
9	1.043	0.489	0.482	0.379	0.363	0.775	0.786
10	0.967	0.502	0.472	0.412	0.426	0.820	0.873

TABLE XII

PHYSICAL PROPERTIES OF SPANISH PEANUTS AS DESCRIBED BY ONE AND TWO KERNEL ELLIPSOIDS

No.	2a in.	2b in.	2c in.	Volume Meas. in^3	Volume Calc. in^3	Deviation %	P. Area Meas. in^2	P. Area Calc. in^2	Deviation %	S. Area Calc.
1*	1.133	0.722	0.681	0.2622	0.2916	11.20	0.6668	0.6423	3.68	2.2084
2*	1.133	0.796	0.725	0.3420	0.3423	0.08	0.7859	0.7081	9.92	2.4326
3*	0.795	0.548	0.500	0.1216	0.1141	6.16	0.3572	0.3422	4.20	1.172
4*	0.547	0.458	0.417	0.0525	0.0547	4.20	0.1905	0.1968	3.31	0.7038
5*	0.664	0.496	0.447	0.0811	0.0771	4.93	0.2385	0.2587	8.47	0.8948
6+	0.816	0.466	0.427	0.0915	0.0850	7.10	0.3059	0.2985	2.42	0.9913
7+	0.774	0.456	9.414	0.0853	0.0741	13.14	0.3000	0.2771	7.63	0.9198
8+	0.791	0.488	0.474	0.0974	0.0958	1.64	0.3333	0.3031	9.35	1.0533
9+	0.875	0.489	0.457	0.0974	0.1025	5.23	0.3167	0.3365	6.25	1.1252
10+	0.894	0.474	0.437	0.1099	0.0970	11.72	0.3582	0.3328	7.10	1.0964

*Single kernel ellipsoids.

+Two kernel ellipsoids. Volume measured by submerging the peanuts in graduated cylinder filled with gasoline.

with the trapezoidal rule (7,24), respectively. No attempt was made to measure the surface area directly. However, comparison of surface area obtained by Wright (41) for cassinoid type of pods and those computed from equation 100 revealed that the mathematical model for Type II pods was justifiable (Table XIII). Surface areas for other types are reported in Tables XII and XIV.

Volume

Volume of each of the peanut pods was measured by submerging them in water with a sinker in accordance with the Archmedes principle. The volume is as follows:

$$\text{Volume of object} = \text{Volume (object + sinker)} - \text{Volume(sinker)} \tag{106}$$

$$\text{Volume of (object + sinker)} = \frac{\text{Weight in air(both)} - \text{weight in water(both)}}{\text{weight density of water}} \tag{107}$$

$$\text{Volume of sinker} = \frac{\text{Weight in air} - \text{weight in water}}{\text{Weight density of water}} \tag{108}$$

A Mettler balance (0-150 gm; 0.0001 gm) was used to weigh the peanuts and sinker for volume measurements. Theoretical values were computed using equations 90, 103 and 104. The integral in equation 103 was evaluated by Romberg's algorithm and checked against equation 104 Computed and theoretical values of volume are presented in Tables XII XIII and XIV.

TABLE XIII

PHYSICAL PROPERTIES OF SPANISH PEANUTS AS DESCRIBED BY CASSINOIDS

No.	L in.	M in.	K in.	B in.	Volume Meas. in^3	Volume Calc. in^3	Deviation %	P. Area Meas. in^2	P. Area Calc. in^2	Deviation %	S. Area Calc. in^2
1*	1.6512	0.5177	0.6118	0.5543	0.3986	0.4381	9.9	0.905	0.9406	3.9	3.278
2*	1.7963	0.6026	0.6699	0.5983	0.5903	0.5985	1.4	1.0955	1.1469	4.7	3.9912
3*	1.4105	0.6026	0.5423	0.4509	0.3561	0.3731	4.8	0.7621	0.8006	5.1	2.7865
4	1.0610	0.3009	0.3899	0.3727	0.1186	0.1073	9.5	0.3900	0.3729	4.4	1.3034
5	1.0964	0.3009	0.402	0.3597	0.1192	0.1156	3.0	0.4049	0.3934	2.8	1.3762
6	1.000	0.446	0.3871	0.3164	0.1300	0.1400	7.7	0.3467	0.4126	19.0	1.4378
7	0.9700	0.476	0.382	0.2988	0.1398	0.1443	3.2	0.3582	0.4118	15.0	1.4411
8+	0.938	0.422	0.3636	0.2962	0.1145	0.1168	2.0	-	0.3649	-	1.2720
9	0.922	0.402	0.3556	0.2934	0.1098	0.1067	2.8	0.3443	0.3461	0.5	1.2053
10	0.813	0.416	0.3229	0.2470	0.0854	0.0899	5.3	0.3000	0.2973	0.9	1.0431

*Degenerated Spanish variety.

+ Reported in (41).
1.0675 S. Area.

TABLE XIV

PHYSICAL PROPERTIES OF SPANISH PEANUTS AS DESCRIBED BY PAIRED ELLIPSOIDS

No.*	2a	2b	2c	Volume Meas. in^3	Volume Calc. in^3	Deviation %	P. Area Meas. in^2	P. Area Calc. in^2	Deviation %	S. Area Calc. in^2
1N	0.8318	0.5540	0.530	0.3231	0.1279	5.4	0.3572	0.4159	16.0	1.2654
1S	1.0247	0.6265	0.529		0.1778		0.5477	0.5124	6.4	1.6193
2N	0.892	0.6265	0.725	0.6063	0.2121	19.4	0.4525	0.446	1.4	1.7487
2S	1.061	0.6752	0.737		0.2764		0.6192	0.5305	14.3	2.1118
3N	0.9653	0.6752	0.679	0.3698	0.2317	11.3	0.5001	0.4826	3.5	1.863
3S	1.0123	0.6026	0.563		0.1798		0.5001	0.5061	1.2	1.6187
4N	0.6026	0.4460	0.493	0.1649	0.0694	17.1	0.2385	0.3013	26.3	0.8265
4S	0.6265	0.4460	0.460		0.0673		0.2385	0.3133	31.4	0.8145
5N	0.5301	0.4097	0.408	0.0900	0.0464	12.3	0.1905	0.2850	39.0	0.6316
5S	0.6026	0.4336	0.400		0.0547		0.2143	0.2052	4.24	0.7137

*N-(north); S-(south) are two ellipsoids constituting a peanut.

Accuracy of Measurement and Computation

Perhaps the most inaccurate of all the measurements is the volume readings. Though the weights of peanuts in air and water could be measured up to 4 decimal places, there is no guarantee that the errors due to soaking of water by the hull and presence of micro bubbles at the surface of the hull due to surface tension effects will not distort the volume measurements. This error could have been minimized by using Toluene in place of water or adding some wetting agent in water to minimize the presence of bubbles. The accuracy attained by such procedures would be meaningless without the knowledge of inherent error present in computed and theoretical values. Since the required dimensions were obtained by a micrometer (0.001), a linear scale and a caliper, the ends of which were ground to reach the crevices of peanut joints, an upper bound on error due to these measurements can be obtained by considering the log derivative of volume of the general ellipsoid and taking the worst case for maximum tolerance band (34).

$$V = \frac{4}{3}\pi abc \qquad (90)$$

$$\log V = \log(a) + \log(b) + \log(c) \qquad (109)$$

or

$$\frac{\Delta V}{V} = \frac{\Delta a}{a} + \frac{\Delta b}{b} + \frac{\Delta c}{c} \qquad (110)$$

where Δ is the half of the smallest scale division. Taking Δa, Δb, and Δc of the same magnitude, and the smallest dimension, c, for Type IV pods we get,

$$\frac{\Delta V}{V} = \pm 3 \frac{\Delta c}{c} \tag{111}$$

$$= \pm 3(\frac{1}{128})(\frac{1}{0.3})$$

$$= \pm 7.8\%$$

Thus, volume of the general ellipsoid evaluated with the measured dimensions has a maximum of 8% inherent error. This is also the maximum error in measuring the surface and projected areas.

An estimate of inherent error in measured values can be partially evaluated by examining the difference between the peanut weights obtained before and after soaking in water. The water absorbed was between 0.05 to 0.1 gm for each pod. It is questionable if this soaking resulted in immediate expansion of the peanut hull. Therefore, an increase in volume due to expansion cannot be determined. However, if only the change in weight was taken into consideration then measured volume readings reported in Tables XVII, XVIII and XIV are larger by an amount of 0.003 to 0.006 in^3. It amounts to approximately 6% error (negative correction) in each volume measurement. Thus the inherent error associated with the readings in the volume columns of Tables XII, XIII and XIV are of the same order. Nothing can be said about the sign of the error in equation 111. This suggests that greater precautions in volume measurement would not have contributed to significant changes in deviations.

Romberg's algorithm can be regarded exact since a comparison of integrated and explicit volumes of cassinoids showed no round off error up to 4 decimal places. The Gaussian scheme for surface area of general ellipsoids must also be exact since it was found exact for the cases of equal a, b and c (sphere), equal b and c (prolate spheriod) and equal a and c (oblate spheriod). Therefore, there are no errors due to truncation or round off in the computed values. Any errors associated with the numbers presented in Tables XII, XIII and XIV are attributed to measurement techniques only.

Fitness of Models

The fact that the observed and predicted values agree remarkably well suggests that the chosen models do describe the peanut pod geometry. In general it can be said that one-half of the peanuts in bulk can be described by a cassinoid and the other half by a general ellipsoid. It should be interesting to solve the heat and mass transfer equations using ellipsoidal or cassinoidal models developed here.

Conclusions

The four models adopted to describe the peanut pod geometry were found to give satisfactory values of projected area, surface area, and volume of Spanish peanuts. The peanut Types I, III and IV essentially represent one geometry (ellipsoid) and Type II another (cassinoid). Either geometry divides a random sample approximately in two halves. An ellipsoid is perhaps the most useful geometry to describe the shape of biological materials.

APPENDIX B

AIR FLOW MEASUREMENT

Air flow was measured using an orifice plate with Vena Contracta taps as shown in Figure 44 and computed from the formula (12,13).

$$Q_h = 45.465\ K\ Y\ d^2 \left[\sqrt{h\ (\frac{\gamma_m - \gamma_s}{\gamma})}\right] \qquad (112)$$

Where:

Q_h = Flow rate at density γ, ft^3/hr

K = Orifice factor

$$= (\frac{C}{\sqrt{1 - \beta^4}}) \qquad (113)$$

C = Orifice discharge coefficient

β = Ratio of diameter of orifice to internal diameter of pipe

Y = Expansion factor

d = Diameter of orifice, in

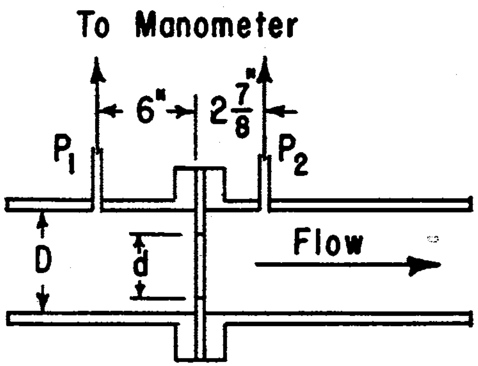
D = The internal pipe diameter, in

h = The differential reading of the manometer, in

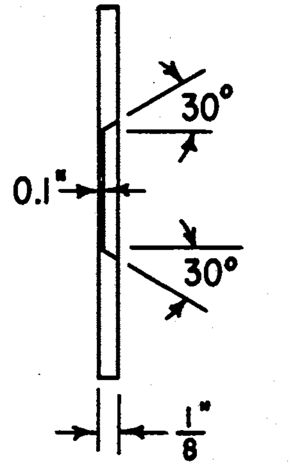
γ_m = The density of manometric liquid, lb_m/ft^3

γ_s = The density of the fluid above the manometric liquid, lb_m/ft^3

γ = The density of the flowing medium, lb_m/ft^3



$$Q = 45.465\, C d^2 \left[\frac{1}{\sqrt{1-\beta^4}} \sqrt{h\left(\frac{\gamma_m-\gamma_s}{\gamma}\right)} \right]$$



ORIFICE PLATE

D = 6"
d = 4"

Figure 44. Air Flow Measurement. Orifice Plate Meter with Vena Contracta Taps.

$$Y = 1 - [0.41 + 0.35\beta^4 (1 - \frac{P_2}{P_1}) \frac{1}{R}] \tag{114}$$

P_1 = Upstream static pressure, lb_f/ft^2

P_2 = Down stream static pressure, lb_f/ft^2

R = Ratio of specific heat at constant pressure to specific heat at constant volume, 1.4 for air

The value of K is assumed to compute the approximate flow rate using equation 112. A new value of K is then computed using this flow rate. This procedure is repeated until the difference between two consecutive values of K is less than 0.0005. The flow rate is obtained using this value of K. Additional equations to be used are:

$$K_0 = K + B\Lambda \tag{115}$$

$$K_0 = 0.5922 + 0.4252[(\frac{0.0006}{D^2\beta^2 + 0.01\ D}) + \beta^4 + 1.25\beta^{16})] \tag{116}$$

$$B = 0.00025 + 0.002325\ (\beta + 1.75\beta^4 + 10.0\beta^{12} + 2.0\ D\beta^{16}) \tag{117}$$

$$\Lambda = 1{,}000/\sqrt{R_D} \tag{118}$$

Where:

K_0 = Limiting value of K for any specific values of D and β when R_D becomes infinitely large

R_D = Reynolds number based on pipe diameter D

Since the values of d, γ_m, γ_s are known, a working equation for the flow rate can be given as

γ_m = Density of water at NLC x Specific gravity of manometric oil at NLC

= 62.23 x 0.827

$= 51.464\ lb_m/ft^3$

γ_s = Density of air at NLC

$= 0.0735\ lb_m/ft^3$

$d = 4$ in

Substitution in equation 112 yields

$$Q_h = 5214.8\ KY\sqrt{h/\gamma} \qquad (119)$$

The value of γ is obtained as the reciprocal of the humid volume from psychrometric data as a function of temperature, pressure and relative humidity (3) of air at the orifice. Thus the flow rate past the inlet pipe is determined by

$$Q_s = \frac{5214.8}{3600}\ K\ Y\ \sqrt{h/\gamma}\ \frac{\rho_0}{\rho_a} \qquad (120)$$

$$= 1.449\ K\ Y\ \sqrt{h/\gamma}\ \frac{\rho_0}{\rho_a} \qquad (121)$$

Where:

Q_s = Flow rate in the inlet pipe, ft^3/sec

$\rho_0 = \gamma$ = Density of air at orifice, lb_m/ft^3

ρ_a = Density of air at inlet pipe, lb_m/ft^3

APPENDIX C

DIMENSIONLESS GROUPS AND RELATED DATA

Description of Quantities in Appendix C Tables

EXP = Experimental series

CR = Concentration Efficiency

REB = Reynolds Number

FO = Fourier Number

TR = Temperature ratio

GR = Geometry ratio

DR = Diameter ratio

SF = Size factor

IC = Initial concentration

C = Concentration at time θ

CO = Concentration at time zero

CE = Equilibrium concentration at NLC

HC = Height of column, in

DB = Diameter of bed, in

DC = Diameter of column, in

VB = Volume of bed, cu-ft

PA = Static pressure at the column inlet, lb_f/in^2

TA = Air temperature at the inlet, ^oF

TD = Dew point temperature at the inlet, ^oF

GAMAA = Inlet air density, lb_m/cu-ft

AM = Viscosity of inlet air, lb_m/ft-sec

CP = Specific heat at constant pressure, Btu/lb_m ^oR

AKT = Orific discharge coefficient

Y = Expansion factor

P = Static pressure at upstream orifice, lb_f/in^2

H = Differential pressure across the orifice, inches of oil

GAMAO = Air density at orifice, lb_m/cft

QH = Flow rate at orifice, cuft/hr

QS = Flow rate at orifice, cuft/sec

TABLE XV

DIMENSIONLESS GROUPS FOR CONCENTRATION DIFFUSION IN SPOUTED BED

EXP	CR	REB	FO	TR	GR	DR	SF	IC
223	0.5600	851.9	2.486	1.11	1.2857	6.0	32.1429	0.2854
252	0.5600	589.1	2.486	1.11	1.2857	6.0	32.1429	0.3032
231	0.5614	628.3	2.486	1.11	1.2857	6.0	32.1429	0.3167
231	0.5600	625.9	2.486	1.11	1.2857	6.0	32.1429	0.3167
253	0.5700	638.1	2.486	1.11	1.2857	6.0	32.1429	0.3090
213	0.4900	661.1	2.486	1.11	1.2857	6.0	32.1429	0.3016
233	0.5356	700.3	2.486	1.11	1.2857	6.0	32.1429	0.2962
221	0.5600	694.2	2.486	1.11	1.2857	6.0	32.1429	0.3124
214	0.5400	725.2	2.486	1.11	1.2857	6.0	32.1429	0.3034
211	0.4900	777.9	2.486	1.11	1.2857	6.0	32.1429	0.3213
212	0.5500	774.5	2.486	1.11	1.2857	6.0	32.1429	0.3213
224	0.6344	783.1	2.486	1.11	1.2857	6.0	32.1429	0.3074
232	0.5200	802.1	2.486	1.11	1.2857	6.0	32.1429	0.3229
241	0.5179	796.3	2.486	1.11	1.2857	6.0	32.1429	0.2893
242	0.5600	832.1	2.486	1.11	1.2857	6.0	32.1429	0.2856
251	0.5000	913.4	2.486	1.11	1.2857	6.0	32.1429	0.3033
222	0.5000	917.2	2.486	1.11	1.2857	6.0	32.1429	0.2934
243	0.6000	1069.4	2.486	1.11	1.2857	6.0	32.1429	0.3033
391	0.0805	738.9	0.829	1.11	1.2857	6.0	32.1429	0.1950
391	0.1909	737.4	1.657	1.11	1.2857	6.0	32.1429	0.1950
391	0.2635	736.8	2.486	1.11	1.2857	6.0	32.1429	0.1950
391	0.3356	736.3	3.314	1.11	1.2857	6.0	32.1429	0.1950
391	0.4330	736.6	4.143	1.11	1.2857	6.0	32.1429	0.1950
361	0.0699	625.8	0.414	1.11	1.2857	6.0	32.1429	0.2150
361	0.1074	623.6	0.829	1.11	1.2857	6.0	32.1429	0.2150
361	0.2864	629.2	1.657	1.11	1.2857	6.0	32.1429	0.2150
361	0.3938	631.8	2.486	1.11	1.2857	6.C	32.1429	0.2150
361	0.4296	631.0	3.314	1.11	1.2857	6.0	32.1429	0.2150
361	0.5011	631.4	4.143	1.11	1.2857	6.0	32.1429	0.2150
361	0.5727	631.3	4.971	1.11	1.2857	6.0	32.1429	0.2150
361	0.6085	631.2	5.800	1.11	1.2857	6.0	32.1429	0.2150
341	0.3479	985.2	1.657	1.11	1.2857	6.0	32.1429	0.3110
342	0.4625	979.7	2.486	1.11	1.2857	6.0	32.1429	0.3110
343	0.6025	991.1	4.143	1.11	1.2857	6.0	32.1429	0.3110
344	0.6280	989.3	4.971	1.11	1.2857	6.0	32.1429	0.3110
345	0.6704	991.1	5.800	1.11	1.2857	6.0	32.1429	0.3110
346	0.7103	999.3	6.628	1.11	1.2857	6.0	32.1429	0.3110
331	0.1119	916.5	0.414	1.11	1.2857	6.0	32.1429	0.3177
332	0.2233	916.6	0.829	1.11	1.2857	6.0	32.1429	0.3177
333	0.3490	912.1	1.657	1.11	1.2857	6.0	32.1429	0.3177
334	0.4386	914.8	2.486	1.11	1.2857	6.0	32.1429	0.3177
335	0.5742	913.4	4.143	1.11	1.2857	6.0	32.1429	0.3177
351	0.3730	799.9	0.414	1.11	1.2414	6.0	32.1429	0.4268
351	0.4880	799.9	0.829	1.11	1.2857	6.0	32.1429	0.4268
351	0.5679	795.0	1.657	1.11	1.2857	6.0	32.1429	0.4268
351	0.6288	795.6	2.486	1.11	1.2857	6.0	32.1429	0.4268
351	0.6790	799.4	3.728	1.11	1.2857	6.0	32.1429	0.4268
351	0.7445	790.5	4.557	1.11	1.2857	6.0	32.1429	0.4268

TABLE XV (CONTINUED)

EXP	CR	REB	FO	TR	GR	DR	SF	IC
421	0.4424	811.9	2.486	1.09	1.2857	6.0	32.1429	0.3072
422	0.4490	636.6	2.486	1.09	1.2857	6.0	32.1429	0.3257
432	0.5536	620.2	2.486	1.11	1.2857	6.0	32.1429	0.3213
433	0.5020	536.5	2.486	1.11	1.2857	6.0	32.1429	0.3025
434	0.5269	908.6	2.486	1.12	1.2857	6.0	32.1429	0.3077
441	0.6344	772.6	2.486	1.13	1.2857	6.0	32.1429	0.3074
442	0.6212	927.9	2.486	1.13	1.2857	6.0	32.1429	0.3025
443	0.6100	840.5	2.486	1.13	1.2857	6.0	32.1429	0.2997
445	0.5889	772.6	2.486	1.13	1.2857	6.0	32.1429	0.3210
447	0.6279	620.6	2.486	1.13	1.2857	6.0	32.1429	0.3125
464	0.8015	610.6	2.486	1.15	1.2857	6.0	32.1429	0.3125
451	0.7172	764.3	2.486	1.15	1.2857	6.0	32.1429	0.3062
452	0.6849	610.7	2.486	1.15	1.2857	6.0	32.1429	0.3062
454	0.7015	612.9	2.486	1.15	1.2857	6.0	32.1429	0.3072
461	0.7659	600.3	2.486	1.17	1.2857	6.0	32.1429	0.3267
462	0.7500	601.6	2.486	1.17	1.2857	6.0	32.1429	0.3059
463	0.7600	697.1	2.486	1.17	1.2857	6.0	32.1429	0.2934
511	0.5794	630.3	2.486	1.11	2.5714	6.0	32.1429	0.3065
512	0.5800	628.4	2.486	1.11	2.5714	6.0	32.1429	0.3047
521	0.5892	632.0	2.486	1.11	1.8000	6.0	32.1429	0.3014
522	0.6252	627.4	2.486	1.11	1.8000	6.0	32.1429	0.3135
523	0.6709	796.3	2.486	1.11	1.4400	6.0	32.1429	0.3012
534	0.6432	628.4	2.486	1.11	1.2857	6.0	32.1429	0.3028
531	0.6398	661.1	2.486	1.11	1.2857	6.0	32.1429	0.2959
541	0.6054	640.9	2.486	1.11	1.1250	6.0	32.1429	0.3087
543	0.5821	624.2	2.486	1.11	1.1250	6.0	32.1429	0.3095
551	0.4904	624.2	2.486	1.11	1.0000	6.0	32.1429	0.3035
552	0.5412	634.0	2.486	1.11	1.0000	6.0	32.1429	0.3135
562	0.5356	700.3	2.486	1.11	0.9000	6.0	32.1429	0.2962
563	0.4358	661.1	2.486	1.11	0.8571	6.0	32.1429	0.2823
611	0.5137	638.1	2.486	1.11	1.2857	9.0	32.1429	0.2900
612	0.5258	589.1	2.486	1.11	1.2857	9.0	32.1429	0.2956
614	0.5956	629.9	2.486	1.11	1.2857	9.0	32.1429	0.2857
624	0.5690	627.2	2.486	1.11	1.2857	7.2	32.1429	0.3125
632	0.5685	627.6	2.486	1.11	1.2857	6.0	32.1429	0.2941
634	0.6085	627.3	2.486	1.11	1.2857	6.0	32.1429	0.3202
641	0.5957	643.2	2.486	1.11	1.2857	5.1	32.1429	0.3095
642	0.5773	694.6	2.486	1.11	1.2857	5.1	32.1429	0.2993
644	0.5847	628.9	2.486	1.11	1.2857	5.1	32.1429	0.3105
654	0.5721	630.1	2.486	1.11	1.2857	4.5	32.1429	0.2946
651	0.5903	695.9	2.486	1.11	1.2857	4.5	32.1429	0.2980
652	0.5721	694.2	2.486	1.11	1.2857	4.5	32.1429	0.2946
663	0.6103	790.7	2.486	1.11	1.2857	3.6	32.1429	0.3008
664	0.5891	697.1	2.486	1.17	1.2857	3.6	32.1429	0.3135
662	0.5643	894.5	4.971	1.12	1.2857	3.6	32.1429	0.3077
661	0.5921	774.5	2.486	1.11	1.2857	3.6	32.1429	0.3169
665	0.5951	710.3	2.486	1.11	1.2857	3.6	32.1429	0.2956
666	0.6039	908.6	2.486	1.12	1.2857	3.6	32.1429	0.3277

TABLE XV (CONTINUED)

EXP	CR	REB	FO	TR	GR	DR	SF	IC
711	0.6014	905.9	2.486	1.11	1.2821	6.0	26.7857	0.3384
712	0.6042	904.5	2.486	1.11	1.2500	6.0	26.7857	0.3298
721	0.5994	639.2	2.486	1.11	1.2857	6.0	32.1429	0.3148
722	0.5670	624.0	2.486	1.11	1.2857	6.0	32.1429	0.3163
723	0.5808	780.1	2.486	1.11	1.2857	6.0	32.1429	0.3056
724	0.5585	800.8	2.486	1.11	1.2857	6.0	32.1429	0.3072
725	0.6775	783.1	2.486	1.11	1.2857	6.0	32.1429	0.3074
713	0.5889	462.6	2.486	1.11	1.2883	6.0	37.5000	0.3152
742	0.5374	464.6	2.486	1.11	1.2727	6.0	37.5000	0.2771
751	0.5537	555.1	2.486	1.11	1.2903	6.0	42.8571	0.3110
752	0.5071	529.5	2.486	1.11	1.2973	6.0	42.8571	0.2682
753	0.4934	354.9	2.486	1.11	1.2903	6.0	42.8571	0.3367
754	0.5445	356.1	2.486	1.11	1.2973	6.0	42.8571	0.3095
755	0.5537	555.1	2.486	1.11	1.2834	6.0	42.8571	0.3110
727	0.5852	564.0	2.486	1.11	1.2903	6.0	42.8571	0.2712
801	0.3841	627.7	2.486	1.11	1.2857	6.0	32.1429	0.1950
802	0.3935	625.8	2.486	1.11	1.2857	6.0	32.1429	0.2150
811	0.3938	631.0	2.486	1.11	1.2857	6.0	32.1429	0.2150
821	0.4337	621.6	2.486	1.11	1.2857	6.0	32.1429	0.2434
823	0.4622	537.9	2.486	1.11	1.2857	6.0	32.1429	0.2434
822	0.5071	941.3	2.486	1.11	1.2857	6.0	32.1429	0.2682
832	0.5889	575.3	2.486	1.11	1.2857	6.0	32.1429	0.3152
831	0.6126	827.3	2.486	1.11	1.2857	6.0	32.1429	0.3200
834	0.6218	711.6	2.486	1.11	1.2857	6.0	32.1429	0.3278
841	0.5992	689.3	2.486	1.11	1.2857	6.0	32.1429	0.3440
842	0.5927	625.8	2.486	1.11	1.2857	6.0	32.1429	0.3520
861	0.7155	805.3	2.486	1.11	1.2857	6.0	32.1429	0.3877
871	0.7600	797.6	2.486	1.11	1.2857	6.0	32.1429	0.4119
881	0.7280	792.4	2.486	1.11	1.2857	6.0	32.1429	0.4460

TABLE XVI

BED AND PARTICLE CHARACTERISTICS

EXP	C	CO	CE	HC	DB	DC	VB
223	0.1678	0.2854	0.0753	14.0	18.0	3.0	1.3969
252	0.1756	0.3032	0.0753	14.0	18.0	3.0	1.3969
231	0.1812	0.3167	0.0753	14.0	18.0	3.0	1.3969
231	0.1815	0.3167	0.0753	14.0	18.0	3.0	1.3969
253	0.1758	0.3090	0.0753	14.0	18.0	3.0	1.3969
213	0.1907	0.3016	0.0753	14.0	18.0	3.0	1.3969
233	0.1779	0.2962	0.0753	14.0	18.0	3.0	1.3969
221	0.1796	0.3124	0.0753	14.0	18.0	3.0	1.3969
214	0.1802	0.3034	0.0753	14.0	18.0	3.0	1.3969
211	0.2008	0.3213	0.0753	14.0	18.0	3.0	1.3969
212	0.1860	0.3213	0.0753	14.0	18.0	3.0	1.3969
224	0.1602	0.3074	0.0753	14.0	18.0	3.0	1.3969
232	0.1942	0.3229	0.0753	14.0	18.0	3.0	1.3969
241	0.1785	0.2893	0.0753	14.0	18.0	3.0	1.3969
242	0.1678	0.2856	0.0753	14.0	18.0	3.0	1.3969
251	0.1893	0.3033	0.0753	14.0	18.0	3.0	1.3969
222	0.1844	0.2934	0.0753	14.0	18.0	3.0	1.3969
243	0.1665	0.3033	0.0753	14.0	18.0	3.0	1.3969
391	0.1854	0.1950	0.0753	14.0	18.0	3.0	1.3969
391	0.1721	0.1950	0.0753	14.0	18.0	3.0	1.3969
391	0.1635	0.1950	0.0753	14.0	18.0	3.0	1.3969
391	0.1548	0.1950	0.0753	14.0	18.0	3.0	1.3969
391	0.1432	0.1950	0.0753	14.0	18.0	3.0	1.3969
361	0.2052	0.2150	0.0753	14.0	18.0	3.0	1.3969
361	0.2000	0.2150	0.0753	14.0	18.0	3.0	1.3969
361	0.1750	0.2150	0.0753	14.0	18.0	3.0	1.3969
361	0.1600	0.2150	0.0753	14.0	18.0	3.0	1.3969
361	0.1550	0.2150	0.0753	14.0	18.0	3.0	1.3969
361	0.1450	0.2150	0.0753	14.0	18.0	3.0	1.3969
361	0.1350	0.2150	0.0753	14.0	18.0	3.0	1.3969
361	0.1300	0.2150	0.0753	14.0	18.0	3.0	1.3969
341	0.2290	0.3110	0.0753	14.0	18.0	3.0	1.3969
342	0.2020	0.3110	0.0753	14.0	18.0	3.0	1.3969
343	0.1690	0.3110	0.0753	14.0	18.0	3.0	1.3969
344	0.1630	0.3110	0.0753	14.0	18.0	3.0	1.3969
345	0.1530	0.3110	0.0753	14.0	18.0	3.0	1.3969
346	0.1436	0.3110	0.0753	14.0	18.0	3.0	1.3969
331	0.2906	0.3177	0.0753	14.0	18.0	3.0	1.3969
332	0.2636	0.3177	0.0753	14.0	18.0	3.0	1.3969
333	0.2331	0.3177	0.0753	14.0	18.0	3.0	1.3969
334	0.2114	0.3177	0.0753	14.0	18.0	3.0	1.3969
335	0.1785	0.3177	0.0753	14.0	18.0	3.0	1.3969
351	0.2957	0.4268	0.0753	14.5	18.0	3.0	1.4706
351	0.2553	0.4268	0.0753	14.0	18.0	3.0	1.3969
351	0.2272	0.4268	0.0753	14.0	18.0	3.0	1.3969
351	0.2058	0.4268	0.0753	14.0	18.0	3.0	1.3969
351	0.1881	0.4268	0.0753	14.0	18.0	3.0	1.3969
351	0.1651	0.4268	0.0753	14.0	18.0	3.0	1.3969

TABLE XVI (CONTINUED)

EXP	C	CO	CE	HC	DB	DC	VB
421	0.2046	0.3072	0.0753	14.0	18.0	3.0	1.3969
422	0.2133	0.3257	0.0753	14.0	18.0	3.0	1.3969
432	0.1851	0.3213	0.0753	14.0	18.0	3.0	1.3969
433	0.1885	0.3025	0.0753	14.0	18.0	3.0	1.3969
434	0.1853	0.3077	0.0753	14.0	18.0	3.0	1.3969
441	0.1602	0.3074	0.0753	14.0	18.0	3.0	1.3969
442	0.1614	0.3025	0.0753	14.0	18.0	3.0	1.3969
443	0.1628	0.2997	0.0753	14.0	18.0	3.0	1.3969
445	0.1763	0.3210	0.0753	14.0	18.0	3.0	1.3969
447	0.1636	0.3125	0.0753	14.0	18.0	3.0	1.3969
464	0.1224	0.3125	0.0753	14.0	18.0	3.0	1.3969
451	0.1406	0.3062	0.0753	14.0	18.0	3.0	1.3969
452	0.1481	0.3062	0.0753	14.0	18.0	3.0	1.3969
454	0.1445	0.3072	0.0753	14.0	18.0	3.0	1.3969
461	0.1342	0.3267	0.0753	14.0	18.0	3.0	1.3969
462	0.1330	0.3059	0.0753	14.0	18.0	3.0	1.3969
463	0.1277	0.2934	0.0753	14.0	18.0	3.0	1.3969
511	0.1725	0.3065	0.0753	7.0	18.0	3.0	0.3661
512	0.1717	0.3047	0.0753	7.0	18.0	3.0	0.3661
521	0.1682	0.3014	0.0753	10.0	18.0	3.0	0.8079
522	0.1646	0.3135	0.0753	10.0	18.0	3.0	0.8079
523	0.1497	0.3012	0.0753	12.5	18.0	3.0	1.1761
534	0.1565	0.3028	0.0753	14.0	18.0	3.0	1.3969
531	0.1548	0.2959	0.0753	14.0	18.0	3.0	1.3969
541	0.1674	0.3087	0.0753	16.0	18.0	3.0	1.6915
543	0.1732	0.3095	0.0753	16.0	18.0	3.0	1.6915
551	0.1916	0.3035	0.0753	18.0	18.0	3.0	1.9860
552	0.1846	0.3135	0.0753	18.0	18.0	3.0	1.9860
562	0.1779	0.2962	0.0753	20.0	18.0	3.0	2.2805
563	0.1921	0.2823	0.0753	21.0	18.0	3.0	2.4278
611	0.1797	0.2900	0.0753	14.0	18.0	2.0	1.3248
612	0.1798	0.2956	0.0753	14.0	18.0	2.0	1.3248
614	0.1604	0.2857	0.0753	14.0	18.0	2.0	1.3248
624	0.1775	0.3125	0.0753	14.0	18.0	2.5	1.3610
632	0.1697	0.2941	0.0753	14.0	18.0	3.0	1.3969
634	0.1712	0.3202	0.0753	14.0	18.0	3.0	1.3969
641	0.1700	0.3095	0.0753	14.0	18.0	3.5	1.4326
642	0.1700	0.2993	0.0753	14.0	18.0	3.5	1.4326
644	0.1730	0.3105	0.0753	14.0	18.0	3.5	1.4326
654	0.1691	0.2946	0.0753	14.0	18.0	4.0	1.4678
651	0.1666	0.2980	0.0753	14.0	18.0	4.0	1.4678
652	0.1691	0.2946	0.0753	14.0	18.0	4.0	1.4678
663	0.1632	0.3008	0.0753	14.0	18.0	5.0	1.5368
664	0.1732	0.3135	0.0753	14.0	18.0	5.0	1.5368
662	0.1766	0.3077	0.0753	14.0	18.0	5.0	1.5368
661	0.1739	0.3169	0.0753	14.0	18.0	5.0	1.5368
665	0.1645	0.2956	0.0753	14.0	18.0	5.0	1.5368
666	0.1753	0.3277	0.0753	14.0	18.0	5.0	1.5368

TABLE XVI (CONTINUED)

EXP	C	CO	CE	HC	DB	DC	VB
711	0.1802	0.3384	0.0753	11.7	15.0	2.5	0.8118
712	0.1761	0.3298	0.0753	12.0	15.0	2.5	0.8425
721	0.1712	0.3148	0.0753	14.0	18.0	3.0	1.3969
722	0.1797	0.3163	0.0753	14.0	18.0	3.0	1.3969
723	0.1718	0.3056	0.0753	14.0	18.0	3.0	1.3969
724	0.1777	0.3072	0.0753	14.0	18.0	3.0	1.3969
725	0.1502	0.3074	0.0753	14.0	18.0	3.0	1.3969
713	0.1739	0.3152	0.0753	16.3	21.0	3.5	2.2116
742	0.1687	0.2771	0.0753	16.5	21.0	3.5	2.2517
751	0.1805	0.3110	0.0753	18.6	24.0	4.0	3.2938
752	0.1704	0.2682	0.0753	18.5	24.0	4.0	3.2676
753	0.2077	0.3367	0.0753	18.6	24.0	4.0	3.2938
754	0.1820	0.3095	0.0753	18.5	24.0	4.0	3.2676
755	0.1805	0.3110	0.0753	18.7	24.0	4.0	3.3200
727	0.1566	0.2712	0.0753	18.6	24.0	4.0	3.2938
801	0.1490	0.1950	0.0753	14.0	18.0	3.0	1.3969
802	0.1600	0.2150	0.0753	14.0	18.0	3.0	1.3969
811	0.1600	0.2150	0.0753	14.0	18.0	3.0	1.3969
821	0.1705	0.2434	0.0753	14.0	18.0	3.0	1.3969
823	0.1657	0.2434	0.0753	14.0	18.0	3.0	1.3969
822	0.1704	0.2682	0.0753	14.0	18.0	3.0	1.3969
832	0.1739	0.3152	0.0753	14.0	18.0	3.0	1.3969
831	0.1701	0.3200	0.0753	14.0	18.0	3.0	1.3969
834	0.1708	0.3278	0.0753	14.0	18.0	3.0	1.3969
841	0.1830	0.3440	0.0753	14.0	18.0	3.0	1.3969
842	0.1880	0.3520	0.0753	14.0	18.0	3.0	1.3969
861	0.1642	0.3877	0.0753	14.0	18.0	3.0	1.3969
871	0.1561	0.4119	0.0753	14.0	18.0	3.0	1.3969
881	0.1762	0.4460	0.0753	14.0	18.0	3.0	1.3969

TABLE XVII

PROPERTIES OF AIR AT THE INLET PIPE

EXP	PA	TA	TD	PHIA	GAMAA	AM	CP
223	14.25	100.0	55.0	22.5	0.0677	0.12758E-04	0.2405
252	15.26	100.0	42.0	13.8	0.0729	0.12758E-04	0.2405
231	14.99	100.0	36.0	10.9	0.0718	0.12758E-04	0.2405
231	15.10	100.0	36.0	10.9	0.0723	0.12758E-04	0.2405
253	15.05	100.0	42.0	13.8	0.0720	0.12758E-04	0.2405
213	15.06	100.0	44.5	15.2	0.0719	0.12758E-04	0.2405
233	15.12	100.0	44.0	14.9	0.0722	0.12758E-04	0.2405
221	14.96	100.0	41.5	13.6	0.0715	0.12758E-04	0.2405
214	14.86	100.0	39.0	12.3	0.0711	0.12758E-04	0.2405
211	14.90	100.0	41.0	13.3	0.0713	0.12758E-04	0.2405
212	14.79	100.0	41.5	13.6	0.0707	0.12758E-04	0.2405
224	14.56	100.0	43.0	14.4	0.0696	0.12758E-04	0.2405
232	14.88	100.0	45.5	15.8	0.0711	0.12758E-04	0.2405
241	14.42	100.0	44.0	14.9	0.0688	0.12758E-04	0.2405
242	14.54	100.0	43.5	14.7	0.0695	0.12758E-04	0.2405
251	14.51	100.0	42.2	13.9	0.0693	0.12758E-04	0.2405
222	14.51	100.0	42.0	13.8	0.0693	0.12758E-04	0.2405
243	14.67	100.0	51.5	19.8	0.0699	0.12758E-04	0.2405
391	14.36	100.0	50.0	18.7	0.0684	0.12758E-04	0.2405
391	14.36	100.0	51.0	19.5	0.0684	0.12758E-04	0.2405
391	14.36	100.0	51.5	19.8	0.0683	0.12758E-04	0.2405
391	14.36	100.0	52.0	20.2	0.0683	0.12758E-04	0.2405
391	14.36	100.0	51.5	19.8	0.0683	0.12758E-04	0.2405
361	15.00	100.0	36.0	10.9	0.0718	0.12758E-04	0.2405
361	14.99	100.0	35.0	10.5	0.0718	0.12758E-04	0.2405
361	14.99	100.0	45.0	15.5	0.0716	0.12758E-04	0.2405
361	15.00	100.0	44.0	14.9	0.0717	0.12758E-04	0.2405
361	14.99	100.0	45.0	15.5	0.0716	0.12758E-04	0.2405
361	15.00	100.0	44.0	14.9	0.0717	0.12758E-04	0.2405
361	15.00	100.0	44.0	14.9	0.0716	0.12758E-04	0.2405
361	14.99	100.0	44.0	14.9	0.0716	0.12758E-04	0.2405
341	14.38	100.0	55.5	22.9	0.0683	0.12758E-04	0.2405
342	14.37	100.0	54.5	22.1	0.0683	0.12758E-04	0.2405
343	14.36	100.0	52.0	20.2	0.0683	0.12758E-04	0.2405
344	14.36	100.0	50.0	18.7	0.0684	0.12758E-04	0.2405
345	14.36	100.0	55.0	22.5	0.0682	0.12758E-04	0.2405
346	14.36	100.0	55.0	22.5	0.0682	0.12758E-04	0.2405
331	14.52	100.0	40.5	13.1	0.0694	0.12758E-04	0.2405
332	14.52	100.0	40.0	12.8	0.0695	0.12758E-04	0.2405
333	14.52	100.0	40.5	13.1	0.0694	0.12758E-04	0.2405
334	14.51	100.0	41.5	13.6	0.0694	0.12758E-04	0.2405
335	14.51	100.0	42.2	13.9	0.0693	0.12758E-04	0.2405
351	14.23	100.0	49.5	18.4	0.0678	0.12758E-04	0.2405
351	14.23	100.0	49.5	18.4	0.0678	0.12758E-04	0.2405
351	14.28	100.0	50.0	18.7	0.0680	0.12758E-04	0.2405
351	14.28	100.0	49.0	18.1	0.0680	0.12758E-04	0.2405
351	14.27	100.0	49.5	18.4	0.0680	0.12758E-04	0.2405
351	14.27	100.0	49.5	18.4	0.0680	0.12758E-04	0.2405

TABLE XVII (CONTINUED)

EXP	PA	TA	TD	PHIA	GAMAA	AM	CP
421	14.54	90.0	42.5	19.2	0.0707	0.12583E-04	0.2404
422	14.91	90.0	49.5	25.0	0.0723	0.12583E-04	0.2404
432	14.87	100.0	40.5	13.1	0.0711	0.12758E-04	0.2405
433	14.79	100.0	41.5	13.6	0.0707	0.12758E-04	0.2405
434	14.51	105.0	41.5	11.7	0.0688	0.12844E-04	0.2405
441	14.56	110.0	43.0	10.7	0.0683	0.12931E-04	0.2406
442	14.62	110.0	55.2	16.9	0.0682	0.12931E-04	0.2406
443	14.25	110.0	55.0	16.8	0.0665	0.12931E-04	0.2406
445	14.56	110.0	43.0	10.7	0.0683	0.12931E-04	0.2406
447	14.85	110.0	47.5	12.7	0.0696	0.12931E-04	0.2406
464	15.08	120.0	34.5	5.8	0.0698	0.13102E-04	0.2406
451	14.59	120.0	42.0	7.8	0.0673	0.13102E-04	0.2406
452	14.88	120.0	45.5	8.9	0.0686	0.13102E-04	0.2406
454	15.23	120.0	59.0	14.6	0.0698	0.13102E-04	0.2406
461	15.02	130.0	60.0	11.5	0.0676	0.13272E-04	0.2407
462	15.10	130.0	36.0	4.7	0.0686	0.13272E-04	0.2407
463	14.86	130.0	39.0	5.3	0.0675	0.13272E-04	0.2407
511	14.93	100.0	47.5	17.1	0.0712	0.12758E-04	0.2405
512	14.93	100.0	45.0	15.5	0.0713	0.12758E-04	0.2405
521	15.02	100.0	47.0	16.8	0.0717	0.12758E-04	0.2405
522	15.01	100.0	52.0	20.2	0.0715	0.12758E-04	0.2405
523	14.42	100.0	44.0	14.9	0.0688	0.12758E-04	0.2405
534	14.93	100.0	45.0	15.5	0.0713	0.12758E-04	0.2405
531	15.06	100.0	44.5	15.2	0.0719	0.12758E-04	0.2405
541	14.91	100.0	50.0	18.7	0.0710	0.12758E-04	0.2405
543	15.05	100.0	49.5	18.4	0.0717	0.12758E-04	0.2405
551	15.05	100.0	49.5	18.4	0.0717	0.12758E-04	0.2405
552	14.99	100.0	46.0	16.1	0.0715	0.12758E-04	0.2405
562	15.12	100.0	44.0	14.9	0.0722	0.12758E-04	0.2405
563	15.06	100.0	44.5	15.2	0.0719	0.12758E-04	0.2405
611	15.05	100.0	42.0	13.8	0.0720	0.12758E-04	0.2405
612	15.26	100.0	42.0	13.8	0.0729	0.12758E-04	0.2405
614	14.98	100.0	42.0	13.8	0.0716	0.12758E-04	0.2405
624	14.98	100.0	45.0	15.5	0.0715	0.12758E-04	0.2405
632	15.09	100.0	42.5	14.1	0.0721	0.12758E-04	0.2405
634	14.90	100.0	40.0	12.8	0.0713	0.12758E-04	0.2405
641	14.99	100.0	42.0	13.8	0.0717	0.12758E-04	0.2405
642	14.96	100.0	40.0	12.8	0.0716	0.12758E-04	0.2405
644	15.01	100.0	40.0	12.8	0.0718	0.12758E-04	0.2405
654	14.96	100.0	45.5	15.8	0.0714	0.12758E-04	0.2405
651	14.89	100.0	37.5	11.6	0.0713	0.12758E-04	0.2405
652	14.96	100.0	41.5	13.6	0.0715	0.12758E-04	0.2405
663	14.89	100.0	37.5	11.6	0.0713	0.12758E-04	0.2405
664	14.86	130.0	39.0	5.3	0.0675	0.13272E-04	0.2407
662	14.50	105.0	42.0	11.9	0.0687	0.12844E-04	0.2405
661	14.79	100.0	41.5	13.6	0.0707	0.12758E-04	0.2405
665	14.87	100.0	40.0	12.8	0.0711	0.12758E-04	0.2405
666	14.51	105.0	41.5	11.7	0.0688	0.12844E-04	0.2405

TABLE XVII (CONTINUED)

EXP	PA	TA	TD	PHIA	GAMAA	AM	CP
711	14.91	100.0	41.5	13.6	0.0713	0.12758E-04	0.2405
712	14.89	100.0	41.5	13.6	0.0712	0.12758E-04	0.2405
721	15.26	100.0	40.5	13.1	0.0730	0.12758E-04	0.2405
722	14.98	100.0	38.5	12.1	0.0717	0.12758E-04	0.2405
723	15.18	100.0	47.0	16.8	0.0724	0.12758E-04	0.2405
724	14.54	100.0	42.5	14.1	0.0695	0.12758E-04	0.2405
725	14.56	100.0	43.0	14.4	0.0696	0.12758E-04	0.2405
713	15.05	100.0	42.5	14.1	0.0719	0.12758E-04	0.2405
742	15.12	100.0	41.0	13.3	0.0723	0.12758E-04	0.2405
751	14.36	100.0	54.0	21.7	0.0683	0.12758E-04	0.2405
752	14.50	100.0	44.0	14.9	0.0692	0.12758E-04	0.2405
753	15.05	100.0	42.0	13.8	0.0720	0.12758E-04	0.2405
754	15.10	100.0	40.0	12.8	0.0722	0.12758E-04	0.2405
755	14.36	100.0	54.0	21.7	0.0683	0.12758E-04	0.2405
727	14.41	100.0	40.0	12.8	0.0689	0.12758E-04	0.2405
801	14.90	100.0	47.0	16.8	0.0711	0.12758E-04	0.2405
802	14.46	100.0	42.0	13.8	0.0691	0.12758E-04	0.2405
811	14.99	100.0	45.0	15.5	0.0716	0.12758E-04	0.2405
821	14.93	100.0	47.0	16.8	0.0713	0.12758E-04	0.2405
823	14.83	100.0	41.5	13.6	0.0709	0.12758E-04	0.2405
822	14.50	100.0	44.0	14.9	0.0692	0.12758E-04	0.2405
832	14.92	100.0	42.5	14.1	0.0713	0.12758E-04	0.2405
831	14.44	100.0	44.0	14.9	0.0690	0.12758E-04	0.2405
834	15.18	100.0	46.5	16.4	0.0725	0.12758E-04	0.2405
841	14.47	100.0	43.0	14.4	0.0691	0.12758E-04	0.2405
842	14.46	100.0	42.0	13.8	0.0691	0.12758E-04	0.2405
861	14.50	100.0	44.0	14.9	0.0692	0.12758E-04	0.2405
871	15.35	100.0	46.0	16.1	0.0733	0.12758E-04	0.2405
881	14.50	100.0	44.0	14.9	0.0692	0.12758E-04	0.2405

TABLE XVIII

DATA FOR COMPUTING THE AIR FLOW AT INLET PIPE AND ORIFICE

EXP	AKT	Y	PO	H	GAMAO	QH	QS
223	0.6952	0.5888	14.77	10.8	0.0723	26099.5	7.7384
252	0.6970	0.5895	15.68	4.8	0.0772	16899.9	4.9683
231	0.6967	0.5894	15.32	5.6	0.0753	18462.8	5.3846
231	0.6967	0.5894	15.42	5.6	0.0747	18538.8	5.3236
253	0.6965	0.5894	15.62	5.6	0.0777	18173.0	5.4548
213	0.6964	0.5894	15.43	6.1	0.0766	19094.5	5.6544
233	0.6961	0.5893	15.53	6.8	0.0772	20071.9	5.9638
221	0.6961	0.5893	15.26	6.8	0.0759	20250.8	5.9717
214	0.6959	0.5892	15.23	7.4	0.0762	21076.7	6.2748
211	0.6956	0.5891	15.32	8.5	0.0764	22540.1	6.7147
212	0.6956	0.5891	15.23	8.5	0.0757	22638.6	6.7387
224	0.6956	0.5891	15.12	8.8	0.0748	23177.7	6.9245
232	0.6955	0.5890	15.22	9.2	0.0751	23647.3	6.9429
241	0.6955	0.5890	14.99	9.2	0.0740	23820.7	7.1148
242	0.6953	0.5890	15.13	9.9	0.0752	24506.6	7.3690
251	0.6948	0.5887	15.08	11.9	0.0755	26783.7	8.1055
222	0.6948	0.5887	15.07	12.0	0.0755	26894.5	8.1369
243	0.6943	0.5883	15.25	16.6	0.0744	31806.2	9.4165
391	0.6958	0.5891	14.76	8.0	0.0732	22349.5	6.6464
391	0.6958	0.5891	14.76	8.0	0.0729	22399.3	6.6352
391	0.6958	0.5891	14.75	8.0	0.0728	22417.1	6.6317
391	0.6958	0.5891	14.75	8.0	0.0727	22432.7	6.6288
391	0.6958	0.5891	14.74	8.0	0.0727	22424.1	6.6296
361	0.6967	0.5894	15.33	5.6	0.0747	18538.3	5.3591
361	0.6968	0.5894	15.32	5.6	0.0742	18608.1	5.3405
361	0.6966	0.5894	15.31	5.6	0.0756	18436.1	5.4066
361	0.6966	0.5894	15.32	5.6	0.0762	18355.9	5.4230
361	0.6966	0.5894	15.32	5.6	0.0760	18380.3	5.4213
361	0.6966	0.5894	15.33	5.6	0.0761	18369.7	5.4191
361	0.6966	0.5894	15.33	5.6	0.0761	18371.5	5.4208
361	0.6966	0.5894	15.32	5.6	0.0761	18373.3	5.4213
341	0.6946	0.5885	15.00	14.2	0.0737	29581.5	8.8753
342	0.6946	0.5885	15.00	14.0	0.0739	29331.6	8.8247
343	0.6945	0.5885	15.00	14.4	0.0736	29816.1	8.9214
344	0.6946	0.5885	15.00	14.4	0.0733	29871.7	8.8948
345	0.6945	0.5885	15.00	14.4	0.0736	29816.8	8.9351
346	0.6945	0.5884	15.00	14.6	0.0738	29975.6	9.0094
331	0.6948	0.5887	15.10	11.9	0.0760	26691.5	8.1179
332	0.6948	0.5887	15.10	11.9	0.0760	26689.3	8.1172
333	0.6948	0.5888	15.09	11.8	0.0759	26598.2	8.0804
334	0.6948	0.5887	15.09	11.9	0.0757	26742.1	8.1107
335	0.6948	0.5887	15.08	11.9	0.0755	26783.7	8.1055
351	0.6955	0.5890	14.84	9.4	0.0731	24225.0	7.2561
351	0.6955	0.5890	14.84	9.4	0.0731	24225.0	7.2561
351	0.6955	0.5890	14.84	9.3	0.0730	24116.0	7.1895
351	0.6955	0.5890	14.84	9.3	0.0731	24099.3	7.1910
351	0.6955	0.5890	14.83	9.4	0.0730	24239.4	7.2334
351	0.6955	0.5890	14.83	9.2	0.0729	23994.4	7.1534

TABLE XVIII (CONTINUED)

EXP	AKT	Y	PO	H	GAMAO	QH	QS
421	0.6954	0.5890	15.10	9.2	0.0749	23683.8	6.9653
422	0.6966	0.5894	15.23	5.6	0.0752	18473.3	5.3395
432	0.6968	0.5894	15.21	5.6	0.0734	18710.6	5.3645
433	0.6974	0.5896	15.05	4.0	0.0767	15484.8	4.6672
434	0.6948	0.5887	15.09	11.9	0.0757	26742.1	8.1832
441	0.6956	0.5891	15.12	8.8	0.0748	23177.7	7.0482
442	0.6948	0.5886	14.92	13.1	0.0728	28617.1	8.4790
443	0.6952	0.5888	14.77	10.8	0.0723	26099.5	7.8767
445	0.6956	0.5891	15.12	8.8	0.0748	23177.7	7.0482
447	0.6966	0.5894	15.19	5.6	0.0755	18438.2	5.5600
464	0.6967	0.5894	15.40	5.6	0.0750	18500.2	5.5303
451	0.6955	0.5891	15.16	8.8	0.0752	23119.5	7.1707
452	0.6966	0.5894	15.22	5.6	0.0751	18493.3	5.6236
454	0.6967	0.5894	15.53	5.6	0.0756	18430.3	5.5483
461	0.6967	0.5894	15.36	5.6	0.0744	18577.8	5.6858
462	0.6967	0.5894	15.42	5.6	0.0747	18538.8	5.6089
463	0.6959	0.5892	15.23	7.4	0.0762	21076.7	6.6111
511	0.6966	0.5894	15.30	5.6	0.0758	18402.1	5.4445
512	0.6966	0.5894	15.26	5.6	0.0754	18457.8	5.4238
521	0.6966	0.5894	15.35	5.6	0.0762	18350.2	5.4245
522	0.6967	0.5894	15.36	5.6	0.0751	18491.1	5.3998
523	0.6955	0.5890	14.99	9.2	0.0740	23820.7	7.1148
534	0.6966	0.5894	15.26	5.6	0.0754	18457.8	5.4238
531	0.6964	0.5894	15.43	6.1	0.0766	19094.5	5.6544
541	0.6965	0.5894	15.26	5.8	0.0757	18735.7	5.5494
543	0.6967	0.5894	15.38	5.6	0.0743	18589.8	5.3519
551	0.6967	0.5894	15.38	5.6	0.0743	18589.8	5.3519
552	0.6965	0.5894	15.31	5.6	0.0767	18289.8	5.4514
562	0.6961	0.5893	15.53	6.8	0.0772	20071.9	5.9638
563	0.6964	0.5894	15.43	6.1	0.0766	19094.5	5.6544
611	0.6965	0.5894	15.62	5.6	0.0777	18173.0	5.4548
612	0.6970	0.5895	15.68	4.8	0.0772	16899.9	4.9683
614	0.6966	0.5894	15.28	5.6	0.0757	18411.7	5.4109
624	0.6966	0.5894	15.19	5.6	0.0751	18493.0	5.3948
632	0.6967	0.5894	15.40	5.6	0.0752	18485.8	5.3539
634	0.6966	0.5894	15.19	5.6	0.0751	18491.7	5.4126
641	0.6965	0.5894	15.27	5.8	0.0763	18667.7	5.5204
642	0.6961	0.5893	15.23	6.8	0.0760	20238.8	5.9693
644	0.6966	0.5894	15.22	5.6	0.0755	18442.3	5.3876
654	0.6966	0.5894	15.26	5.6	0.0758	18407.2	5.4281
651	0.6961	0.5893	15.19	6.8	0.0763	20197.0	6.0064
652	0.6961	0.5893	15.26	6.8	0.0759	20250.8	5.9717
663	0.6955	0.5891	15.19	8.8	0.0763	22947.6	6.8245
664	0.6959	0.5892	15.23	7.4	0.0762	21076.7	6.6111
662	0.6949	0.5887	14.78	11.8	0.0740	26940.2	8.0641
661	0.6956	0.5891	15.23	8.5	0.0757	22638.6	6.7387
665	0.6960	0.5893	15.22	7.1	0.0761	20652.8	6.1445
666	0.6948	0.5887	15.09	11.9	0.0757	26742.1	8.1832

TABLE XVIII (CONTINUED)

EXP	AKT	Y	PO	H	GAMAO	QH	QS
711	0.6966	0.5894	15.25	5.6	0.0755	18437.4	5.4278
712	0.6966	0.5894	15.23	5.6	0.0753	18465.8	5.4274
721	0.6965	0.5894	15.56	5.6	0.0780	18141.2	5.3863
722	0.6967	0.5894	15.30	5.6	0.0743	18595.8	5.3544
723	0.6956	0.5891	15.65	8.4	0.0778	22212.6	6.6249
724	0.6954	0.5890	15.10	9.2	0.0749	23683.8	7.0920
725	0.6956	0.5891	15.12	8.8	0.0748	23177.7	6.9245
713	0.6966	0.5894	15.36	5.6	0.0757	18421.8	5.3837
742	0.6966	0.5894	15.42	5.6	0.0763	18341.1	5.3812
751	0.6945	0.5885	15.00	14.2	0.0740	29531.2	8.8902
752	0.6947	0.5887	15.05	12.6	0.0758	27500.6	8.3607
753	0.6966	0.5894	15.37	5.6	0.0760	18383.8	5.3924
754	0.6966	0.5894	15.40	5.6	0.0765	18321.7	5.3906
755	0.6945	0.5885	15.00	14.2	0.0740	29531.2	8.8902
727	0.6944	0.5885	15.06	14.2	0.0764	29054.5	8.9529
801	0.6966	0.5894	15.24	5.6	0.0752	18480.3	5.4307
802	0.6966	0.5894	14.81	5.7	0.0734	18865.9	5.5721
811	0.6966	0.5894	15.32	5.6	0.0760	18380.3	5.4213
821	0.6968	0.5894	15.25	5.6	0.0737	18667.4	5.3660
823	0.6973	0.5896	15.09	4.0	0.0771	15442.1	4.6674
822	0.6947	0.5887	15.05	12.6	0.0758	27500.6	8.3607
832	0.6970	0.5895	15.19	4.6	0.0768	16585.7	4.9634
831	0.6953	0.5890	15.05	9.9	0.0743	24651.6	7.3803
834	0.6960	0.5893	15.58	7.0	0.0775	20328.7	6.0405
841	0.6962	0.5893	14.91	6.9	0.0737	20693.7	6.1341
842	0.6966	0.5894	14.81	5.7	0.0734	18865.9	5.5721
861	0.6954	0.5890	15.04	9.3	0.0749	23802.0	7.1537
871	0.6955	0.5891	15.85	8.7	0.0785	22495.2	6.6922
881	0.6955	0.5890	15.04	9.0	0.0749	23418.7	7.0385

APPENDIX D

SAMPLE COMPUTATION OF PI TERMS

The values of all the variables on which these Pi terms are calculated are listed in Table XIX.

Concentration Efficiency:

$$C_r = \frac{C_o - C}{C_o - [C_e]^*} = \frac{30 - 15}{30 - 7.53} \qquad (122)$$

$$= \frac{15}{22.47} = 0.667$$

Reynold's Number:

$$R_{eb} = \frac{\rho_a \; Q_a [D_{pe}]}{[g_c] \mu_a \; D_b^2} \qquad (123)$$

$$= \frac{0.0716 \times 5.4213 \times 0.56 \times 12}{0.1276 \times 10^{-4} \times 18.0 \times 18.0} = 631.2$$

Fourier Number:

$$F_o = [\frac{K_p (1 - \delta_b)}{C_{pp} \; \rho_b \; D_{pe}^2}] \; \Theta \qquad (124)$$

$$= \frac{0.0664(1 - 0.5) \times 144 \times 1.5}{0.46 \times 20 \times 0.56 \times 0.56}$$

$$= 1.657 \; \Theta = 2.486$$

Temperature Ratio:

$$T_r = \frac{T_a}{[T_p]} = \frac{100 + 460}{45 + 460} \qquad (125)$$

---

*Reference values that were treated constant are written in bracket.

TABLE XIX

VALUES OF PERTINENT QUANTITIES

Units	Pertinent Quantity	Value	Remarks
0	C_d	2.1	Extrapolated from (2)
$lb_m H_2O/lb_m$ dry grain	C_e	0.0753	Interpolated from reported data of Karon and Hillery (1) at NLC+
$lb_m H_2O/lb_m$ dry grain	C_0	0.15 - 0.45 ± 0.02	Artificially rewetted for 24 hours
$Btu/lb_m\,^oF$	C_{pp}	0.46	From curves plotted by Wright (42)
in	D_{pe}	0.56	Calculated for peanut en masse at NLC+
$Btu/(hr\ ft\ ^oF)$	K_p	0.0664	Lab measurement at NLC+
in^2	P	0.246	Average for peanut en masse at NLC+
Btu/lb_m	Q_{pl}	1190.0	Calculated for peanut pods at NLC+ (1)
in^2	S	0.984	Average for peanut en masse at NLC+
^oR	T_p	505.0 ± 2	Maintained during the rewetting process

TABLE XIX (CONTINUED)

Units	Pertinent Quantity	Value	Remarks
in^3	V	0.092	Calculated for peanut en masse at NLC+
in	D_b	12.0 - 21 ± 0.25"	Four beds: 12", 15", 18", and 21" diameter
in	D_c	2.0 - 5.0 ±00.02"	Five Columns: 2.0", 2.5", 3.0", 3.5", 4.0", 5.0"
in	H_b	7.0 - 21.0 ± 0.5"	Controlled during tests
in	H_{cl}	18.0 - 36.0 ± 2"	Measured during tests
degrees	λ	90.0 ± 2^{o}	All beds with fixed cone angles
0	δ_b	0.50 ± 0.03	Measured from test peanuts at NLC+
hr	Θ	0.25 - 3.0 ± 0.02 hr	Time for concentration measurement
$Btu/(lb_m\,^{o}R)$	C_{pa}	0.2404 - 0.2407	Adopted from (16)

TABLE XIX (CONTINUED)

Units	Pertinent Quantity	Value	Remarks
$lb_m ft/(lb_f\text{-}sec^2)$	g_c	32.176	Standard value at sea level
$Btu/(hr\text{-}ft\text{-}^oR)$	K_a	0.01539 - 0.01649	Adopted from (16)
lb_f/ft^2	P_a	30 - 40	Measured during tests
ft^3/sec	Q_a	5 - 10	Controlled during tests
^oR	T_a	550 - 590	Controlled during tests
ft^2/hr	α_{ma}	1.01 - 1.12	Adopted from (16)
$lb_m/(sec\text{-}ft)$	μ_a	0.1257×10^{-4} 0.1334×10^{-4}	Adopted from (16)
lb_m/ft^3	ρ_a	0.0723 - 0.0668	Adopted from (16)
percent	ϕ_a	15 ± 3	Controlled during tests
ft^2/hr	α_{hp}	0.00722	Determined from tests at NLC[+]

TABLE XIX (CONTINUED)

Units	Pertinent Quantity	Value	Remarks
ft^2/hr	α_{mk}	0.0782	True diffusivity of kernel (39) at NLC$^+$
ft^2/hr	α_{mh}	0.1579	True diffusivity of hull (39) at NLC$^+$
lb_m/ft^3	ρ_p	40.0 ± 0.5	Lab measurement at NLC$^+$
lb_m/ft^3	ρ_b	20.0 ± 1	Lab measurement at NLC$^+$
0	τ_{pp}	0.65 ± 0.02	Lab measurement at NLC$^+$
0	τ_{pw}	0.30 ± 0.02	Lab measurement on machine steel
0	τ_{pw}	0.25 ± 0.02	Lab measurement on polyethylene plastic

$^+$Normal Laboratory Conditions: Temperature 77^{o}F, Relative Humidity 50% and pressure 1 Atmosphere.

$$= \frac{560}{505}$$

$$= 1.11$$

Geometry Ratio:

$$G_r = \frac{D_b}{H_b} \tag{126}$$

$$= \frac{18}{14}$$

$$= 1.286$$

Diameter Ratio:

$$D_r = \frac{D_b}{D_c} \tag{127}$$

$$= \frac{18}{3}$$

$$= 6.0$$

Size Factor:

$$S_f = \frac{D_b}{[D_{pe}]} \tag{128}$$

$$= \frac{18}{0.56}$$

$$= 32.143$$

Initial Concentration:

$$I_c = C_0 = 0.30 \tag{129}$$

Prandtl Number:

$$P_r = [\frac{g_c \mu_a C_{pa}}{K_a}] \tag{130}$$

$$= \frac{0.1272 \times 10^{-4} \times 0.2405 \times 3600}{0.01561}$$

$$= 0.7055$$

It will be held constant at this value. For the test temperature range the Prandtl Number varies from 0.707 to 0.702.

Mass Diffusivity Index:

$$M_a = [\frac{\alpha_{mp}}{\alpha_{ma}}] \tag{131}$$

Data on diffusivity of water vapor through peanut pods are not available. However the true and apparent diffusivity of hulls and kernels are known (39). Thus M_a can be computed from this data at normal laboratory conditions.

$$M_{a(Kernel)} = \frac{0.0782}{0.981}$$

$$= 0.0797$$

$$M_{a(Hull)} = \frac{0.1579}{0.981}$$

$$= 0.161$$

Schmidt Number:

$$S_c = [\frac{g_c \mu_a}{\rho_a \alpha_{ma}}] \tag{132}$$

$$= \frac{0.1541}{0.2515}$$

$$= 0.613^{+}$$

Molecular Diffusivity Index:

$$M_{01} = [\frac{\alpha_{mp}\ \rho_p\ C_{pp}}{K_p}] \qquad (133)$$

$$= \frac{\alpha_{mp}}{\alpha_{hp}}$$

Heat diffusivity for kernels and hulls is not available and mass diffusivity for pods is not available. Hence an appropriate value of the molecular diffusivity index cannot be calculated. An estimate of M_{01} can be obtained from the values of α_m(Kernel), α_m(Hull) and α_h(Peanuts).

$$M_0(\text{Hull}) = \frac{0.1579}{0.00788}$$

$$\simeq 20.04$$

$$M_0(\text{Kernel}) = \frac{0.0782}{0.00788}$$

$$\simeq 9.92$$

Molecular Diffusivity Index

$$M_{o2} = \frac{\rho_a\ C_{pa}\ [\alpha_{ma}]}{[K_a]} \qquad (134)$$

$$= \frac{0.0723 \times 0.2404 \times 1.01}{0.01539} = 1.141$$

$^{+}$Based on $g_c\mu/\rho$ = 0.1541 cm^2/sec at 77°F for dry air and α_{ma} = 0.2515 cm^2/sec at 77°F (16).

It varies from 1.141 to 1.092 over the test air temperature range.

Heat Ratio:

$$H_r = \frac{[C_{pp}]}{[C_{pa}]} \tag{135}$$

$$= \frac{0.46}{0.2404} = 1.91$$

Conductivity Ratio:

$$K_r = [\frac{K_p}{K_a}] \tag{136}$$

$$= \frac{0.0664}{0.01539} = 4.31$$

Floor Angle:

$$F_a = [\lambda] = 90^o \tag{137}$$

Particle-Particle Friction:

$$F_p = [\tau_{pp}] = 0.65 \tag{138}$$

Particle-Wall Friction:

$$F_{w(Steel)} = [\tau_{pw}] = 0.30 \tag{139}$$

$$F_{w(Plastic)} = 0.25$$

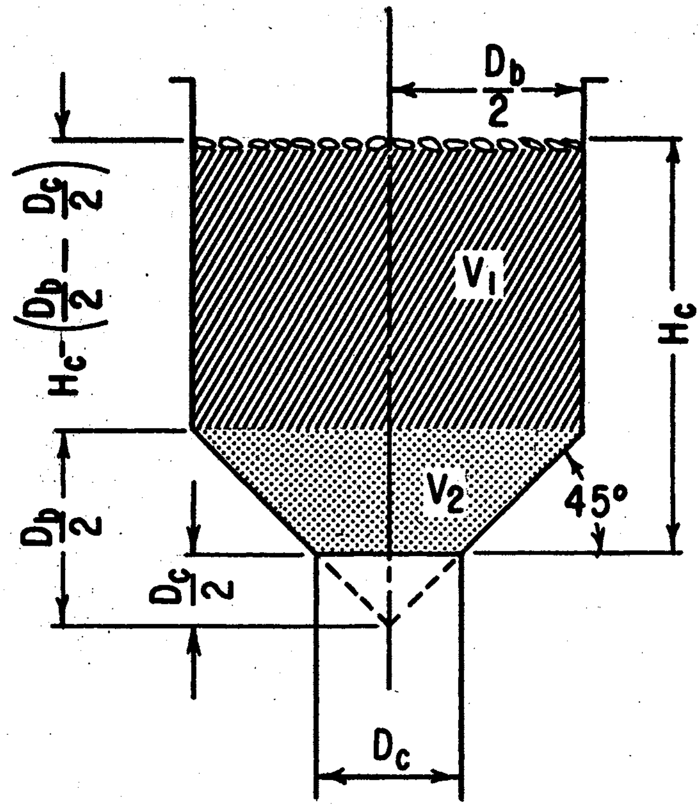


Figure 45. Method of Determination of Bed Volume

Volume of Bed:

$$V_b = V_1 + V_2 \tag{140}$$

$$V_1 = \pi r_b^2 (H_c + r_c - r_b) \tag{141}$$

$$= \pi\ 9 \times 9\ (14 + 1.5 - 9)$$

$$= 1654.0\ in^3$$

$$V_2 = \frac{\pi}{3}\,(r_b^2 - r_c)(r_b^2 + r_b r_c + r_c^2) \qquad (142)$$

$$= \frac{\pi}{3}\,(9 - 1.5)[(9 \times 9) + (9 \times 1.5) + (1.5 \times 1.5)]$$

$$= 759.87\ in^3$$

$$V_b = \frac{1654.0 + 759.87}{1728}$$

$$V_b = 1.4\ ft^3$$

Heat Spent During Drying

The effectiveness of spouted bed dryer can be determined by either of the two bases; they are:

H_v = Total heat used per ft^3 of wet peanuts, Btu/ft^3

H_w = Total heat used to remove one pound of water, Btu/lb_m

The amount of water removed during drying is given by the equation,

$$W_w = \frac{(C_0 - C)}{1 + C_0}\ V\ \rho_b \qquad (143)$$

Total heat present in the drying air can be obtained by summing the sensible heat and latent heat.

$$H_t = 60\ h_a\ \rho_a\ Q''\ \Theta\ V \qquad (144)$$

Where:

$$h_a = 0.24\ T + W(1060.8 + 0.45\ T) \quad (145)$$

W_w = Weight of water removed, lb_m

W = Absolute humidity of air, lb_m water/lb_m dry air

H_t = Total heat present in the drying air, Btu

h_a = Heat content of air-water vapor mixture, Btu/lb_m dry air referred to zero degrees for air, and 32^oF for water vapor

V = Volume of wet peanut at C_0, ft^3

ρ_b = Mass density of wet peanuts at C_0, lb_m/ft^3

ρ_a = Mass density of dry air, lb_m/ft^3

Q'' = Volume flow rate of drying air through grain per minute per cuft wet peanuts, CFM/ft^3

Θ = Time required to lower the concentration of peanuts from C_0 to C, hrs

C_0 = Initial mass concentration, lb_m/lb_m dry peanut

C = Mass concentration at time Θ.

Thus,

$$H_v = H_t/V \quad (146)$$

$$H_w = H_t/W_w \quad (147)$$

APPENDIX E

NOMENCLATURE

Symbol	Quantity	Units
a	Semi-major axis of pods	in
b	Semi-minor axis of pods	in
c	Semi-transverse axis of pods	in
C	Mass concentration at time Θ	--
C_a	Volumetric specific heat of entering air	Btu/in -^oF
C_e	Equilibrium mass concentration	--
C_d	Drag Coefficient	--
C_{pa}	Specific heat of air	$Btu/lb_m{}^oF$
C_{pp}	Specific heat of peanut en masse	$Btu/lb_m{}^oF$
C_r	Mass transfer efficiency	--
C_o	Initial mass concentration	--
D_b	Diameter of bed	in
D_c	Diameter of column or inlet pipe	in
D_r	Diameter ratio, D_b/D_c	--
D_{pe}	Equivalent diameter of peanut en masse	in
F	Feed rate	lb_m/hr
F_a	Floor angle	degree
F_o	Fourier number	--
F_{rb}	Froude number based on superficial velocity of air in bed and particle diameter	--

Symbol	Quantity	Units
F_{rc}	Froude number based on velocity of air in column and particle diameter	--
F_p	Particle-particle friction	--
F_w	Particle-wall friction	--
g_c	Gravitational constant	lb_m-ft/lb_f-sec^2
G_r	Geometry ratio, D_b/H_b	--
H_b	Height of bed	in
H_{cl}	Height of lift of column material	in
I	Modified Bessel's function series, also current in amperes	--
I_c	Initial mass concentration	--
K_a	Thermal conductivity of air	Btu/hr-ft^{o}F
K_p	Thermal conductivity of peanut en masse	Btu/hr-ft^{o}F
L	Length of pods	in
M	Smallest dimension of cassinoid	in
M_a	Mass diffusivity index	--
$M_{01,2}$	Molecular diffusivity indices	--
P	Projected area of peanut	in^2
P_r	Prandtl number	--
P_s	Saturation vapor pressure of water	Kgf/cm^2
Q	Heat input	Watts
Q_a	Air flow rate through inlet pipe, during stable spouting	ft^3/sec
Q_{ai}	Air flow rate through inlet pipe, at incipient spout	ft^3/sec

Symbol	Quantity	Units
Q_{am}	Air flow rate (minimum) through inlet pipe, during stable spouting. Further reduction leads to spout collapse	ft^3/sec
Q_{aq}	Air flow rate through inlet pipe, during quiscent phase	ft^3/sec
Q'	Air flow rate	$ft^3/min-ft^2$
Q''	Air flow rate	$ft^3/min-ft^3$
Q_{pl}	Latent heat of vaporization of peanut	Btu/lb_m
R_{eb}	Reynolds number based on superficial velocity of air in bed and particle diameter	--
R_{ec}	Reynold's number based on velocity in the inlet column and particle diameter	--
S	Surface area of peanut	in
S_f	Size factor, D_b/D_{pe}	--
T_a	Temperature of drying air	^oF
T_c	Critical temperature of air	^oF
T_d	Dew point temperature	^oF
T_p	Temperature of peanut en masse	^oF
T_1	Ideal exit temperature following a wet bulb drying process	^oF
W_w'	Amount of water removed	lb_m/hr
y_1	Thickness of drying layer	in
y_2	Rate of movement of trailing drying edge	in/hr
y_3	Time of departure of trailing drying edge,	hours
y_4	Time for entire mass of nuts to reach one half equilibrium	hrs

Symbol	Quantity	Units
y_5	Final moisture content of bottom layer,	% dry basis
α_{hp}	Heat diffusivity of peanut en masse	ft^2/hr
α_{mp}	Mass diffusivity of peanut en masse	ft^2/hr
α_{ma}	Mass diffusivity of air	ft^2/hr
β	Ratio of orifice diameter to pipe diameter	--
γ	Density of flowing medium	lb_m/ft^3
δ_b	Porosity, ratio of volume of voids to total volume	--
ΔP	Power input to the peanuts from the radio frequency field minus the power input at the same field strength to dry peanuts	Btu/min-in
ΔP_a	Pressure drop, bed inlet to exit, during stable spouting	lb_f/ft
ΔP_1	Pressure drop, bed inlet to exit, during quiescent phase	lb_f/ft
ΔP_2	Pressure drop (maximum), bed inlet to exit, at incipient spout	lb_f/ft
Θ	Drying time	hr
Θ_m	Median diameter bed turn over time, time it takes one peanut to return to the top of a spouting bed when it is placed on top of bed half way between the spout and wall of the container	sec
Θ_w	Wall diameter bed turn-over time, time it takes one test peanut to return to the top of a spouting bed when it is placed on top of the bed at the wall of container	sec

Symbol	Quantity	Units
Θ_r	Random cycle bed turn over time, average time per cycle of a test peanut allowed to make 10 random cycles to the top of the spouting bed	sec
λ	Cone angle	--
μ_a	Absolute viscosity of air	lb_f-sec/ft^2
π	Constnat, 3.14169	--
Π_1	Moisture loss	% d.b.
Π_2	Free mass potential	--
Π_3	Temperature potential	--
Π_4	Air Velocity time parameter	--
Π_5	Electrical power input parameter	--
Π_7	Depth of sample parameter	--
ρ_a	Mass density of air	lb_m/ft^3
ρ_b	Bulk density of peanut en masse in bed	lb_m/ft^3
ρ_p	Solid density of peanuts	lb_m/ft^3
τ_{pp}	Particle-particle friction coefficient	--
τ_{pw}	Particle-wall friction coefficient	--
ϕ	Relative humidity	%

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VITA

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