DESIGN PARAMETERS OF FLUIDIZATION PRINCIPLES FOR FORAGE HARVESTING AND PROCESSING

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ABSTRACT

DESIGN PARAMETERS OF FLUIDIZATION PRINCIPLES FOR FORAGE HARVESTING AND PROCESSING

By Lester Frank Whitney

The value of the annual hay crop in the United States exceeds $2.3 billion, with conservative estimates of 28% loss using conventional harvest and storage practices. To reduce this loss, a different system approach is considered.

The concept involves stripping the leaves from growing alfalfa plants and allowing the stems to grow new leaves for future harvest. The leaves and minor stems would then be rapidly dried utilizing fluidization drying. The design parameters for continuous fluidized drying are the main concern of this research.

Leaf stripping of alfalfa plants was attempted on a limited experimental basis and was found to be feasible. The desirability of leaf stripping as a cultural practice has yet to be established. The possibility of accomplishing leaf stripping by mechanical means has yet to be developed. Such a procedure is necessary because of the incompatibility of fluidizing both stems and leaves in the same operation. Furthermore, seventy percent of the nutritive value of the plant is in the leaves and can be recovered by removal of 50% of the plant water. The drying is enhanced by the more desirable heat and mass transfer properties of the leaf.

Susceptibility of leaves to damage at the high temperatures associated with this dehydration was investigated by single leaf studies and the mathematical description of the time-temperature-damage point was determined. Leaves were dried to equilibrium with air at 500°F in 15 seconds without damage to the product. The drying rates of alfalfa leaves at high temperatures up to 800°F were established as a family of exponential functions.

Flake particle behavior relating the sphericity of the particle to the change in moisture content in a fluidized bed was investigated. This parameter is of vital concern in predicting the fluidizing velocities and voidage of the bed. Single leaf sphericity values were determined using a mercury displacement method developed for this study. The sphericity data were statistically analyzed and this parameter was found to be nearly constant for the total moisture content range. A discernible difference was found between small and large alfalfa leaves.

Mass behavior of leaves in a small diameter drying tower was investigated to relate the mass velocity of the drying medium to a drying index of the leaves under study. This parameter had been previously investigated using pilot process, continuous flow equipment at inlet temperatures above 720°. However, the macroscopic scale of the laboratory apparatus developed for this study yielded similar relationships at inlet temperatures of 200 to 300°F. The small diameter drying tower required the use of leaves smaller than alfalfa. Birdsfoot trefoil, another trifoliate plant, was used in this phase of the study.

Fluidization drying principles were found to be well adapted to forage leading to the conclusion that the system concept was feasible, warranting further research activity. Application of this system might appear as a farmstead process perhaps utilizing unused noncombustible silos or a field alfalfa leaf combine.

Approved Carl W. Hall

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DESIGN PARAMETERS OF FLUIDIZATION PRINCIPLES FOR FORAGE HARVESTING AND PROCESSING

By

Lester Frank Whitney

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INTRODUCTION

The value of the annual hay crop in the United States exceeds $2.3 billion and in Michigan is $60 million. Conservative estimates indicate losses of 28% caused by present harvest, handling and storage practices. Because of these losses and the uncertainties imposed by weather-related factors, the utilization of present systems which result in dried forage as a crop form is being seriously questioned. It appears that radically different system approaches to this problem are needed to minimize crop losses, harvest costs and weather dependence, thus substantially increasing the desirability and efficiency of dried forage systems.

Ideally, such a system should have the following characteristics and requirements:

1. Virtual independence of the weather insofar as drying is concerned.

2. Minimal number of machine components and process operations.

3. Simplicity of operation.

4. Forage product should evolve as one which lends itself to completely automatic bulk handling methods.

5. Forage quality should be high.

6. Adaptable to all sized units--the family farm as well as the commercial enterprise.

7. Initial investment should be economically sound.

8. Costs of operation should be partially offset by a decrease in yield losses now incurred.

In brief, a concept is presented herein along with results of initial investigations which support the feasibility of such an idealized system. It involves the stripping of leaves from the growing alfalfa plant, leaving the standing stems to regenerate new leaves for future harvest. The stripped leaves and minor stems at 75% m.c., w.b., would then be dried immediately to 20% m.c. utilizing fluidization drying principles at high temperatures. The dried leaves could in turn be pelletized and handled in bulk, much as the current practice in handling grains. A process flow diagram illustrates the possibilities as shown in Figure 1 for either a field system, such as an alfalfa combine or a farmstead system, as might be constructed from a noncombustible silo.

The key to success of these systems is the continuous drying process by the fluidization of alfalfa leaves. Application of known physical laws indicates the incompatibility of the simultaneous suspension of stems and leaves. Experimentation has verified that the theoretical terminal velocity required for a dried stem section of

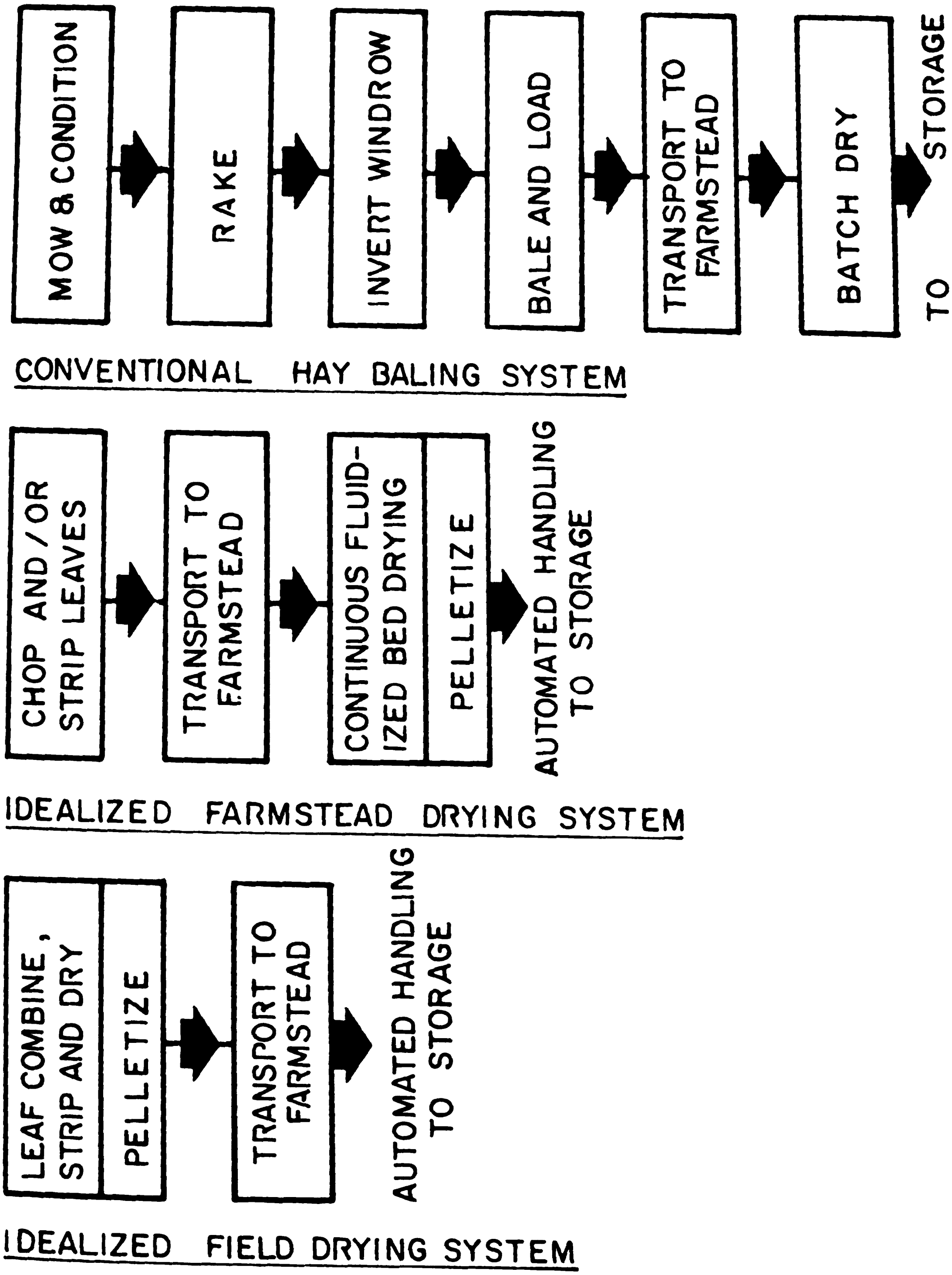


FIGURE 1. PROCESS FLOW DIAGRAM

arbitrary length exceeds that which will vertically transport a fresh-cut leaf. Thus, stems would need to be altered from their natural configuration to be considered in the same drying stage as leaves.

Since approximately 70% of the food value in the alfalfa plant is in the leaves and minor stems, the advisability of drying stems is questioned. Schrenk reports that leaves make up 51.1% of the plant weight at the one tenth bloom stage of maturity. Thus, by removing 50% of the plant water, 70% of the food value is recovered. Moreover, the water in the leaf is far easier to remove, since, among other factors, the smallest dimension is of the order of 0.01 inches while that of the stem is approximately 0.1 inches. Since the time required to dry a particle to a given moisture content increases approximately as the square of the least dimension, according to Van Arsdel (1963), theoretically it should take about one hundred times as long to dry the stem to the same stage as the leaf. The rate of leaf drying will be higher than for the plant as a whole.

The work reported in this thesis is an analysis of this overall concept with research activity specifically directed to the determination of the design parameters of fluidization principles for alfalfa dehydration.

Fragmentary initial findings relative to the cultural practices and plant physiology which relate to such a system are included.

Since this concept is far from traditional methods of forage harvesting, supporting basic information applicable to the system is lacking. Further, it is anticipated that eventual application of such a drying process might encompass other agricultural products as well.

REVIEW OF LITERATURE

The general concept of stripping alfalfa leaves with immediate dehydration in the field or farmstead appears not to have been reported as a specific research activity. However, considerable research has been reported which is applicable to alfalfa dehydration. As a result, many large commercial installations have been built and successfully operated over the past thirty years. However, very little basic information is available on this process for alfalfa which would be adaptable to systems involving leaves only. Further, the cost of dehydration equipment which has been developed for commercial use is prohibitive for smaller farm-sized units.

Such a system might be found by using fluidized bed drying principles. Fluidization has provoked widespread interest in the petro-chemical industry and has resulted in tremendous research efforts in the past twenty years. These research efforts have dealt almost exclusively with non-biological, granular materials. Paralleling this interest, food researchers have developed fluidized bed drying and spray drying processes for a wide variety of agricultural products. Consequently, the process is well defined both mathematically and experimentally insofar as mass and heat transfer relationships are concerned.

Thus, the literature review will be directed to the establishment of the design parameters for fluidized bed drying of alfalfa leaves.

Desirability of Drying Leaves Only

Stripping leaves from the growing alfalfa plant as a possible cultural practice, thereby allowing the plant stems to produce more leaves, is a relatively new idea submitted by Hall, McColly, and Buchele (1959). However, although not supported by research results, there appears to be sound basis for considering this since leaves contain twice as much protein as stems as reported by Schrenk, et al (1959); carotene content and vitamin A are similarly associated. Considering an alfalfa leaf product and basing calculations on information by Schrenk (1959), it can be shown that a relatively constant product of 25% protein might be expected for stages of maturity before full bloom. This is consistent with the requirements of commercial alfalfa dehydrators who prefer to cut at early stages of maturity to get high quality alfalfa with a high percentage of leaves. Present practice results in a product with continuing decrease in protein content as the season progresses, necessitating the blending of low and high protein content material to meet the guarantee specifications. According to Towle (1962), storage for various grades and subsequent blending constitute additional costs and quality control problems, (which might be reduced by considering leaves only). Grinding in preparation for pelleting appears to be unnecessary, which might result in further savings when considering leaves alone.

It has also been reported by Schrenk (1959) that leaves constitute approximately 50% of the weight of the plant. Since leaves and stems have about the same moisture content (with seasonal variations), it can be concluded that by removing 50% of the water that 70% of the protein can be retained in a dry product with 25% protein. This process may make dehydration more justifiable for farm-sized units as well as for the large commercial ones.

The present practice of handling and curing hay results in huge losses. Field losses of 28%, mentioned by Hall (1957), 39%, by Schoenleber (1949), and 40%, by Bohnstedt (1944), are just a few of the references suggesting the magnitudes which add to the undesirability of a dried forage form. Thus, without elaborating on the inherent problems associated with the unevenness of drying of the various plant parts, it becomes apparent that a process which permits the harvesting of fresh cut material by a single pass should result in less losses.

From a physical standpoint, leaves dry much quicker than unaltered stems as reported by Pederson (1960). This is because of the relative magnitudes of the least dimensions as well as the relatively large surface area exposure, in addition to other physiological factors. Leaf thickness dimensions are of the order of 0.01 in. while those of the stems are of the order of 0.1 in. Altering the natural stem configuration changes this relationship. Bhan (1959) demonstrated that the drying rate of stems cut ½ in. long approached that of leaves. He further showed that by increasing the exposed area by splitting the stem, the drying rate is significantly increased. Pederson (1960) demonstrated similar behavior by various other treatments of hay and found that "hard crushed" stems dried faster than leaves.

Other factors which affect the drying rate of leaves depend on diffusion and certain internal mechanisms which are not completely understood. Whitney and Weeks (1963) observed that for high temperature - short time vacuum drying of pre-frozen samples where the cells were killed and ruptured, the leaf literally exploded. Deducing that the stomata behavior might be involved, observations were made using a well known method whereby a silicon cast is made of the leaf epidermis. The cast is then coated with clear fingernail polish. After drying, the resulting peel is observed directly under a microscope revealing the stomata behavior. Alfalfa leaves on the growing plant were "observed" at a time when stomata were thought to be open. After the initial impressions were made, the plant was cut and five minutes later impressions were taken of adjacent leaves when it was found that the stomata were completely closed. This is clearly shown in Figures 2 and 3. It is well known through studies of transpiration by Loftfield (1921) and many others, that the transfer of water from the growing plant is controlled by the stomata cells. From the available information, it is still difficult to predict behavior of stomata because of the interrelation of uncontrolled factors such as light, temperature, relative humidity, wind velocity, and soil moisture. When the stomata are closed, the epidermis is very effectively sealed. From these considerations it appears that the condition of the stomata may influence the transfer of plant held water. This points to the desirability of immediate field drying when the stomata are open, effecting an accelerated mass transfer of water. No information is available relating high temperature drying rates with the condition of stomata cells.

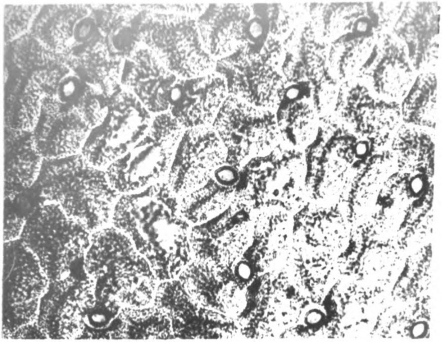


Figure 2. Impression Of Alfalfa Upper Epidermis-1200X
Stomata Fully Open; Growing Plant

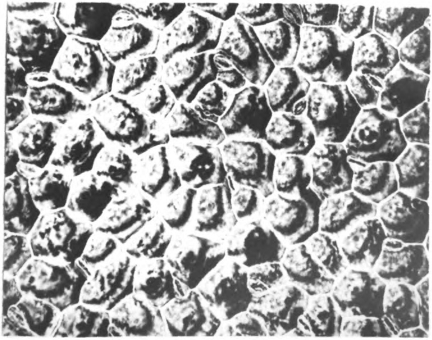


Figure 3. Impression Of Alfalfa Upper Epidermis-1200X
Stomata Closed After Cut Five Minutes

High Temperature-Short Time Drying of Heat Sensitive Materials

Drying rates of alfalfa as well as other plant parts are well established for many temperatures with most research conducted at temperatures below 200°F. Research on drying alfalfa is virtually nonexistent for temperatures at which damage is known to occur although it has been well established that prolonged heating at temperatures above 160°F. results in dry matter loss and/or damage. However, heat sensitive materials, such as alfalfa, are in fact dried at much higher temperatures. Schoenleber (1950) reports inlet temperatures for dehydration of alfalfa at 1000°F. with the outlet at 250-325°F. Schrenk, et al (1959) report inlet temperatures as high as 1500°F. However, the susceptibility to damage of alfalfa at high temperatures and resulting damage point relationship are not reported. Headley and Hall (1963) report a method for determining damage points and drying rates of corn kernels at various high temperatures up to 800°F. Their method of presenting these relationships are particularly applicable to alfalfa drying.

Corder, et al (1956) report on the drying of sawdust at 1200°F. with little tendency to char or burn. The short time exposure of this material to high temperatures permits this process. Particles at high moisture content upon entering a high temperature medium remain at the adiabatic saturation temperature of the gas. For air, this depends on the wet bulb temperature and is usually below 212°F. until the moisture is evaporated on the surface during the constant rate period of drying. Heat evaporates the water after it moves to the surface of the particle by vapor diffusion during the falling rate period of drying and subsequently cools the air. For these processes, by the time the moisture has been removed from the particle moving along with the gas medium, the gas has cooled to such a low temperature that there is negligible damage to the particle before it passes out of the process stage. Subsequent cooling of the particle may be necessary. Contact times vary from a few seconds for the suspension drying of sawdust to three minutes for alfalfa dehydration. The larger particles tend to move more slowly through a given stage while the smaller particles have a higher velocity. The larger particles, which require a longer time to be heated, remain in the heat transfer medium longer. As a result, the various sized particles attain a fairly uniform moisture content upon leaving a process stage.

Fluidized Bed Drying of Alfalfa

High temperature - short time drying of forage is associated with continuous processes usually utilizing direct heating, for which several such systems have been developed. The most predominant system in alfalfa processing according to Schoenleber (1949) is the rotary drum dehydrator which permits a wide variation of particle size for a chopped alfalfa plant. In an effort to increase the drying area, the material is maintained in a quasi-fluidized state by the mechanical rotation of the drum with subsequent tumbling of the material resulting in parallel flow drying. Another continuous process which might be adapted to alfalfa is the fluidized bed dryer. Schrenk, et al (1959) described this process in some detail to which they refer as a pneumatic type alfalfa dryer. Several foreign manufacturers of such a system for which claims are made of successful drying of chopped grasses, alfalfa, sugar beet tops, etc. are cited. A pertinent remark is of interest: "Material having the shape of a flake is ideally suited for drying to low-moisture values in a pneumatic-type dryer because of short distances moisture migrates." This thought has been expressed by several researchers. As a result of this recognition, experimental direct-fired pneumatic dryers, for which many of the operating design parameters have been established concerning the mass velocities, drying tower dimensions, feed rates and temperature requirements, have been constructed and tested at Kansas State University. A relationship between the mass flow rates of the drying medium and the initial and final moisture content of alfalfa has been established for inlet temperatures above 720°F. These results show that as the mass velocity of the drying medium increases, the residence time of the particle decreases and consequently, the amount of moisture removed decreases. This was previously reported by Gregg (1955) in his work on the suspension drying of sawdust.

Schrenk concludes that the pneumatic type dryer shows promise in the field of artificial drying of alfalfa, but that further work is required to determine the proper degree of field chopping and control features to yield a dried product of uniform quality. The apparent need for evaluating the behavior of alfalfa leaves is clearly implied.

Theoretical considerations of fluidized bed drying have been similarly well established both mathematically and experimentally. Leva (1959) has written one of the most recent texts which summarizes the significant works in fluidization. Mass and heat transfer experimental results are presented in semi-empirical form. Over one hundred papers are presented each year in the general area of fluidization. However, non-biological materials which can be idealized as spheres are usually considered. Applicability of these findings to biological materials is not obvious.

Behavior of Fluidized Biological Materials

When considering particles in a fluidized state, (which might be idealized as spheres, i.e. sand, catalysts, granules, and coal dust) it can be assumed that volumes do not change except for such mechanical processes as attrition.

A biological material such as sawdust might also be idealized, since it does not change substantially in shape; however, it does shrink somewhat. Rice (1960) explored the behavior of various shapes and sizes of particles in vertical air streams for which he was able to determine terminal velocities and relative stabilities. Pettyjohn and Christiansen (1948) conducted extensive studies on isometric particle terminal velocities.

The behavior of a particle which changes density, shape, and size, all simultaneously, is not readily idealized. An alfalfa leaf is such a particle. Initially, a leaf might be considered as a thin wafer or disk. When a disk is oriented such that the large cross-sectional area is normal to the stream of fluid, it experiences a drag force for which a particular drag coefficient is obtainable.

Later, as the particle orients itself such that the normal of the large area becomes perpendicular to the stream, the drag coefficient decreases. Thus, based on data by Binder (1943), the drag force can be calculated and shown to be continually changing while the gravitational force remains relatively constant. A resulting oscillating motion can be expected. In addition, the shape has been shown to change quite radically because of wilting, curling, and shriveling--each stage with indeterminate drag coefficients resulting in a completely randomized motion much as might be visualized for molecular movement of a gas. Othmer (1956) reports that particle movement is not entirely random. Particles will rise at the center of the bed where the gas velocity is highest and fall at the wall of the vessel where the velocity of gas is at a minimum. The value of individual particle observation is questioned by Quinn (1963). He suggests a statistical approach to this problem for fluidized bed studies. Persson (1957) reports a similar approach for air separation of grain combine materials. Bailey, Fan and Stewart (1961) predict the instability of a fluidized bed by statistical analysis.

Kennet (1950) followed by Anderson (1951) conducted research on the simultaneous grinding and drying of alfalfa to reduce the particle size before the drying process, to obtain a more rapid drying rate. The principle was demonstrated but resulted in extremely high power costs and instability of the grinding machinery, virtually rendering the process unworkable. However, the mass transfer coefficients were determined.

Kennet (1950) expressed the mass transfer of water from small particles of alfalfa to the carrying medium for a pilot direct-fired dryer as follows:

$$W = \frac{.00014\ G\ A\ V\ \Delta P_m}{P_{gf}\ M_m} \left(\frac{D_p\ G}{\mu}\right)^{1.24} \left(\frac{\rho D_v}{\mu}\right)^{2/3}$$

Where:

W - rate of mass transfer, No. moles/hr.

G - mass velocity, $lb/ft^2/hr$.

a - effective area of mass transfer/unit volume of bed, sq. ft./cu. ft.

M_m - mean molecular wt. of the gas stream, lbs/mole

V - volume of mass transfer space, cu. ft.

ΔP_m - log mean partial pressure difference at the terminals, atmospheres

P_{gf} - log mean partial pressure of the non-transferred gases in the gas film, atmospheres

D_p - diameter of particle, ft.

μ - dynamic viscosity of gas, lb/hr. ft.

ρ - density of gas stream, lb/cu. ft.

D_v - diffusivity of gas in the film, sq. ft./hr.

$\frac{D_p G}{\mu}$ - Reynold's number, dimensionless

$\frac{\mu}{\rho D_v}$ - Schmidt's number, dimensionless

The rapid rate of drying in a fluidized bed was due to the great drying surfaces, and not particularly to the high mass transfer coefficient. This is shown by a statement by Corder (1955) in which he states "...the drying rate of wood is governed by heat transfer rather than diffusion when the wood particle is less than ¼ in. thick. Heat transfer, therefore, is the controlling factor in suspension drying."

Divergence of Velocity Field

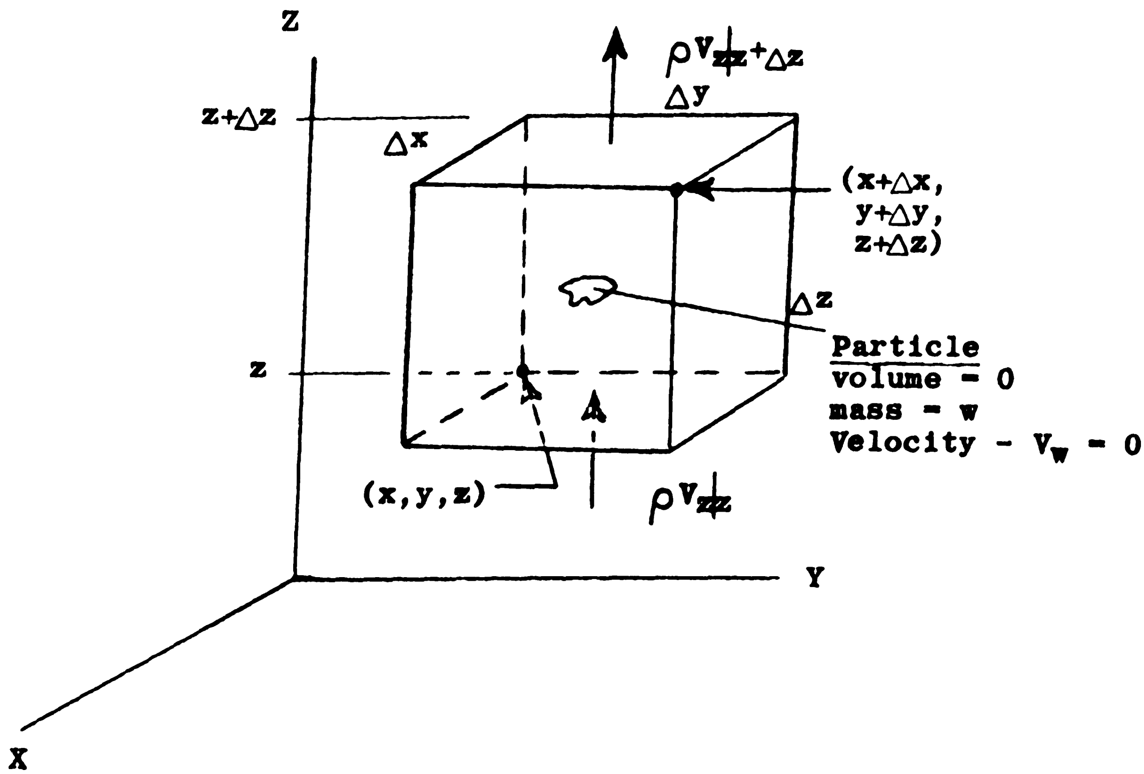
The effects of the size and shape of particles in a fluidized bed are well established. The velocity requirements for such a particle as it loses moisture are not readily understood from the literature. As a particle of a given moisture content is suspended in a vertical stream of hot air, the particle progressively loses moisture, thus becoming lighter. What was once the terminal velocity, later becomes the vertical transport velocity and the particle moves upward until such time as the velocity of the air decreases to a value where the particle will again remain suspended. The particle drying in a tower requires a negatively diverging velocity field according to the definition by Davis (1952). This idea has been implied by Gregg (1955) and Schrenk (1959) noted the sensitivity of velocity to temperature, but did not describe the divergence of the velocity field. For a finite stage of a tower process, a particular residence time would be required as governed by the mass and heat transfer and damage point relationship. Since the velocity controls residence time, it becomes necessary to determine the divergence for proper design. Velocity divergence can be obtained structurally with a tower which is smaller at the bottom. Such a device, referred to as a diffuser, is described by Neel, et al (1954) for a pilot plant model of an air-lift dryer used for potato granules. Schrenk also describes a similar device in their experimental dryer, which is apparently used to separate large stems from the field chopped material before drying further up in the tower.

Negative velocity divergence, as a result of the negative temperature divergence, is desirable from a drying time standpoint and may be of considerable consequence. The temperature decreases owing to cooling of the heat transfer medium, as a result of evaporating water from the leaf surface and by heat loss from the hot tower to the surrounding atmosphere at a lower temperature. This phenomenon is exemplified by stack design in which the carbon particles in flue gases must be expelled out of the stack. Here, a constant velocity, or possibly a positively diverging velocity is required. Smoke stacks are usually smaller at the top to structurally negate the effects of the negative temperature divergence. The diverging velocity is undesirable in this particular case.

The positive divergence due to addition of water vapor as it is evaporated from a moist particle progressing up the tower must be added to the negative divergence produced by the cooling effect on the heat transfer medium. It can be shown that this partially negates the desirable velocity divergence and must be accounted for in a differential equation which considers the laws of continuity, motion and thermodynamics. The treatment is based largely on the approach presented by Bird, Stewart, and Lightfoot (1962).

THEORETICAL CONSIDERATIONS

In order to obtain the differential equation leading to the relationships of momentum, heat, and mass transfer, the law of conservation of mass is applied to a small volume element within a flowing fluid, in which a particle having "zero" volume is suspended. The particle is assumed to have an arbitrary moisture content which is releasing water vapor at the rate $\frac{\partial w}{\partial t}$.



The volume $\Delta x \Delta y \Delta z$ is fixed in space through which a fluid of density ρ and velocity V is flowing and suspending a particle of "zero" volume.

The equation of conservation of mass leads directly to the equation of continuity as follows:

$$\begin{Bmatrix}\text{rate of mass}\\ \text{accumulation}\end{Bmatrix} = \begin{Bmatrix}\text{rate of mass}\\ \text{in}\end{Bmatrix} - \begin{Bmatrix}\text{rate of mass}\\ \text{out}\end{Bmatrix}$$

$$\Delta x\Delta y\Delta z \frac{\partial \rho}{\partial t} + \Delta x\Delta y\Delta z \frac{\partial w}{\partial t} = \Delta y\Delta z \left[(\rho V_x)|_x - (\rho V_x)|_{x+\Delta x}\right] + \Delta x\Delta z \left[(\rho V_y)|_y - (\rho V_y)|_{y+\Delta y}\right] + \Delta x\Delta y \left[(\rho V_z)|_z - (\rho V_z)|_{z+\Delta z}\right] + w \cdot \overset{0}{\cancel{V_w}}$$

Divide right hand side (rhs) and left hand side (lhs) by $\Delta x\Delta y\Delta z$ and take limits as Δx, Δy, Δz approach zero:

$$\frac{\partial \rho}{\partial t} + \frac{\partial w}{\partial t} = -\left[\frac{\partial}{\partial x}\rho V_x + \frac{\partial}{\partial y}\rho V_y + \frac{\partial}{\partial z}\rho V_z\right] + 0 \qquad (1)$$

$$= -\rho\frac{\partial V_x}{\partial x} - V_x\frac{\partial \rho}{\partial x} - \cdots$$

Rearranging terms:

$$\frac{\partial \rho}{\partial t} + V_x\frac{\partial \rho}{\partial x} + V_y\frac{\partial \rho}{\partial y} + V_z\frac{\partial \rho}{\partial z} + \frac{\partial w}{\partial t} = -\rho\left[\frac{\partial V_x}{\partial x} + \frac{\partial V_y}{\partial y} + \frac{\partial V_z}{\partial z}\right]$$

This is the most general case of the equation of continuity with the additional term accounting for the mass release of water vapor by a particle in suspension. Since a compressible gas with changing density and viscosity is considered, the general form must be used throughout.

Similarly, the equation of motion can be written by summing forces on the system:

$$\left\{\begin{matrix}\text{rate of momentum}\\ \text{(acceleration)}\end{matrix}\right\} = \left\{\begin{matrix}\text{rate of}\\ \text{momentum}\\ \text{in}\end{matrix}\right\} - \left\{\begin{matrix}\text{rate of}\\ \text{momentum}\\ \text{out}\end{matrix}\right\} + \left\{\begin{matrix}\text{sum of}\\ \text{forces}\\ \text{on system}\end{matrix}\right\}$$

This can be expanded to indicate the nature of the forces as follows:

$$\left\{\begin{matrix}\text{rate of increase}\\ \text{of momentum per}\\ \text{unit volume - fluid}\end{matrix}\right\} + \left\{\begin{matrix}\text{rate of increase}\\ \text{of momentum per}\\ \text{unit volume - vapor}\end{matrix}\right\} =$$

$$\left\{\begin{matrix}\text{rate of momentum}\\ \text{gain by convection}\\ \text{per unit volume}\end{matrix}\right\} + \left\{\begin{matrix}\text{pressure force}\\ \text{on element per}\\ \text{unit volume}\end{matrix}\right\} +$$

$$\left\{\begin{matrix}\text{rate of momentum}\\ \text{gain by viscous}\\ \text{transfer per u.v.}\end{matrix}\right\} + \left\{\begin{matrix}\text{gravitational}\\ \text{force on}\\ \text{element per u.v.}\end{matrix}\right\} +$$

$$\left\{\begin{matrix}\text{gravitational}\\ \text{force on}\\ \text{particle mass}\end{matrix}\right\} + \left\{\begin{matrix}\text{Drag force on}\\ \text{particle}\end{matrix}\right\}$$

By Newton's Law of Viscosity, the viscous forces acting on the faces of the volume element for laminar flow are:

$$\frac{F}{A} = \mu \frac{V}{Y}$$

That is, the force per unit area is proportional to the velocity decrease in the distance from the location of force F; the constant of proportionality, μ, is the viscosity of the fluid. The force per unit volume is the stress on the surface. The shear stress exerted in the x-direction on a fluid surface of constant y by the fluid in the region of lesser y is designated as τ_{xy}, and the x-component of the fluid velocity vector is V_x. Thus, Newton's law can be written:

$$\tau_{xy} = \tau_{yx} = -\mu \frac{dV_x}{dy}$$

Six expressions for the stresses can be obtained in terms of the velocities:

$$\tau_{xx} = -2\mu \frac{\partial V_x}{\partial x} + 2/3\mu \left[\frac{\partial V_x}{\partial x} + \frac{\partial V_y}{\partial y} + \frac{\partial V_z}{\partial z} \right]$$

plus two similar expressions for τ_{yy} and τ_{zz}. Expressions for $\tau_{yz} = \tau_{zy}$ and $\tau_{zx} = \tau_{xz}$ are similar to:

$$\tau_{xy} = \tau_{yx} = -\mu \left[\frac{\partial V_x}{\partial y} + \frac{\partial V_y}{\partial x} \right]$$

The equation of motion can be written for the components:

$$\frac{\partial}{\partial t} \rho V_x + \frac{\partial}{\partial t} w V_x = -\left[\frac{\partial}{\partial x} \rho V_x V_x + \frac{\partial}{\partial y} \rho V_y V_x + \frac{\partial}{\partial z} \rho V_z V_x \right]$$
$$-\left[\frac{\partial}{\partial x} \tau_{xx} + \frac{\partial}{\partial y} \tau_{yx} + \frac{\partial}{\partial z} \tau_{zx} \right]$$
$$- \frac{\partial p}{\partial x} + \rho g_x + (w.g_x - w.F_{dx}),$$

plus two more equations for y and z components.

The equation of motion for the system can be rearranged with the help of the equation of continuity and substitution for the stress terms; considering the x component as follows:

$$\rho\frac{DV_x}{Dt} + \frac{\partial w}{\partial t}\; V_x = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left[2\mu\frac{\partial V_x}{\partial x} - \frac{2}{3}\mu\left(\frac{\partial V_x}{\partial x} + \frac{\partial V_y}{\partial y} + \frac{\partial V_z}{\partial z}\right)\right] + \frac{\partial}{\partial y}\left[\mu\left(\frac{\partial V_x}{\partial y} + \frac{\partial V_y}{\partial x}\right)\right] + \frac{\partial}{\partial z}\left[\mu\left(\frac{\partial V_z}{\partial x} + \frac{\partial V_x}{\partial z}\right)\right] + \rho g_x$$

plus two more equations for y and z components, where $\frac{DV_x}{Dt}$ is the substantial time derivative. These equations along with the equations of state, the dependency of viscosity and the boundary and initial conditions completely determine the pressure, density and velocity components in a flowing isothermal fluid with a suspended particle. The equations can be expressed in terms of cylindrical coordinates (r, θ, z). Since the z-coordinate is the only one of interest in the simplest case, the equation can be written as follows:

$$\frac{\partial V_z}{\partial t} + V_r\frac{\partial V_z}{\partial r} + \frac{V_\theta}{r}\frac{\partial V_z}{\partial \theta} + V_z\frac{\partial V_z}{\partial z} + \frac{\partial}{\partial t}\; w\; V_z = \rho g_z + -\frac{\partial p}{\partial z} - \left[\frac{1}{r}\frac{\partial}{\partial r}(r\,\tau_{rz}) + \frac{1}{r}\frac{\partial \tau_{\theta z}}{\partial \theta} + \frac{\partial \tau_{zz}}{\partial z}\right]$$

where:

$$\tau_{zz} = -\mu\left[2\frac{\partial V_z}{\partial z} - \frac{2}{3}\left(\frac{1}{r}\frac{\partial}{\partial r}(r\,V_r) + \frac{1}{r}\frac{\partial V_\theta}{\partial \theta} + \frac{\partial V_z}{\partial z}\right]\right.,$$

$$\tau_{\theta z} = -\mu\left[\frac{\partial V_\theta}{\partial z} + \frac{1}{r}\frac{\partial V_z}{\partial \theta}\right],$$

$$\tau_{rz} = -\mu\left[\frac{\partial V_z}{\partial r} + \frac{\partial V_r}{\partial z}\right]$$

The equation of mechanical energy can now be written by forming the scalar product of the local velocity $\overline{V}$ with the equation of motion:

$$\left\{\begin{matrix}\text{rate of increase}\\ \text{in kinetic energy}\\ \text{per unit volume}\\ \text{of fluid and vapor}\end{matrix}\right\} =$$

$$\left\{\begin{matrix}\text{net rate of input of}\\ \text{kinetic energy by}\\ \text{virtue of bulk flow}\end{matrix}\right\} - \left\{\begin{matrix}\text{rate of work done}\\ \text{by pressure of}\\ \text{surroundings on}\\ \text{volume element}\end{matrix}\right\} +$$

$$- \left\{\begin{matrix}\text{rate of reversible}\\ \text{conversion to}\\ \text{internal energy}\end{matrix}\right\} - \left\{\begin{matrix}\text{rate of work done}\\ \text{by viscous forces}\\ \text{on volume element}\end{matrix}\right\} +$$

$$- \left\{\begin{matrix}\text{rate of irrever-}\\ \text{sible conversion}\\ \text{to internal energy}\end{matrix}\right\} - \left\{\begin{matrix}\text{rate of work done}\\ \text{by gravity force}\\ \text{on volume element}\end{matrix}\right\}$$

The increase of internal energy due to the simultaneous heat transfer of the system must be added. The energy balance expressing the first law of thermodynamics is as follows:

$$\left\{\begin{matrix}\text{rate of accumulation}\\ \text{of internal}\\ \text{kinetic energy}\end{matrix}\right\} =$$

$$\left\{\begin{matrix}\text{rate of internal}\\ \text{and kinetic energy}\\ \text{in,}\\ \text{by convection}\end{matrix}\right\} - \left\{\begin{matrix}\text{rate of internal}\\ \text{and kinetic energy}\\ \text{out,}\\ \text{by convection}\end{matrix}\right\} +$$

$$\left\{\begin{matrix}\text{net rate of heat}\\ \text{added by}\\ \text{conduction}\end{matrix}\right\} - \left\{\begin{matrix}\text{net rate of work}\\ \text{done by system}\\ \text{on surroundings}\end{matrix}\right\}$$

The rate of accumulation of internal kinetic energy within $\Delta x \Delta y \Delta z$ is:

$$\Delta x \Delta y \Delta z \frac{\partial}{\partial t} (\rho U + \tfrac{1}{2} \rho V^2) + \Delta x \Delta y \Delta z \frac{\partial}{\partial t} (\tfrac{1}{2} w V^2)$$

where U is the internal energy per unit mass of the fluid in the element.

The rate of convection of internal and kinetic energy into the element is:

$$\Delta y \Delta z \left\{ V_x \ (\rho U + \tfrac{1}{2}\rho V^2)\Big|_x - V_x \ (\rho U + \tfrac{1}{2}\rho V^2)\Big|_{x+\Delta x} \right.$$
$$\left. + \ . \ . \ . \ \text{(two more terms)} \right.$$

The net rate of energy input by conduction is:

$$\Delta y \Delta z \left\{ qx\big|_x - qx\big|_{x+\Delta x} \right\} + \ . \ . \ .$$

where q_x, q_y, and q_z are the x, y, and z-components of the heat flux vector $\overline{q}$.

Work done by the fluid element against its surroundings is accountable in two parts: the work against the volume forces (e.g. gravity) and the work against the surface forces (e.g. bouyant or drag). The rate of doing work against the gravitational force $\overline{g}$ per unit mass is:

$$-\rho \Delta x \Delta y \Delta z \quad (V_x g_x + V_y g_y + V_z g_z) - \cancel{wV_w}^{\,0}(g_x - g_y - g_z)$$

plus the drag force on the particle $+ \cancel{wV_w}^{\,0}(F\ d_x - F_{dy} - F_{d_z})$

Since the particle is assumed to be stationary, there is no rate of work.

The rate of doing work against the static pressure p at the six faces of $\Delta x \Delta y \Delta z$ is:

$$\Delta y \Delta z \left\{ (pV_x)\big|_{x+\Delta x} - (pV_x)\big|_x \right\} + \ . \ . \ .$$

Similarly, the rate of doing work against the viscous forces is:

$$\Delta y \Delta z \left\{ (\tau_{xx} v_x - \tau_{xy} v_y - \tau_{xz} v_z) \Big|_{x+\Delta x} - (\tau_{xx} v_x - \tau_{xy} v_y - \tau_{xz} v_z) \Big|_{x} \right\}$$
$$+ \ . \ . \ .$$

Summing the above expressions for energy and equating according to the first law of thermodynamics, then treating as in the derivation for the equation of continuity, the equation of energy can be obtained in terms of the energy and momentum fluxes. The following equation of energy is in terms of C_V, the heat capacity at constant volume and T, the temperature as it changes with respect to time $\frac{\partial T}{\partial t}$. Appropriate consideration is made of the potential energy change. The expression in cylindrical coordinates is:

$$\rho C_V \left[\frac{\partial T}{\partial t} + v_r \frac{\partial T}{\partial r} + \frac{v}{r} \theta \frac{\partial T}{\partial \theta} + v_z \frac{\partial T}{\partial z} \right] + \frac{\partial}{\partial t} (\tfrac{1}{2} w v^2) =$$
$$- \left[\frac{1}{r} \frac{\partial}{\partial r} (r q_r) + \frac{1}{r} \frac{\partial q_\theta}{\partial \theta} + \frac{\partial q_z}{\partial z} \right] +$$
$$- T \left[\frac{\partial p}{\partial T} \right]_\rho \left[\frac{1}{r} \frac{\partial}{\partial r} (r v_r) + \frac{1}{r} \frac{\partial v_\theta}{\partial \theta} + \frac{\partial v_z}{\partial z} \right] +$$
$$- \left\{ \tau_{rr} \frac{\partial v_r}{\partial r} + \tau_{\theta\theta} \frac{1}{R} \left[\frac{\partial v_\theta}{\partial \theta} + v_r \right] + \tau_{zz} \frac{\partial v_z}{\partial z} \right\} +$$
$$- \left\{ \tau_{r\theta} \left[r \frac{\partial}{\partial r} \left(\frac{v_\theta}{r} \right) + \frac{1}{r} \frac{\partial v_r}{\partial \theta} \right] + \tau_{rz} \left(\frac{\partial v_z}{\partial r} - \frac{\partial v_r}{\partial z} \right) + \right.$$
$$\left. + \tau_{\theta z} \left(\frac{1}{r} \frac{\partial v_z}{\partial \theta} + \frac{\partial v_\theta}{\partial z} \right) \right\}$$

where $q_r = -k \frac{\partial T}{\partial r}$, $q_\theta = -k \frac{1}{r} \frac{\partial T}{\partial \theta}$, and $q_z = -k \frac{\partial T}{\partial z}$

k = thermal conductivity

For the most general case, μ and ρ are functions of T and are not constant which does not permit the usual simplifications. Thus, the general form of the equation of energy has been written which must be used with the added term for the vapor producing effect of the suspended particle. These equations have been based on laminar flow. If turbulent flow is considered, the values in the equation are for "time-smoothed" quantities to which terms must be added to account for the fluctuations about the "time-smoothed" curves.

Applying the energy equation to obtain the differential equation for flow in a round vertical pipe, the z-components only are considered, making simplifying assumptions as follows, neglecting turbulent fluctuations:

$V_\theta = V_r = 0$

V_z not a function of θ $\therefore \frac{\partial V_z}{\partial \theta} = 0$

V_z is a function of r, but if r is large,

$V_z \approx$ constant and $\frac{\partial V_z}{\partial r} = 0$

Similarly for T and μ, $\therefore \frac{\partial \mu}{\partial \theta} = \frac{\partial T}{\partial r} = \frac{\partial^2 T}{\partial r^2} = 0$. Thus, by omitting the inappropriate terms, the energy equation reduces to:

$$C_v\left(\frac{\partial T}{\partial t} + V_z \frac{\partial T}{\partial z}\right) - \frac{\partial}{\partial t}\left(\tfrac{1}{2}\, w\, V_z^2\right) = k \frac{\partial^2 T}{\partial z^2} - T\left(\frac{\partial p}{\partial t}\right)_\rho \left(\frac{\partial V_z}{\partial z}\right) - \frac{4}{3}\mu\left(\frac{\partial V_z}{\partial z}\right)^2$$

where $\rho = \rho(T)$ and $\mu = \mu(T)$

This second order differential equation would need to be solved for V_z and T_z between the limits of the boundary conditions. However, with the complexities of changing ρ and μ, the equation is virtually unsolvable; especially with the vapor producing effect of the particle in suspension. However, the "unsolvability" of the equation is generally implied by reason of the usual requirements for assuming that the density, viscosity, and fluid mass of the system remain constant. As a result, semi-empirical and dimensional analysis approaches have been taken, e.g. Chilton and Colburn (1934), Kettenring, et al (1950) and Sieder and Tate (1936), to mention but a few researchers in this area.

By examination of this equation, several predictions and generalizations can be made:

1) The equation is of second order for both temperature and pressure.

2) The divergence of velocity and temperature play prominent roles in the mathematical description of the process.

3) The addition of the vapor producing effect from a "zero" volume particle is evident and directly influences the effect of the divergence.

4) Turbulent flow, necessitating the addition of terms to account for the fluctuations of velocity and temperature would further complicate the differential equation,

The solution of this equation would probably be best carried out using numerical methods or finite difference methods, but will not be pursued further herein.

It has been assumed that the particle is in a suspended state with zero velocity. This suggests a terminal velocity, the calculation of which is applicable to non-isometric particles. One such empirical formula for non-spherical, isometric particles results from extensive work by Pettyjohn and Christiansen (1948). Stoke's law was modified with an application accuracy of ± 2%, as follows:

$$V_t = \frac{K\,(\rho_s - \rho_f)\,g_c\,d_p^2}{18\mu} \quad \text{(laminar flow)}$$

where $K = 0.843 \log \frac{\phi_s}{0.065}$, Stoke's law shape factor

Application is for isometric particles only with sphericity ϕ_s of not less than 0.60. Sphericity has been found to be a satisfactory criterion of the effect of particle shape on the resistance to motion of particles moving in a fluid. The extent to which it can be applied to non-isometric particles is not known.

Under the effect of highly turbulent flows, the following equation (Pettyjohn and Christiansen, 1948) can be used with an accuracy of ± 4%.

$$V_t = \sqrt{\frac{4}{3}\,\frac{d_s\,(\rho_s - \rho_f)\,g_c}{C_r\,\rho_f}} \qquad (3000 < Re < 200{,}000)$$

where C_r = 5.31 - 4.88ϕ_s, the coefficient of resistance

d_s = spherical diameter (diameter of sphere having the same volume as the particle), cm

d_p = projected diameter of particle, cm

g_c = acceleration of gravity, cm/sec^2

ρ_f = density of the fluid, g/cc

ρ_s = density of the particle, g/cc

μ = viscosity of fluid, g/cm sec

V_t = terminal velocity of particle (terminal velocity), cm/sec

Sphericity is a parameter of considerable interest. It is defined by Leva (1959) as follows:

$$\phi_s = \frac{A_p}{A} \quad \text{(dimensionless)}$$

where A = the surface area of an arbitrarily shaped particle

A_p = the surface area of a spherical particle having the same volume as the particle of arbitrary shape

Since a spherical particle is a body that will provide a given mass with the least surface area, values of ϕ_s will always be less than unity. By applying the basic geometrical relationships, a more convenient form results:

$$\phi_s = \frac{V^{2/3}}{0.205A}$$

where V = volume of particle, in^3; A = area of particle, in^2

While the nature of granular particles does not permit direct calculation of sphericity because of dimensions and uneveness of surface, sphericity of flakes, e.g. alfalfa leaves, is obtainable directly from measurements. Pressure drop tests and displacement determinations are used to obtain ϕ_s for granules. No information is available for alfalfa leaves, especially as sphericity may be affected by a progressive change in moisture content.

Minimum fluid voidage, ϵ_{mf}, is of particular interest because of the relationship of the overall space requirements for a process. The least ϵ_{mf} expected can be calculated from the relation as follows:

$$G_{mf} = \frac{0.005\ D_p^2\ g_c\ \rho_f\ (\rho_s - \rho_f)\ \phi_s^2\ \epsilon_{mf}^3}{(1 - \epsilon_{mf})}$$

where G_{mf} = fluid mass velocity for minimum fluidization, lb/hr. ft^2

However, this expression is derived for particles with ϕ_s far in excess for that which might be expected for a particle such as a leaf. This seriously limits the value of the above correlation. A generalization is offered by the important observation that as ϕ_s decreases, ϵ_{mf} increases. Thus, the population of particles per unit volume is much less dense for a flake than for a sphere. Further, according to Leva, the less spherical the particle, the more interstitial space will be required to permit motion. The diameter of a particle such as a leaf is far beyond that which is referred to in the literature for which the voidage ϵ_{mf} can be predicted.

Fluidization in the classical sense begins with a fixed bed and gradual increase in the flow rate of fluid until the particles become fluidized. It is questionable whether a fluidized state can be induced from a fixed bed of particles of the characteristics of alfalfa leaves without some means of agitation. Thus, it appears that the particles must enter the fluidizing vessel in a suspended state.

Prediction of the point of incipient fluidization is based on the relationships as presented; but for flake particles these relations have been found to be unreliable and beyond the range of the published research results to date.

STATEMENT OF THE PROBLEM

The general objective of this research is to determine the design parameters and supporting information for a continuous drying process for alfalfa leaves which is fulfilled by fluidization drying principles. Since these principles are well established insofar as the behavior of particles and the mechanics of heat and mass transfer for non-biologicals, the specific objectives will be oriented to biological applications. Several aspects will be investigated for which initial determinations will be made as follows:

1. To determine the tolerance and susceptibility to damage of alfalfa plant parts exposed to air flows at high temperatures.

2. To determine the drying rates of alfalfa leaves at high temperatures incidental to the damage point determination.

3. To determine the behavior of alfalfa plant parts in vertical hot air streams as the plant part loses water.

4. To determine the air velocity divergence requirements in a model drying tower which might also provide the required drying time for an arbitrary drying stage.

5. To indicate possible cultural practices and plant physiological factors which relate to the mass transfer of plant held water, and how these may affect the drying process.

PRELIMINARY INVESTIGATIONS

An evaluation of the fluidized bed drying process for any arbitrary material must be preceded by a knowledge of its physical characteristics. Specifically, the dimensions and physical phenomena associated with forage must be considered as a prelude to such a study.

Forage Plant Selection

Two types of plants are in common usage for dried forage forms--grasses and legumes. Neither plant type in a basally severed, unaltered form can be considered as capable of being fluidized in the normal sense. To approach some semblance of becoming fluidized, grasses would need to be chopped finely, still with some degree of non-homogeneity between the chopped stem and leaf blade. Similarly, even greater non-homogeneity is encountered when considering the various parts of a trifoliated plant because the stems constitute one half of the weight. After consideration of the relative merits and value of the various plants and their parts, the broad leaf has been chosen to most nearly approach acceptability for this drying process study. Any plant part, were it chopped or ground finely enough, might be fluidized provided that the adverse affects of juicing and subsequent agglomeration of particles could be overcome. Kennet (1950) was seriously handicapped because of his inability to overcome this difficulty. He partially negated this effect by feeding back dried material.

There are several legumes which are commonly grown for dried forage of which a few are: alfalfa, clovers (white, red, ladino), lespedeza and birdsfoot trefoil. Of these, alfalfa is of the most economic importance, and was selected as the main object of study.

Leaf sizes vary considerably on any given alfalfa plant with a leaf weight ratio (maximum: minimum sized leaves) usually greater than 3:1. An arbitrary classification of leaf size was made, based largely on visual inspection as to population on the plant. Only plants in the pre-bloom to 10% bloom stage were considered to reduce the effects of culture and plant oriented variables. DuPuits variety of alfalfa was selected because of the seedling vigor and quick recovery after cutting. Also, birdsfoot trefoil, which has smaller leaves with a maximum leaf weight ratio of about 1.5:1, was also used because of the miniaturization required for small bore pilot studies.

Figure 4A illustrates an alfalfa plant with widely varying sizes of leaves in which the saw tooth edge of the leaf can be seen easily; Figure 4B shows $\frac{1}{4}$ in. diameter

Figure 4. Alfalfa And Birdsfoot Trefoil Leaves

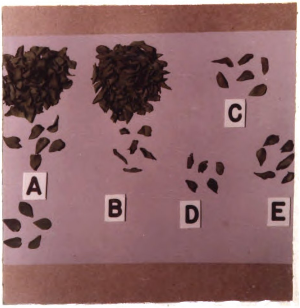


Figure 5. Dried Birdsfoot Trefoil Leaves

leaf disks made with a conventional paper punch. This size of flake particle was found to be most compatible with small bore column drying, however, because of the difficulties in producing large quantities of these small disks, it was decided to use birdsfoot trefoil leaves. Figure 4C illustrates typical trefoil showing smooth edges on individual leaves and the uniformity in size of leaves growing on the plant stem. Leaves as shown were plucked individually from the plant to exclude the minor stem attachment. This eliminated hair like appendages which were found to interfere with the freedom of particle movement in a small bore column.

Plant Part Dimensions

The dimensions of various trifoliate plant parts are listed in Table 1 to provide some index of the relative sizes which were considered. The data obtained were for fresh cut, typical plant types; pre-bloom - 10% bloom stage of maturity. Leaf sizes were dependent on a visual selection based on the most frequently occurring size range. Tabulated values are the numerical average of ten typical plant parts in each category. The one inch stem section was taken at the midheight of the plant.

TABLE 1. PHYSICAL PROPERTIES OF FRESH CUT TRIFOLIATE PLANT PARTS

Leaf Type	Weight, g	Projected Area, in^2	Volume, ml	Thickness, in	Density, lb/ft^3	Surface Area, ft^2/lb
Alfalfa-large	0.060±.006	0.50±.06	0.062±.006	0.0095	41.0	62.6
Alfalfa-medium	0.040±.014	0.32±.12	0.042±.014	0.0095	41.0	62.4
Alfalfa-small	0.020±.006	0.16±.04	0.022±.006	0.0095	41.0	62.4
Birdsfoot Trefoil	0.0164	0.122	0.0251	0.0124	41.7	47.9
Red Clover	0.1557	1.57	0.242	0.0093	41.0	64.9
Ladino Clover	0.0964	0.98	0.149	0.0092	41.2	64.0
Major Stem Type	**Weight, g/in**	**Diameter, in**	**Cross-section Area, in^2**	**Volume, ml**	**Density, lb/ft^3**	**Surface Area ft^2/lb**
Alfalfa	0.0831	0.090	0.00688	0.1042	50.20	10.30
Birdsfoot Trefoil	0.0366	0.059				
Red Clover	0.2058	0.150				
Ladino Clover	0.0402	0.072				

Measurements were obtained by various means, and the dimensions presented are in the raw units commensurate with the particular instrument used.

Weights were obtained using a Mettler analytical balance, accurate to 0.00005 g, shown in Figure 10. The accuracy used in this study was 0.0001 g because the natural moisture loss from a leaf during the time required to make the measurement was usually discernable.

Projected leaf areas were obtained with a planimeter. The leaf was placed under a transparent plastic film and the perimeter was traced three times to obtain an average area, in^2. Because of the saw tooth edge of the alfalfa leaf, an average perimeter was measured along what might be roughly compared to the pitch circle of a gear. Accuracies obtainable were $\pm$ 0.005 in^2.

One other way of measuring leaf areas is to punch out a disk of known area from an object leaf, weigh this disk, weigh the remainder of the object leaf and then relate the weight of the known area to the weight of the unknown. The obvious disadvantage of this is the destructiveness of the measuring technique. It is necessary to keep the leaf intact as volume measurements are made at different moisture contents. One other disadvantage is that if the disk is cut out of a leaf area with veins, the area or volume of the leaf may be distorted. The punch method was not used because of these reasons.

Leaf thicknesses and stem diameters were obtained using a one-inch micrometer with accuracies of $\pm$ 0.0001 in. However, because of the lack of hardness of a leaf or stem, the necessary feel for micrometer measurements was difficult to obtain, and an accuracy of $\pm$ 0.001 was estimated. Extremely delicate handling was required to reduce the possibility of crushing of the leaf cells. Leaves were measured in the non-veinous zones of constant thickness. Stems were idealized as being of round cross section, and measurements were made accordingly.

Volumes at this stage of investigation were determined from the thickness and area measurements. Another method will be discussed later.

Stokes Law Application to Alfalfa Plant Parts

When considering leaves and stems in a vertical stream of air, it appears that leaves might be supported by less velocity than the stem section. Theoretical terminal velocities can be determined from Stoke's law (Binder, 1947).

$$D = \frac{C_d \rho V^2 A}{2}$$

where D = drag force, lbs.

C_d = drag coefficient, dimensionless

ρ = density of fluid, lb/ft^3

A = projected area, ft^2

V = velocity, ft/sec.; V_t = terminal velocity

L = inside diameter of tube, ft.

μ = dynamic viscosity, lb/ft sec^2

W = weight of particle, lb.

At the terminal velocity of a particle, the drag force must equal the weight of the particle:

$$D = W$$

Therefore, the equation can be rewritten:

$$W = \frac{C_d \rho V_t^2}{2}$$

$$V_t^2 = \frac{2W}{\rho C_d A}$$

$$V_t = \sqrt{\frac{2W}{\rho C_d A}}$$

Calculation of the terminal velocities for a typical stem and leaf, both fresh cut and dried were made using this formula. The leaf shape was idealized as a circular disk of constant cross section (the stem as a perfect cylinder), for purposes of calculation and selection of the drag coefficient. The temperature of the air was selected at 300°F in the calculations as shown in the appendix.

A summary of the terminal velocities is as follows:

Alfalfa Plant Part	Stage	Theoretical Terminal Velocity Ft/Min
Leaf	Fresh	71.0
Leaf	Dried	47.0
Stem (1 in. long)	Fresh	174.0
Stem (1 in. long)	Dried	110.0

This demonstrates theoretically that the wet leaf would be vertically transported out of a column at the terminal velocity of the dried stem. Thus, tentatively it can be concluded that the leaf and unaltered stem are incompatible insofar as a given fluidization stage is concerned. Two alternatives might be: 1. to alter the stem by crushing (thus rendering it more nearly the same area-weight ratio as the leaf) or 2. separate the stems from the leaves.

For reasons of simplification, the second alternative was selected for this study, although additional argument has been advanced previously to consider discounting the stems completely.

Preliminary flotation tests in a small bore drying column completely substantiated this hypothesis. The resulting separation of stems from the leaves suggested applications which are in widespread use for other materials and processes. If in a column of vertically rising air (with high temperature heat source at the bottom), the stem was found to drop, subsequent drying and dry matter loss occurred such that the completely charred particle eventually attained an area-weight ratio which allowed it to be transported vertically out of the column. However, the basic objective of the drying process was not met and further consideration was pointless.

Single Particle Behavior in Suspension

The behavior of a flake particle in a vertically rising hot air stream is characterized by a continually changing orientation with respect to the direction of flow. In addition, a decrease in moisture content creates a continually changing area-weight ratio. Both occurrences result in a continual change in terminal velocity requirements.

Qualitative movement of the flake particle could be predicted from the change in drag coefficient for the changes in particle orientation. While a study of individual particle movement is of questionable value, an awareness of this behavior appeared to be worthwhile. In brief, a wildly oscillating movement could be expected with an average velocity of the particle in the upward direction.

To observe this behavior, a small bore glass drying column was used. The location of the particle versus time was recorded using audio-time recording apparatus as shown in Figure 6. The method required the use of a dictaphone as a recorder and an electronic metronome for time indications. The metronome clicks as well as the observed location of the particle were audibly recorded. This record was later transcribed as written data.

Results of these preliminary observations indicate that particle behavior in the center of a column are as expected—i.e., oscillations characterized by large amplitudes and variable periods with eventual movement out of the column. The amplitudes are not constant, varying from a fraction of one inch to ten feet, apparently limited only by the size of apparatus used. Particle behavior in or near the boundary layer is considerably different. The velocity of fluid flowing in a pipe is zero at the inside surface, rapidly increasing in the boundary layer toward the center. For turbulent flow, the velocity rapidly approaches the maximum, such that $V_{Ave} = 0.8 \; V_{Max}$ (Bird et al, 1961). When a particle comes in contact with the reduced velocity zone, it might be expected to drop, since the velocity is below that which will support the particle. This was not observed, however. Not only does the particle change in moisture content and orientation, but it changes in size, and shape, shrivelling and curling at random. Thus, when a curled flake comes in contact with the inside surface, part of the leaf is subjected to relatively high velocities while part is touching the surface. The result can be predicted by Bernoulli's principle for an air-foil section. The resulting lateral force created a frictional force which negated the gravitational force on the particle. In short, the particle may adhere to the inside surface. This was the behavior observed.

For single particles, this adherence is an undesirable phenomenon. Eventually dry matter loss results in product damage even though the temperature at the surface is less than at the center of the stream, and a longer residence time can be tolerated. However, it was found that with sizeable quantities of leaves, a rapid, random, molecular-like motion results. The effects as observed for single particles are considerably reduced and a smaller amplitude, higher frequency (nearly constant) oscillation is evident in all directions in a highly agitated mass. Particles which adhere to the surface are dislodged into the stream and replaced by the other moving particles. A relatively constant velocity of the agitated mass up the column was observed, dependent on temperature differentials and velocities superimposed on the natural draft.

Clusters of leaves joined by minor stems as found in trifoliate plants were observed to behave well in a fluidized state, limited in these studies by the small bore apparatus.

In all cases, the particles were dropped into the air stream from the three foot level. It was found to be extremely difficult to produce a fluidized bed from a fixed bed of flaked particles. For all practical purposes, this method of fluidization would be considered impossible and undesirable because of product damage.

Stripping Leaves As A Cultural Practice

An evaluation of fluidizing (terminal) velocities for forage indicated that leaves would require different process stages than stems. Other information from the literature (Schrenk, 1959) led to the realization that stems could not be dried as economically as leaves. These conclusions supported the suggestion that leaves might be stripped from the stems, possibly as the plant continued to grow in the field.

As a preliminary investigation, this idea was explored on an informal basis. A small plot of alfalfa, variety-DuPuits, was divided into three parts. The experiment was conducted on second crop growth at the pre-bloom stage, the chronology of which is recorded to best illustrate the phenomenom.

On 7/3/62 a third of the plants was manually stripped of leaves by a harsh pulling and squeezing action, leaving the stripped stems standing. The leaves were not plucked singly. Another portion of the plot was cut off leaving conventional two inch stubble; the remainder of the plot was left standing. Unseasonably dry weather prevailed. On 7/6/62, the stripped plants showed signs of leaf recovery with tiny leaves beginning to appear. No growth was evident in the cut section, and the control was in the early stages of bloom.

Continued recovery of the stripped plants was evident on 7/13/62 with remarkable recovery and thick growth of leaves noted. The cut section had sprouted the third crop and was about 2 in. high. The control was well into full bloom with some blossoms turning brown. Continued dry weather approaches drought conditions.

Sixteen days after stripping, the plants had recovered to the point where the first blooms began to appear, with notations made of intent to restrip leaves. The third crop from the cut plot had reached a growth of 4 in. at this time, and the control had gone to seed and was lodging.

Recovery appeared arrested on 7/23 and 7/27 with much smaller leaves noted than control or new growth. Appearance of leaf hoppers was evident with plant damage noted. Bloom stage was not progressing. New growth on cut section had reached height of 8 in.

On July 20, the plants were re-stripped with no apparent growth benefits after July 23. Re-stripping might well have been accomplished a week sooner. The cut section remained at 8 inches, and the control still showed green pigment, but was no longer accounted for.

Upon observation on August 3 (after a heavy rain the previous evening, the first in over a month), the stripped plants showed signs of recovery. New growth in the cut section was up to about 9 in.

The stripped plants continued to show signs of recovery on 8/9 and 8/17 again with small leaves in dense clusters, similar in appearance to the first stripping. The control and cut section had stopped showing signs of growth activity because of the dry weather.

On September 4, the stripped plants exhibited signs of the pre-bloom stage. On September 11 the plant did not show healthy growth signs with continued dry weather prevailing. Leaf hopper damage was evident.

Stripping for the third time was accomplished on September 20, but plants had not progressed much beyond the pre-bloom stage. The cut portion was beginning to show growth activity after some rainfall.

No further growth activity of the stripped plants was noted and the condition of the plants for weathering the winter was extremely poor. An experiment was conducted during the following season with similar results.

It was not the intent of this preliminary study to establish the desirability of leaf stripping as a cultural practice. Quantitatively, leaf production by stripping outproduced the conventionally cut method, and the feasibility of stripping leaves from the growing plant was demonstrated. Obviously, much more research by crop scientists is required to establish the desirability—the details of the cultural practice, and the conditions under which this practice may or may not be justified. In addition, methods for the removal of leaves mechanically would need to be considered and then developed.

Stripping leaves as a prelude to the fluidized bed drying process appears to be highly desirable and should be further explored in a more sophisticated and detailed manner, possibly as a separate research activity.

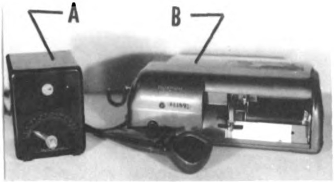


Figure 6. Audio-Time Recording Apparatus

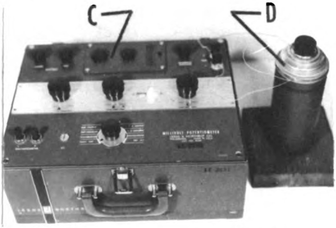


Figure 7. Temperature Indicating Apparatus

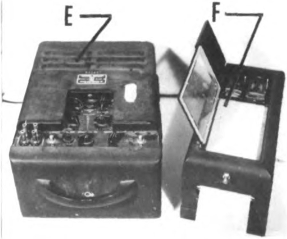


Figure 8. Velocity Recording Apparatus

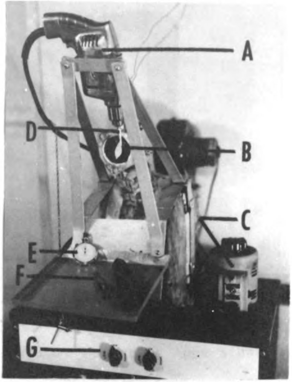


Figure 9. **Single Leaf Drying** Apparatus

Fi ure 10. Analytical Balance

Figure 11. Leaf Volume Measuring Apparatus-Disassembled

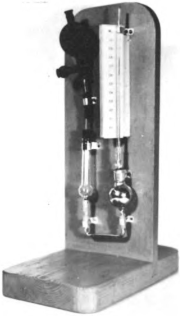


Figure 12. Leaf Volume Measuring Apparatus-Assembled

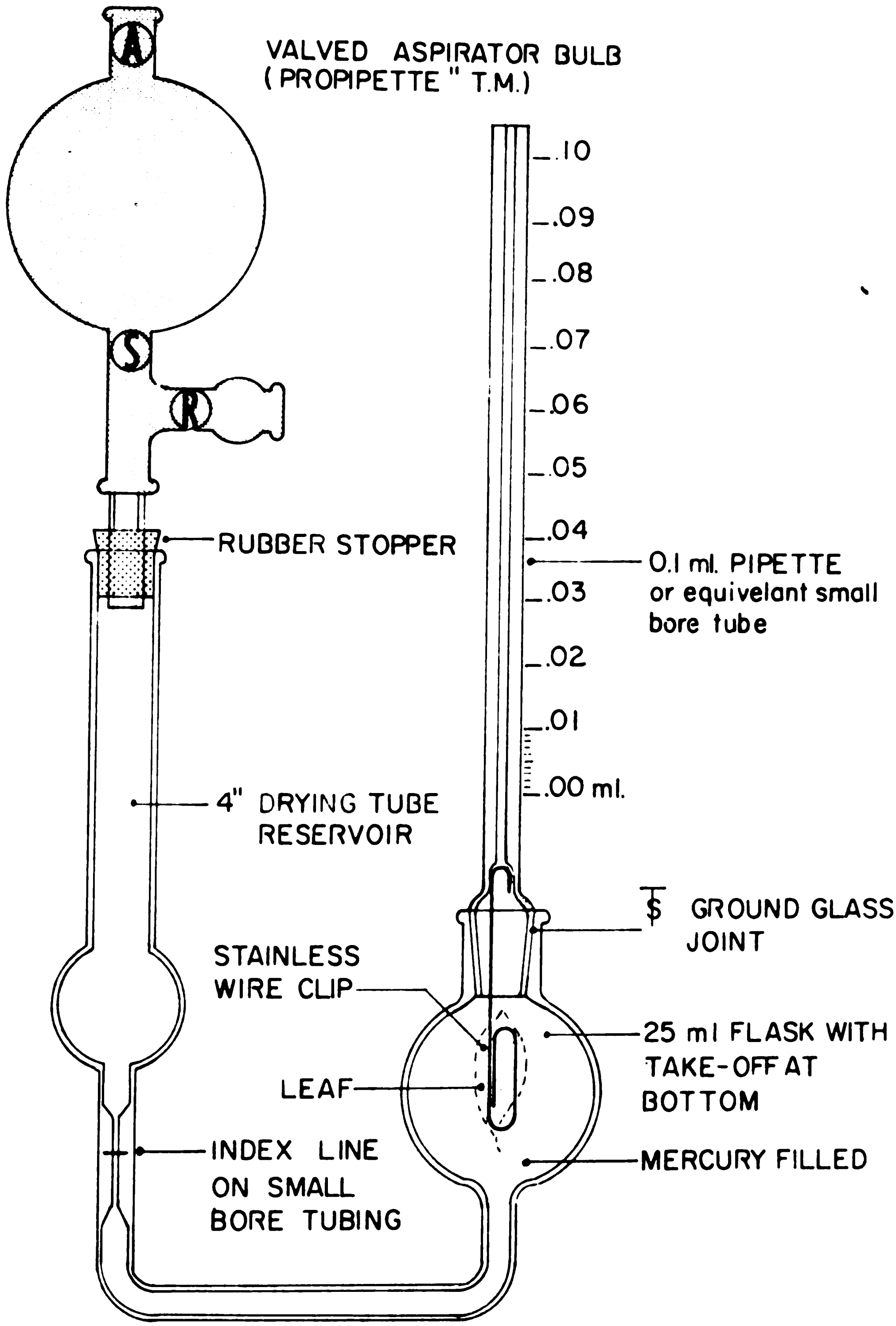
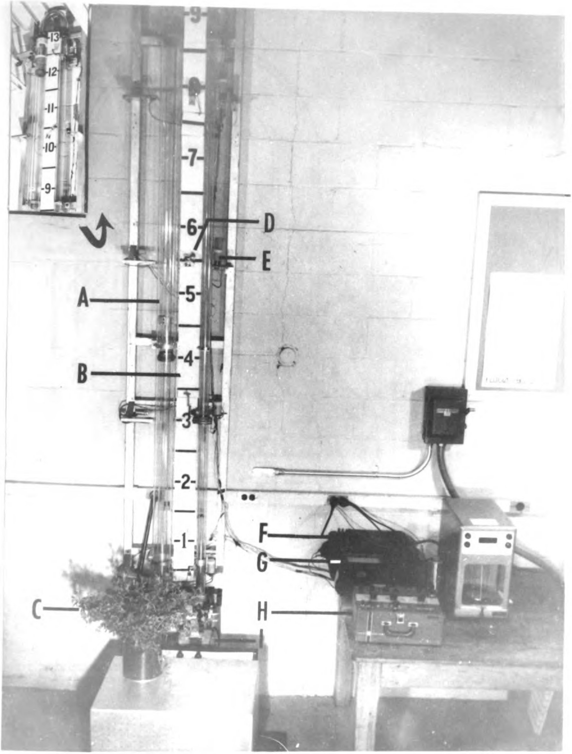


FIGURE 13. VOLUME MEASURING APPARATUS



[illegible] Fluidized Bed [illegible]

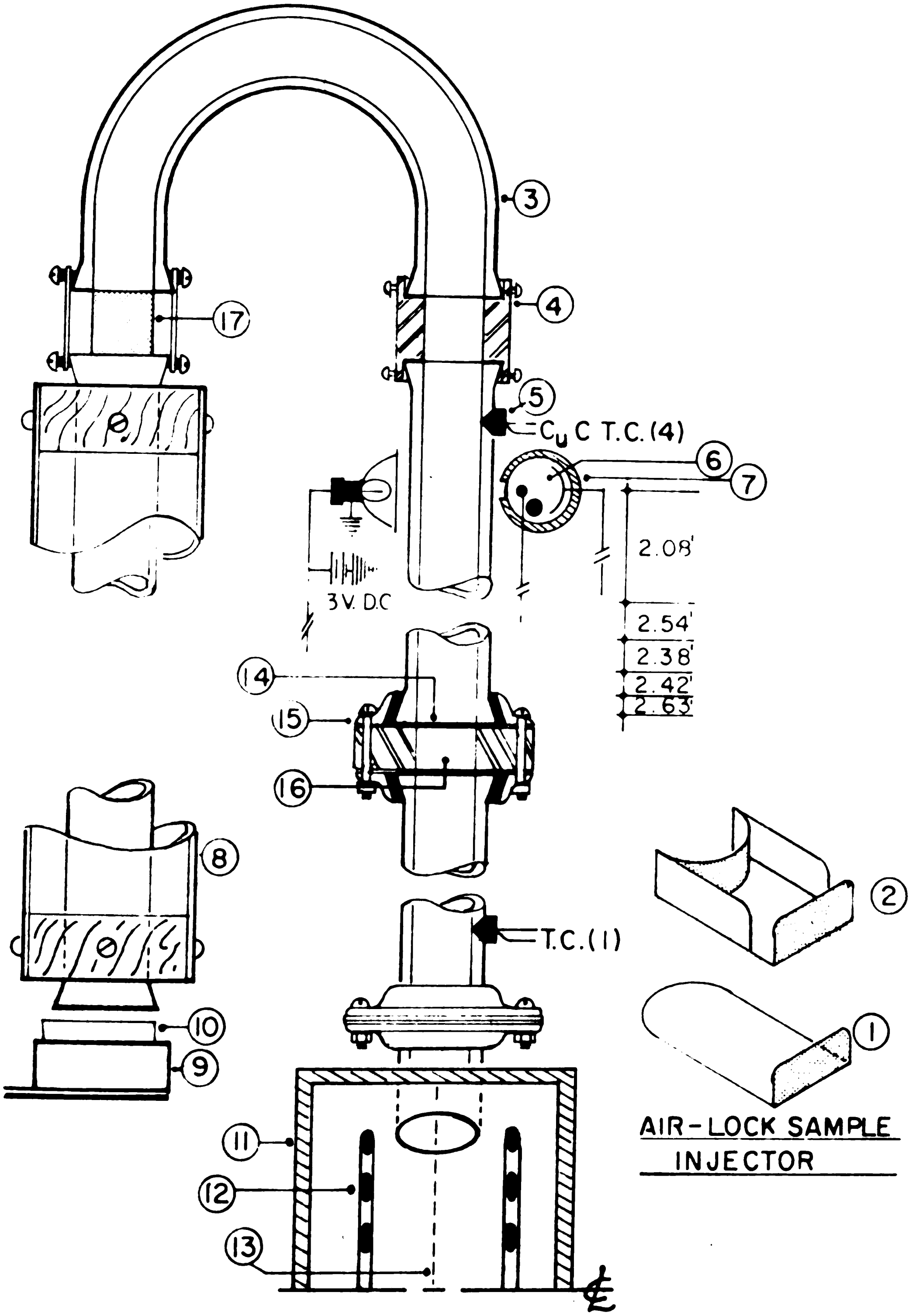


FIGURE 15. DRYING TOWER AND HEAT SOURCE

TABLE 2. MATERIAL FOR DRYING TOWER AND HEAT SOURCE

1. Removable Slide
2. Air Lock Sidewall
3. 1½" I.D. Pyrex Glass and Fittings
4. Stainless Steel Spacer Sleeve
5. Thermocouple Imbedded in Sauereisen Cement
6. #930 RCA Photocell
7. Mailing Tube Shield w/ 1/8" Hole
8. 3-7/8" I.D. Acrylic Plastic Tubing
9. 10 Position Rotary Sample Collector
10. Removable Sample Container
11. Glass Wool Insulation
12. Electric Heating Coils
13. Perforated Plate
14. Asbestos Gasket
15. Aluminum Flange
16. Sample Port
17. 1/8" Mesh Copper Screened Air Outlet

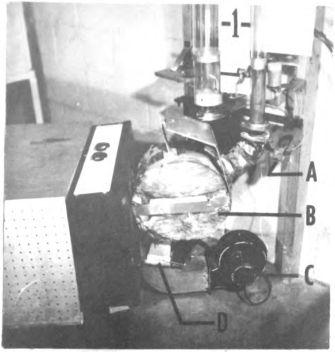


Figure 16. **Drying Tower And Heat** Source
With Sample Port Disassembled

Figure 17. Assembled Drying **Tower And Heat** Source
Showing Smoke Powder Injection

EXPERIMENTAL TECHNIQUES

The broad scope of the system concept for which this research was conducted required a wide range of experimental techniques. While the basic principles of fluidized bed drying have been well defined both mathematically and experimentally, parameters related to forage materials have not been established. The process for flake particles which are heat sensitive and which are subjected to changing moisture content, size and shape has not been reported. As a result, information has been required in several defined sub-phases with apparatus and experimental techniques developed for each as follows:

1. Time-temperature-damage point relationships.
2. Sphericity determinations related to moisture loss.
3. Mass velocity-temperature-moisture removal relationships

Time-Temperature-Damage Point Relationships of Alfalfa Leaves

From the results of the preliminary work, only the leaves of alfalfa were considered in the drying tests. Single leaves were subjected to high temperatures for which the drying rates were determined and the damage points were fixed. The technique and apparatus developed and reported by Headley and Hall (1963) were modified to meet the requirements of alfalfa leaf drying. This apparatus is illustrated in Figure 9 showing the leaf, (B), held by the tip in a small spring clasp (D). This assembly was rotated with the leaf hanging down into a vertical hot air stream. The speed of the universal motor, a ¼ in. electric drill, (A), was varied by means of a variable voltage autotransformer (C).

Heated air was supplied at various temperatures and velocities by varying the speed of a small fan with a variable autotransformer. Two heating coils from a conventional hot plate were placed on edge so that they lay in parallel vertical planes 3 inches apart. In order to aid in converting the radiant energy to convective heating, a perforated steel disk was mounted between the two coils to absorb the radiant energy. The entire assembly was enclosed in a cylindrical sheet metal container and insulated with aluminum foil and glass wool. The electric conductors were external to this assembly for reasons of overheating. Forced air at room temperature was supplied at various velocities through an inlet orifice in the bottom quadrant of the curved surface centering on the burner planes. The air outlet was through an orifice in the top quadrant, then through an attached 90° elbow discharge conduit such that the object being heated could not "see" the intense radiant energy source. Heat was transferred from the radiant energy source to the metal plate; air forced through this assembly was heated primarily by convection heat transfer. Variable temperatures were attained by controlling the voltage applied to the heating coils and by changing the combination of the various segments of the coils by means of the switching controls (G).

Temperatures of the heated air at the outlet were sensed by an iron-constantan thermocouple installed in the center of the hot air discharge such that it too could not "see" the intense radiant energy source. A 3-in. lead wire to the thermocouple formed a probe parallel to the air stream and partially compensated for error from conduction to the outside of the duct. The millivolt output was determined using a Leeds & Northrup manual potentiometer shown in Figure 7C. The reference junction was immersed in an ice bath (7D). Temperature determinations were accurate to $\pm \frac{1}{2}$°F. Calibration of thermocouples was made at 32°F and 212°F.

Air velocities were determined using a vane anemometer; however, the instrument could not be subjected to high temperatures but for a short period. The moisture content of the atmospheric air at the entrance was determined using a sling psychrometer. Time of exposure was determined using a stop watch (9E).

Manipulation of the leaf specimens in the hot air stream required the use of tweezers to handle the leaf (9F), and pliers to open the spring clasp. Time of exposure was taken from the instant the leaf was placed in the center of the air stream. Manipulations were rather cumbersome, requiring as long as three seconds although they did not adversely affect the air flow or exposure of the leaf to the air flow. At ultra high temperatures, where the allowable time of exposure was less than ten seconds, the leaf was fixed to a needle holder by piercing in a loose weave. The holder was then turned by the fingers to provide the desired rotation. The leaf could then be inserted into and out of the air stream in approximately ½ second.

Damage Point Tests

Each test was run at constant temperature and constant air flow. This required a steady state condition for the heating apparatus. To achieve this, an equilibration period of approximately two hours was required. Since the apparatus was dependent on an electrical source, any slight fluctuation in voltage would result in a slight change in temperature.

Discharge temperatures depended on the rate of air flow through the heater for any given power input. To maintain a constant discharge velocity at all temperatures, this required a variable mass velocity at the inlet. All tests were run with an air flow of approximately 60 fpm, the theoretical fluidizing velocity for fresh cut leaves.

The leaf was rotated in the heated air stream at about 45 rpm. This simulated the action that a leaf might undergo in a freely suspended fluidized state. Stationary leaf drying tests did not prove to be satisfactory for two reasons. 1. The downstream side of the leaf was shielded from the air blast, and was not exposed to the same heat transfer condition; and 2. The change in Young's modulus of elasticity (as the leaf progressed from the fresh cut- to the wilted - to the dried) allowed the leaf to be affected by the vertical air flow and to curl up similar to the action of a bimetal thermostat.

Leaf samples were plucked individually from the plant at the time of the test. Field plants were cut at random and kept fresh by immersing the stems in water to reduce the effect of wilting in the laboratory. All minor stems were excluded from the leaf proper.

After procuring the sample, it was weighed on the precision analytical balance (Figure 10) to obtain the wet weight and immediately subjected to the test. After the drying test, it was weighed again to obtain the dried weight. Subsequent drying of the single leaf for a prolonged period at the test temperature was accomplished until no further moisture loss was noted. Final weighing established the bone dry weight.

Time of exposure to cause visible damage was the basic objective of the test. To determine this, an initial period was selected which was estimated to not damage the leaf. The tests were run for a given leaf to a particular moisture content. Subsequent leaves were dried during periods which were gradually increased by 1 second intervals. When the time of exposure was established such that all moisture was removed, further exposure to the drying medium would result in dry matter loss and eventual browning over the entire leaf. This point was one criterion of the damage point definition.

At extremely high temperatures—above 500°F, the leaf was observed to char at the tips and edges. Until the damage points were approached, replicated drying tests were not conducted. In the region of the damage point, as many as ten replicates were made to fix this point, allowing for the variation in moisture content of the leaves, effect of leaf position on the plant, size of leaf and individual plant variations. At extremely high temperatures, the charring point was quite obvious, requiring as few as five replicates.

Four hundred and twenty-five tests at 13 temperatures ranging from 281° to 819° were conducted to provide the data for this phase of the research.

Sphericity—Moisture Content Relationships

Particle sphericity has been designated as a parameter of considerable interest in fluidized bed drying. However, for flake particles the usual methods for determining this criteria are ineffectual. The problem increased in complexity when considering a flake particle with changing moisture content.

The necessary information to determine the sphericity is revealed by the relationship:

$$\phi_s = \frac{V^{2/3}}{0.205A}$$

Measurement of the projected area of a leaf by a planimeter has been described in an earlier section. The total area, A, for the particle would be twice the projected area added to the area of the edge around the perimeter. The perimeter area is of second order magnitude in comparison to the total surface area and was neglected.

Volume indications would be possible using area and thickness data if they were reliable. Because of the veinous structure of the leaf, an average thickness is difficult to obtain; particularly so for the subtle changes when the moisture content is gradually reduced.

As a consequence, another technique was considered using Archimedes principle of displacement. The requirements for the displaced liquid were such that a leaf would be virtually unaffected by absorption, adsorption, or chemical reaction. Kerosene had been used by Kennet (1950) for alfalfa density determinations. Single determinations were required and then the material was discharged with little need for concern with post measurement adhesion. However, with the alternated volume determination and drying tests, this liquid would not lend itself to this procedure. As a consequence, mercury was selected.

Criteria for the volume measuring apparatus were: 1. easy access with an opening large enough to accommodate a leaf without crushing or curling; 2. a range of measurements estimated to be from .005 to .10 ml; 3. simplicity of operation to effect relatively quick reading. No commercial sources for this specialized equipment were found.

Two displacement techniques were considered. The first attempt made use of an open vessel filled to the extreme limits of the meniscus such that the slightest addition resulted in a break in surface tension. The volume spilled into a receiving receptacle was supposedly equal to the volume of the object being measured. For relatively large volumes, this method was reasonably successful. But for extremely small volumes, such as a single leaf with minute changes in volume from a change in moisture content, the method was entirely unsatisfactory.

The method arrived at consisted of immersing the leaf in a vessel sealed with a tightly fitting stopper out of which the displaced liquid could be volumetrically measured to the accuracy required. The apparatus was designed and developed with the use of standard chemical glassware, altered and joined by glass blowing techniques. The finished apparatus is shown in Figures 11 and 12. A schematic diagram, Figure 13, shows additional details of construction.

A 25 ml flask with a standard tapered ground glass opening at the top provided for a receiving vessel with the required ease of access to accommodate a leaf. A take-off at the bottom was added, then fused to 3/16" glass tubing bent at two right angles forming a "U", into a short length of small bore precision glass tubing (0.001 mm dia.). At the top of this leg of the "U", a reservoir (4" drying tube) was fused to form a monolithic glass assembly. Early models were joined using "Tygon" plastic tubing but proved unsatisfactory.

Into the ground glass mouth, a mating hollow stopper was fitted, out of which another length of 0.001 mm tubing was fused so that this stem provided the means for measuring the volume. Actually, a 0.1 ml pipette was used, which provided the built-in calibration required. Further subdivision was made by dividing the 0.01 ml division into ten parts so that readings of 0.001 ml could be discerned.

A small stainless wire clip was bent to fit snugly into the hollow stopper so that when the stem was removed, the clip came out also. This assembly to which the leaf has been fixed can be seen in Figure 11 lying alongside the apparatus. The ground glass seat provided for a precision placement to an accuracy of $\pm$ .001 ml.

The scheme of operation required that the mercury filled apparatus be pumped out of the reservoir under pressure until one leg was indexed to a line on the small bore tubing. The quantity of mercury in the system was adjusted such that the volume would show on the leg of the measuring stem out of the receiving vessel. A precise register was found to be unimportant, providing that the initial level was noted. The system would then be allowed to seek its own level, about half way down into the flask and the stem assembly removed. The leaf whose volume was to be measured was clipped into position, held at the bottom of the leaf so that natural buoyancy tended to keep the leaf in a distended position. The stem was refitted into the joint, and the level of the mercury was again indexed as before. Because of the added displacement of the leaf, the level of the mercury in the measuring stem rose appropriately so that the difference in levels was a direct measure of the volume.

The liquid levels were manipulated by a hand squeezed aspirator bulb fitted into the mouth of the reservoir. First models employed the use of a stop cock in conjunction with a conventional aspirator bulb to hold the liquid levels while readings were taken. However, a much simplified maneuver was possible with the use of a valved aspirator bulb ("Propipette" T.M.). By pressing the various valves marked S, R and A with the fingers while the hand squeezed the bulb, an effective control of the system was possible after much practice.

The instrument was surprisingly effective and capable of detecting extremely small changes in volumes. Two difficulties developed in the measurement of leaves. Repeated measurements inevitably contaminated the mercury such that a coating of dirt appeared on the glass parts. This was particularly troublesome in the small bore tube sections, culminating in a separation of the mercury. This required the periodic removal of all the mercury and complete cleansing of the glassware and the mercury. A gold ring mercury cleaner was found to be particularly helpful in this periodic purge, since the dirt was non-metallic and could be adequately removed by this method.

A second, more serious difficulty, arose from the effect of the relatively high hydrostatic pressure developed by the head of mercury in the measuring stem. This was variable in height, averaging about six inches Hg. This is approximately 7 ft. H_2O and unquestionably affected the leaf cells by crushing them to a small yet underdetermined degree. However, the measured volumes very nearly checked with the calculated volumes from the area-thickness data. The method required considerable delicacy, especially for leaves at low moisture content.

Sphericity Determination Tests At Various Moisture Contents

The objective of these tests was to determine the sphericity of the leaf, and how the sphericity was affected by a continual reduction in moisture content. A series of tests were run on various sizes of alfalfa and birdsfoot trefoil leaves. Samples were procured as before, but with ten replicates examined simultaneously. The procedure follows.

A leaf was plucked from the plant, weighed on the analytical balance; its area was determined by means of three planimeter tracings; its volume was determined as outlined above. The leaf was removed using tweezers taking care to remove any adhering mercury droplets. The leaf was reweighed to assure that no mercury had clung to it and was then placed in a drying receptacle with a screened bottom. This receptacle was subjected to a convective heat source at approximately 160°F. Slight pressure was applied by a small wooden block placed on the leaf while drying to prevent it from curling as it dried. Thus, upon removal after a predetermined period, the procedure could be repeated. The flat configuration was particularly critical for area determinations, especially at the lower moisture contents when the leaf became extremely brittle.

A second leaf was similarly treated and so on until at the end of the 10th leaf, by which time the first had reached a lower moisture content level at which the whole procedure was repeated. The moisture level was brought down to the equilibrium moisture content at 160°F. This level was attained in six steps, with measurements made at each step.

It is interesting to note that volume measurements were made even with the extremely brittle dried leaves without fracturing the leaf. Extreme care in handling was exercised, but the submersion of the leaf in mercury apparently was so gentle that no adverse affects were noted.

Two hundred and seventy-three volume determinations on 60 leaves were made for moisture contents ranging from 300% d.b. to nearly zero moisture content to provide the data for this phase of the research.

Mass Velocity-Temperature-Moisture Removal Relationships

Certain operating parameters of fluidized bed drying of alfalfa, referred to by Schrenk (1959) as a pneumatic type alfalfa dryer, have been established from the pilot process standpoint. The parameters have been established for the chopped whole plant substantiating that stems must be removed at some stage in the process. The behavior of leaves only and their fluidizing velocity requirements as they lose moisture remained to be established.

To observe this behavior, a transparent drying tower was considered to be ideally suited for these studies. Since the temperatures of the drying process were to be considerably higher than the melting point of Acrylic plastic, Pyrex glass pipe was selected as the experimental tower. This equipment is readily available with expanded ends to accommodate standard metal flanged joints; glass fittings such as elbows, Tees and "U" bends are standard equipment. The 1½ in. I.D. tubing was selected for reasons of compatibility with the heat source apparatus available from another phase of the research. The apparatus was designed to comply with laboratory techniques as compared to pilot plant procedures. Available ceiling heights in the drying laboratory limited the effective height of the drying column to 13 ft.

The completely assembled apparatus is shown in Figure 14 with clarifying details shown in Figures 15, 16 and 17, and Table 2.

The heat source previously described was positioned so that the discharge had a vertical orientation. The inlet was fitted with a variable rectangular area orifice. A sliding valve in the inlet duct was provided with a vernier screw adjustment (Figure 16D). The outlet was fitted with a ¼ in. dia. copper tube bent 90° so that smoke could be injected through an orifice in the side of the duct in the direction of flow (17G). Copper mesh screening, 1/16 in., was fitted at the discharge to prevent leaves from accidently dropping into the heat source chamber. Conventional fluidized bed bottoms are of porous vitreous clay, but this is for purposes of small diameter particles and was not considered for this application.

Aluminum glass-pipe flanges permitted tight fitting joints. The assembly was altered slightly so that asbestos gaskets were substituted for rubber ones normally used. At the three foot level joint, an air lock sample injector was installed. The sample injector is shown disassembled at the bottom of the drying tower (Figure 16A). There are three essential parts to this assembly: 1. the aluminum sample port, 2. the sheet metal sliding air valve, and 3. the air lock side wall. These parts are shown as items

No. 16, 1, and 2 in Figure 15. The assembly was bolted between two flanges. Operation of the air lock required the hand assembly of No. 1 and 2 forming a scoop into which the sample was placed. This loose assembly was inserted into the sample port and No. 1 was withdrawn leaving No. 2. in place to form the inner surface of the tube. Thus, the sample became fluidized immediately without blowing back out through the sample port. The assembled sample port is shown in Figure 17E.

The drying tower was completed with the addition of a ten foot section of pipe. At the top, a 6 in. U bend was installed to retrieve the dried sample. A return pipe was installed so that the sample after drying was guided to the sample collection containers below. An opening to provide for the exhaust of the moisture laden air was installed at the base of the U bend on the down leg. Exhausting air in the up leg was impossible because the reduction in velocity would be such that the dried product could not be carried up over and into the return line. The exhaust opening was made from 1/16 in. screening fixed in a cylindrical frame such that the free area was twice that of the cross sectional area of the pipe. A machined stainless pipe spacer on the up leg balanced the dimensional requirements of the system.

Since the apparatus was constructed as a semi-permanent fixture in the drying laboratory to accommodate future research activity, it was decided to partially insulate the down leg by encasing the glass pipe in a 3-7/8 in. I.D. acrylic plastic jacket 1/8 in. thick (Figure 14A). This would alter the heat transfer characteristics of the drying tower and provide for further variation in air velocities when the roles of the two legs were interchanged by merely interchanging the heat source and U bend fixtures.

Dried samples were collected in 10 paper containers fixed on a rotary disk holder. By this method, samples could be collected at various times to determine the drying rates.

Instrumentation of Drying Tower

Instrumentation of the tower provided for temperature and velocity determinations. Copper-constantan thermocouples (No. 24 wire) were imbedded in the glass walls at the 6 in. level and at four foot intervals thereafter. Holes were drilled into the glass walls allowing for the T.C. junctions to be mounted just at the inside surface. Permanent mounting was effected with the use of Saureisen cement, a liquid paste which dried to a heat resistant ceramic. The thermocouple leads were connected to a rotary switch leading to the potentiometer (Figure 14H).

Velocity measurements were made extremely difficult by reason of the low fluidizing velocity requirements, and the high temperatures of the flowing fluid. After exploring many possibilities, smoke injection was selected as the device by which velocity measurements could be most quickly and accurately made. The original scheme involved two #930 RCA photo-electric cells mounted at the top and bottom of the drying tower so that a light beam from a D.C. lamp would shine through the glass onto the sensing element. Any interception in the light beam would cause a signal to be transmitted through an amplifier and appear on a constant chart speed oscillograph. This apparatus group is shown on Figure 8 (E and F). An acid vapor smoke gun was used in early trials, but upon the addition of heat, the vapors were found to not condense sufficiently to be detected by the photocells. As a result, a black powder, "Norit A"—an activated charcoal product, provided the most effective "smoke".

Theoretical considerations predicted the prominent role of a velocity divergence, and this in fact was observed by the noticeable deceleration of the smoke plug in the drying tower for heated air flows. Yet, when the velocity for an isothermal-unheated air flow was observed, there was no perceptible deceleration. As a result, it was decided to increase the number of photocells to four and finally to six to provide five separate velocities along the 13 ft. drying tower. From this information, the velocity divergence $\frac{\partial v}{\partial z}$ could be obtained from a plot of the velocity versus axial distance.

Several troublesome problems arose when the number of photocells was increased from two to six, which are worthy of note for future users of this system. The electronic circuitry best suited for this type of system is a parallel connection of the tubes, as shown in Figure 18. However, as the number of cells was increased, the total resistance of the circuit was decreased and the signal became less and less pronounced requiring greater amplifications. Signal output was improved by shielding the photocell with a small piece of mailing tube, covered on the top, with a 1/8 in. hole in the side. The shield could be rotated to increase or decrease the light intensity so that the system could be balanced. Even with these measures, the total amplification required was in the order of 10^6:1. Pick-up of stray signals was particularly troublesome at this level and even with the most elaborate precautions taken, e.g. metallic shielding of all wire leads, 60 cycle hum was difficult to obliterate. Success was finally achieved after a tenacious trial and error effort which yielded the correct combination of capacitors in parallel and in series with the primary circuit.

Further difficulties in the behavior of the powder smoke signal became apparent with the addition of more photocells. To more clearly understand these problems, consideration of the nature of the signal must be made.

The volume of the powder injection was approximately 0.025 cu. in. mixed with 4 cu. in. of air as the propelling medium supplied by an aspirator bulb squeezed by hand (Figure 17H). The injection velocity was calculated at 13 ft/sec. This was designed to approximate the fluidizing velocity. The plug of smoke emerged as a fairly well defined cylinder about 4 in. long. A particle size analysis of the powder was made and it was found to contain 81% by weight of particles measuring less than 0.05 mm. Terminal velocities of the powder were calculated by Newton's equation, verified by means of a nomograph (see appendix) and observed in a refracted light source to be approximately 0.1 ft/sec. with close agreement.

As the smoke intercepted the first photocell, a clear sharp signal appeared on the oscillograph; paper speed was constant at 25 cm/sec. However, as the smoke progressed up the tower, particles in the boundary layer decelerated sharply, some falling downward, as the bulk continued upward. The effect was that the signal trailed off, becoming weaker as the front continued upward, and finally towards the top of the tower, the signal to two photocells was affected.

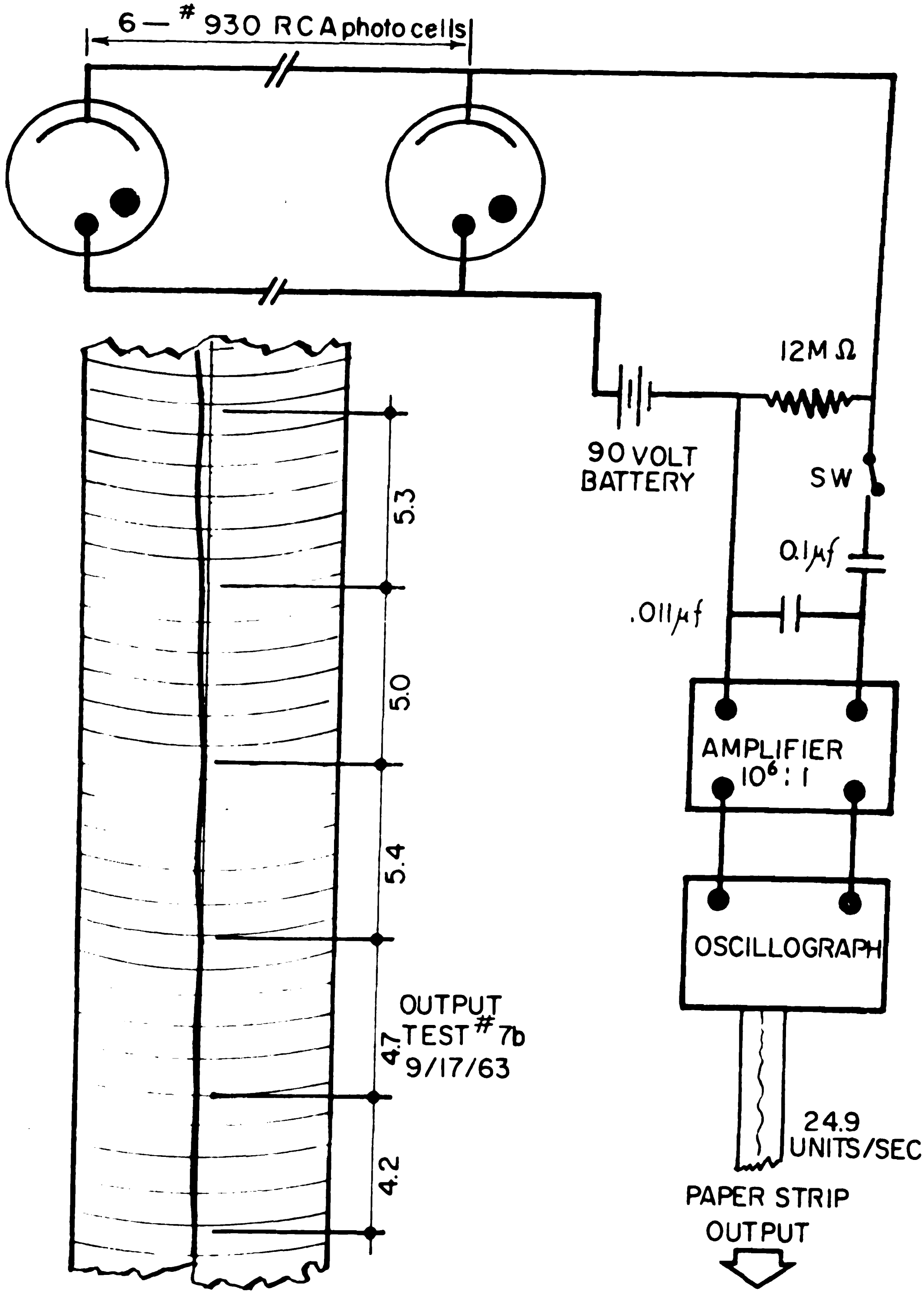


FIGURE 18 PHOTO CELL CIRCUIT & OUTPUT

The net result was very slight signals for the 4th, 5th and 6th photocells. This was partially compensated for by balancing the light signals to decrease or increase the light signal as needed. A sample signal output for which the difficulty of interpretation is apparent is shown in Figure 18. The tangent points of the signal trace was finally considered the most nearly representative of the time required for travel of the smoke plug from one cell to the next. Various appurtenances prevented the equal spacing of the photo cells and this was taken into account in the velocity calculations. For each velocity determination, three replicates were taken as part of the data. Apart from the drying tests, the natural draft velocity characteristics were determined for several temperatures at the tower inlet.

In addition to the previously mentioned temperature and velocity determinations, the temperature profiles at the 2-3/4 ft. and 13 ft. levels were taken for each test condition as well as at the center of the pipe at the "0" level of the drying tower. A thermocouple probe with 3 in. of lead wire parallel to the stream was used for this purpose.

Drying Test Procedures

As already suggested, this small bore drying tower was incompatible with the space requirements for fluidized alfalfa leaves. It was found that ½-in. diameter disks punched from alfalfa leaves were much more desirable from a fluidized bed behavior standpoint. This was correlated with the experiences of Leva (1957) and Gregg (1956), although no information was available to accurately predict the d/D requirements. As a compromise, birdsfoot trefoil was selected to most nearly approach the miniaturization desired. Batch drying tests were considered because of the control made possible by the use of small quantities as well as the opportunity to observe the drying patterns at various fluidizing velocities.

The test batch sample consisted of 100 trefoil leaves, weighed as a mass on the analytical balance. The sample was injected into the hot air stream through the sample port as previously described. At this instant, time was started. The sample either sank immediately forming a fixed bed or became fluidized, depending on the combination of velocities from the natural draft of a particular source temperature and the superimposed forced air velocity. Where the leaves sank immediately, fluidization was not attained until after sufficient moisture removal had been effected such that the partially dried flakes eventually fluidized spontaneously. Or, if the velocity was sufficient to fluidize immediately, the leaves gradually progressed up the tower as an agitating mass, with some dropouts. The initial behavior of the sample was noted as well as the time when the first leaves began to drop down the recovery leg. From this, the average velocity of the sample as it progressed up the tube could be calculated, if required.

After the first dried leaves appeared in the first sample recovery container, ten seconds elapsed before the rotary holder was advanced to the second container and so on. The test was ended at the end of a 4-min. period with a total of twelve samples taken. This meant that after two minutes of sample recovery at 10-sec. intervals, all leaves that would come out had done so. Leaves in each of the containers of the segmented dried sample were then individually counted and weighed. Oven drying followed from which the dry weights were determined. Thus, moisture contents could be determined for purposes of examining the drying patterns.

Three replicates for each temperature-velocity combination were run. Twenty-four combinations were selected from which twelve produced immediate fluidizing velocities. A total of 72 drying tests were conducted for a range of inlet temperatures from 200 to 300°F. The temperature range was limited by the apparatus available. However, the data obtained provided information which had not been reported heretofore.

RESULTS AND DISCUSSION

The sensitivity of alfalfa leaves to damage at high temperatures is one of the basic limiting criteria for the design of a high-temperature, short-time process such as fluidized bed drying. Determination of these relationships on a limited scale has been accomplished as a minor but important phase of the research. The results are presented in a manner similar to those of Headley and Hall (1963) with the necessary modifications to comply with the needs of the product under investigation.

Certain visual observations have necessarily become of qualitative importance and should be mentioned as part of the results. Damage to alfalfa leaves manifests itself as either: 1. a visible charring of the perimeter while the inner areas remain in a green, wilted, partially dried state or, 2. a relatively uniform moisture removal over the entire leaf area to as nearly a bone dry state as possible, after which continued exposure to high temperatures results in dry matter loss with subsequent breakdown of nutritive compounds in the product. The various types of damage can be seen from close inspection of Figure 5. Figure 5A illustrates leaves which have been dried at a temperature of 500°F for 15 seconds, which were removed from the drying medium at the 25% m.c.d.b. level. Below the sample are freshly plucked leaves for color comparison, This important result clearly shows desirable color fixation, indicating a preservation of the nutrients in the product. This is typical of all drying results for leaves at temperatures below 500°F. It was possible to remove moisture to or below the 70°F equilibrium moisture content approaching the bone dry state without visual damage.

For further comparison, Figure 5B shows leaves dried from the fresh cut stage down to the same equilibrium moisture content at 140°F over a conventional long time drying cycle of approximately 8 hours. The dull olive drab green clearly indicates a loss of pigmentation indicative of carotene and other vitamin destruction. The severe curling of these leaves is contrasted with the comparatively unaffected leaves of 5A.

Various types of damage are shown in the remaining samples. The sampling in Figure 5C illustrates the effect of continued exposure of leaves to temperatures of 300 to 500°F with a definite browning over the entire surface of the leaf. Figure 5E illustrates leaves dried at higher temperatures with blackening of the perimeters clearly evident. At the time of the tests, while the edges were brittle and charred, the inner area was still at a wilted, partially dried stage. Finally, Figure 5D shows leaves which can best be described as being "popped". The ultra-high temperatures at which these leaves were exposed for a relatively long time (e.g. 10 seconds, after damage first occurred at 3 seconds) caused the vapor pressure to build up within the leaf so fast that the lower epidermis actually parted from the leaf cell structure. It might be added that later research reported by Whitney and Weeks (1963) disclosed that in all probability, the stomata of the leaf surfaces were closed for these tests effectively sealing the epidermis so that normal mass transfer of the plant held water was not possible with the fast buildup of vapor pressure. All these occurrences are to be expected from basic considerations of the heat and mass transfer phenomena, and could probably be predicted from mathematical analysis. This was not attempted at this stage of development of the research.

Damage Point Relationships

Graphical presentation of the data is presented in Figure 19, in which the quantitive relationships are clearly shown. As stated in an earlier section, damage points at thirteen temperatures were investigated, and each point was established with from 5 to 10 replicates. The data plotted on semi-logarithmic graph paper as two straight lines with a change in slope at 500°F. The need for the statistical determination of a regression line was

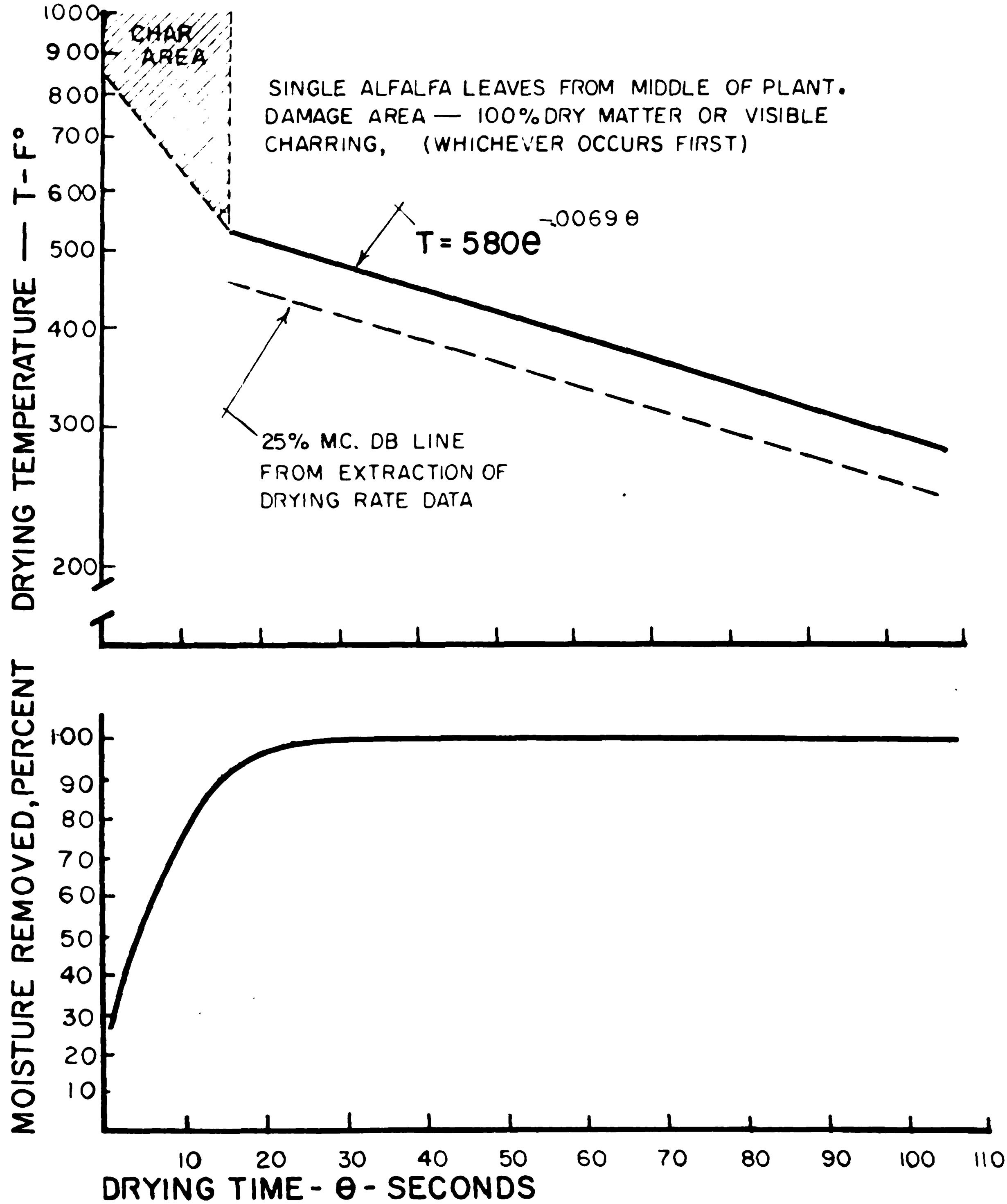


FIGURE 19 DAMAGE POINT RELATIONSHIPS

obviously not necessary in this rare case. Results were surprisingly comparable to those of Headley and Hall (1963) in their work with single kernels of corn, including a similarity in the critical temperature at the break in the curve. The equation of the damage point graph relates the temperature and drying time in the following manner:

$$T = 580\ e^{-.0069}$$

Where T = temperature, °F $\leq$ 500

θ = time, sec.

e = base (2.718) of natural system of logarithms

Directly below, and parallel to this line, another relationship can be seen which has been obtained from the data from which the time to attain a 25% moisture content (d.b.) level can be predicted for the range of temperatures and times explored.

The graph at the bottom half of Figure 19 shows a plot of the percentage of moisture removed before damage versus time, clearly illustrating the effects of drying at temperatures greater than 500°F. From this presentation, it is possible to determine the effects of any drying stage. Starting on the Y-axis at any design temperature and moving horizontally, the damage point on the curve establishes the allowable exposure time. Tracing vertically to the second graph, this point determines the percentage of moisture removal on the ordinate of the lower graph. The value of this presentation in process stage design considerations is self evident.

Drying at Ultra High Temperatures

As a by-product of the data obtained to determine the damage point relationship, certain other drying data were recorded as related to the time of exposure of the single leaf to air at the various temperatures as the damage point was approached from the fresh cut stage. This portion of the experiment was not statistically designed but several other relationships are revealed: 1) drying curves for alfalfa leaves, 2) moisture content ratio-time relationships and 3) a plot of drying constants versus temperature.

A well defined family of drying curves was obtained as shown in Figure 20 for which the percent moisture content (dry basis) was plotted versus time, θ. A table of these results follows:

TABLE 3. DRYING CURVES FOR ALFALFA LEAVES AT ULTRA-HIGH TEMPERATURES

Temperature °F	% Moisture Content, d.b., $\frac{W_w}{W_d} = Ae^{-k\theta}$
281	$251e^{-.027\theta}$
311	$234e^{-.033\theta}$
379	$330e^{-.058\theta}$
427	$488e^{-.099\theta}$
455	$2450e^{-.278\theta}$
524	$1375e^{-.267\theta}$

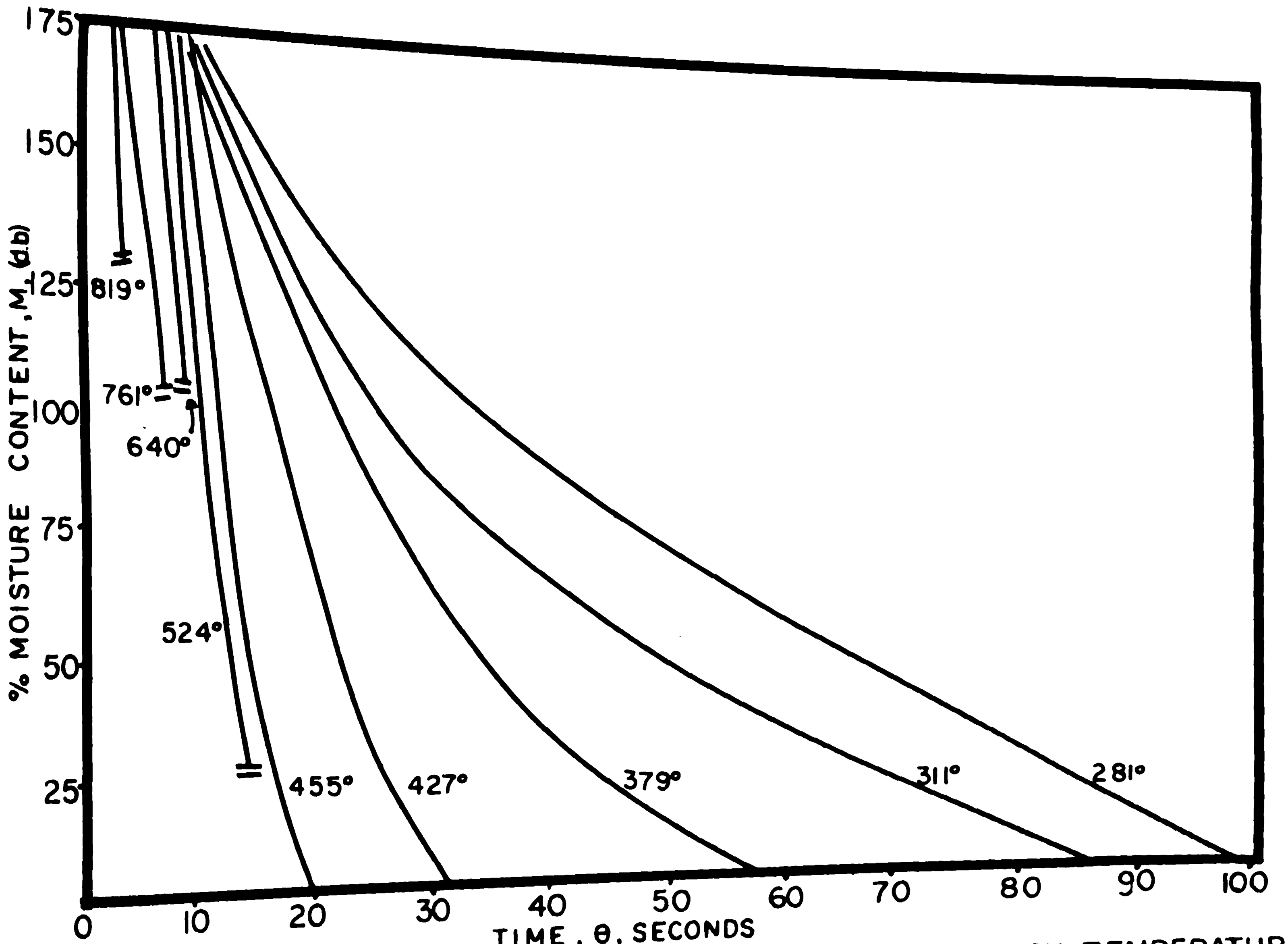


FIGURE 20 DRYING CURVES FOR ALFALFA LEAVES AT ULTRA-HIGH TEMPERATURES

Theoretically, at time "zero" the percent moisture content at all temperatures should be consistent with that of fresh cut material of approximately 300% d.b. However, as can be seen from the equations of the curves, discrepancies are exhibited, possibly due to the effect of the constant drying rate periods at the higher temperatures.

Further analysis of these data in a more conventional way related the logarithm of the moisture content ratio, $\frac{M - M_e}{M_o - M_e}$, to the drying time, θ. The regression lines at the various high temperatures were determined from the data. The equilibrium moisture content, M_e, was found to rapidly approach zero and was neglected in the calculations of the moisture content ratio.

This was permissible as will be shown using data from Bakker-Arkema (1962) to evaluate the constants c and n in equation (2-1) from Hall (1957):

$$1-RH = e^{-cTM_e^n}$$

From Bakker-Arkema

RH = 0.9, T = 120°F (580°A), M_e = 22% d.b.

RH = 0.8, T = 120°F (580°A), M_e = 17% d.b.

Thus, two equations can be written:

$$1 - .9 = e^{-c(580)\ (22)^n}$$

$$1 - .8 = e^{-c(580)\ (17)^n}$$

Solving simultaneously, the unknown constants can be solved as follows:

$c = 0.0000547$

$n = 1.386$

Finally: $1\text{-}RH = e^{-0.0000547TM_e^{1.386}}$

From the psychrometric chart at high temperatures, the relative humidity is seen to rapidly approach zero above 212°F. For example, at a temperature of 250°F, the relative humidity was extrapolated at .001. Solving for M_e in the final expression:

$$1-.001 = .999 = e^{-0.0000547(710)\,M_e^{1.386}}$$

Figure 21 shows the family of regression lines for the various drying temperatures. As before, the curves fail to intercept the Y axis at the expected common initial moisture content ratio $\frac{M - M_e}{M_o - M_e} = 1$.

A tabulation of the equation of the curves is as follows:

TABLE 4. MOISTURE CONTENT RATIO, TIME, AND TEMPERATURE RELATIONSHIPS

Drying Temperatures °F	Moisture Content Ratio $\frac{M - M_e}{M_o - M_e} = Be^{-k\theta}$	Standard Deviation $\pm\sigma$
281	$1.469e^{-0.033\theta}$	0.468
296	$1.847e^{-0.043\theta}$	0.694
311	$4.284e^{-0.065\theta}$	0.911
379	$11.359e^{-0.119\theta}$	0.776
455	$4.712e^{-0.165\theta}$	0.455
515	$22.874e^{-0.424\theta}$	0.943
524	$36.966e^{-0.390\theta}$	0.579
570	$8.248e^{-0.310\theta}$	0.382
640	$11.588e^{-0.428\theta}$	0.321
661	$3.289e^{-0.310\theta}$	0.336
761	$1.600e^{-0.309\theta}$	0.821
819	$1.515e^{-0.336\theta}$	0.448

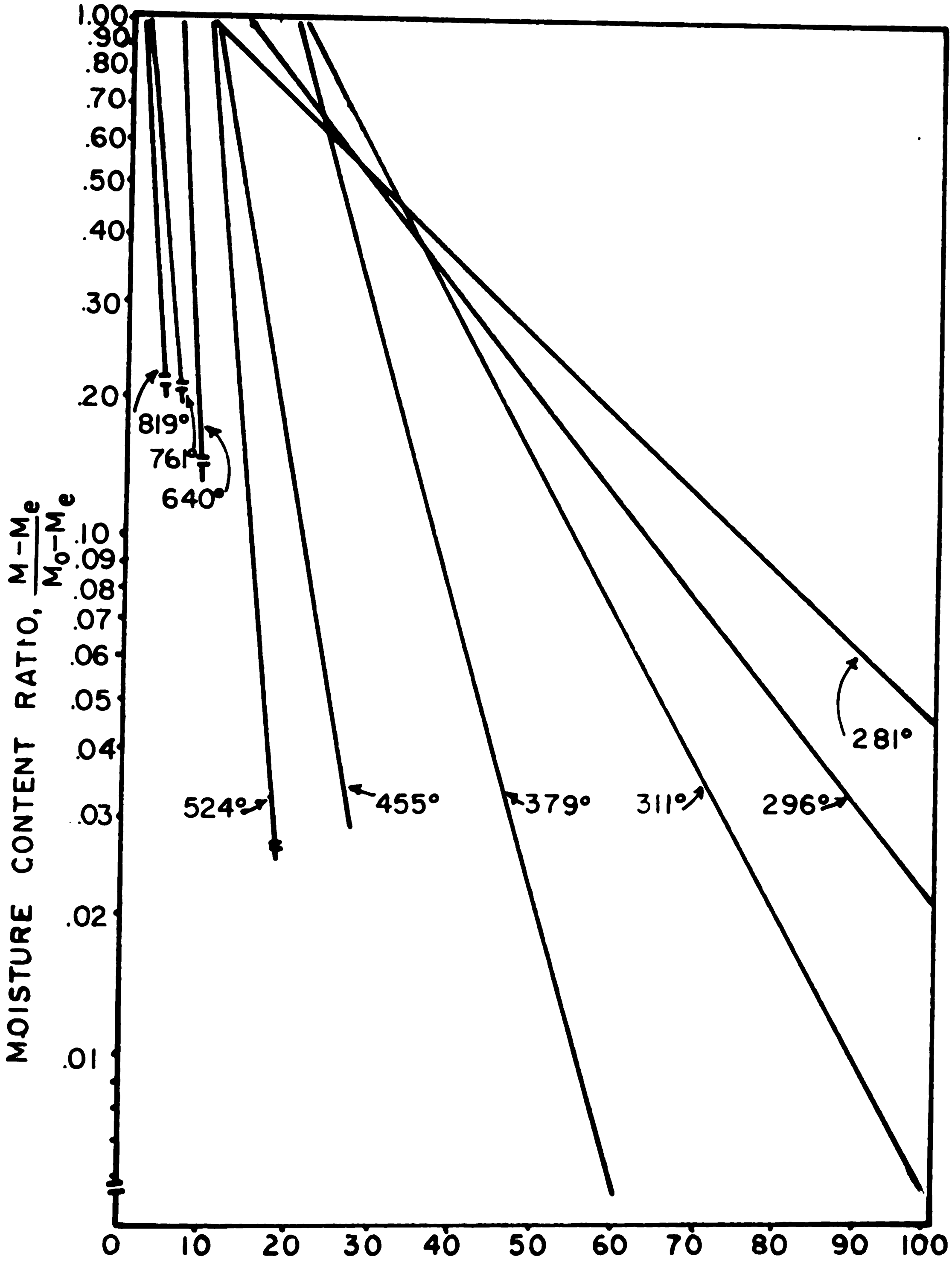


FIGURE 21 RELATION OF MOISTURE CONTENT RATIO TO TIME FOR DRYING ALFALFA LEAVES AT ULTRA-HIGH TEMPERATURES

A semi-log plot of the drying constant, k, reveals the relationship shown in Figure 22. The logarithm of the drying constant, k, was plotted versus the temperature, T, as a straight line up to 524°F. This corresponds to the temperature at which drying occurred without visible charring shown in Figure 19. At higher temperatures, charring occurred at the perimeter of the leaf while the center area was at a much higher moisture content. It can be seen that k remains at a nearly constant level, although much more experimentation is required to verify the various implications of these preliminary results.

The equation of the curve from 281°F to 524°F has been determined as follows:

$$k = 0.0026e^{0.0097T}$$

This relationship can be substituted into a general expression relating the three variables:

$$\frac{M - M_e}{M_o - M_e} = Be^{-0.00260e^{0.0097T}}$$

Further analysis is not attempted here because of the limitations of the data available, and the deviation from the basic objective of the experiment design. However, the results are interesting and worthy of note at this point in the dissertation.

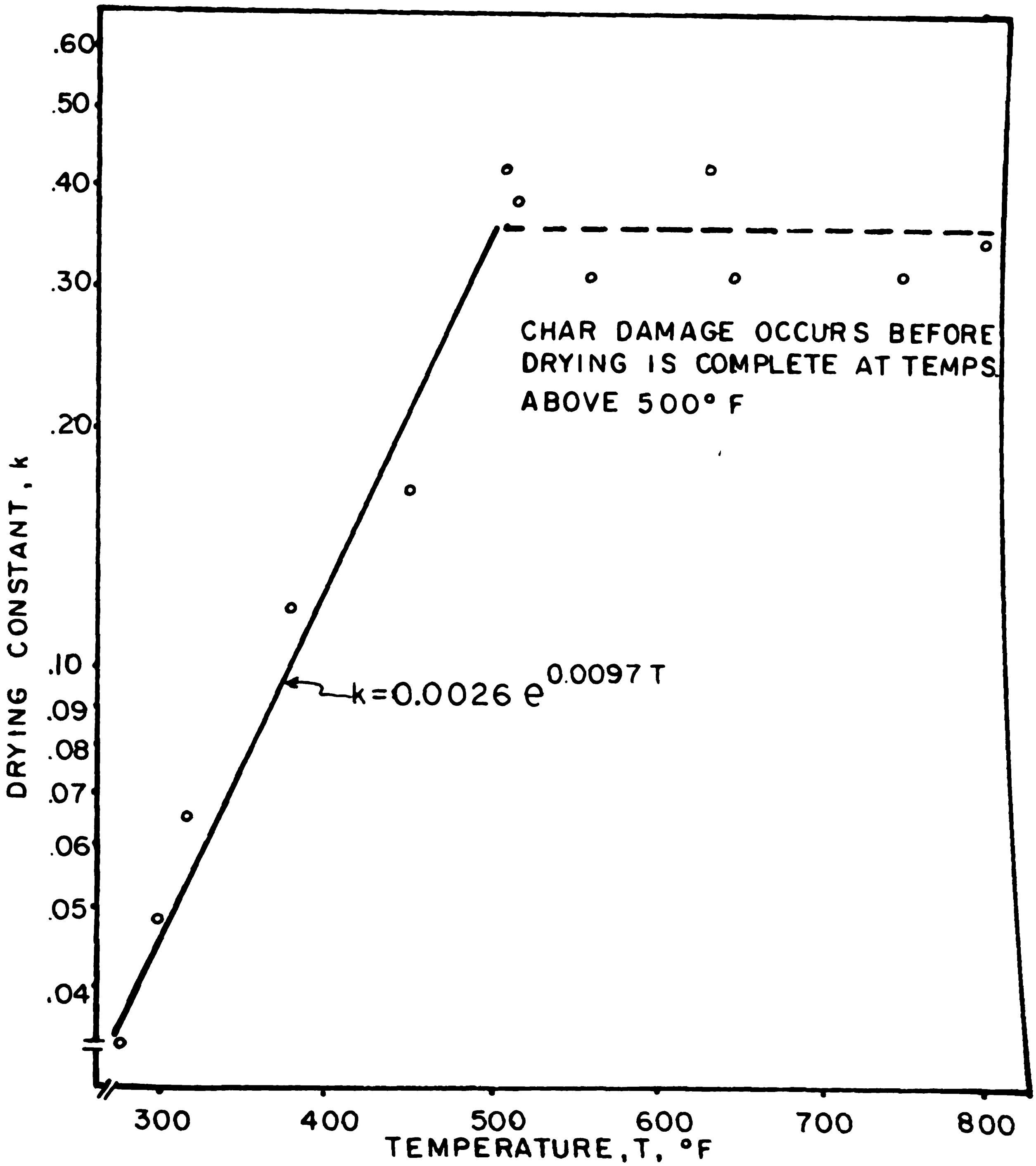


FIGURE 22 RELATIONSHIP OF DRYING CONSTANTS TO AIR TEMPERATURE FOR ALFALFA LEAVES

Sphericity-Moisture Content Relationships

The basic relationships involving the mass rate of flow for fluidization, Gm, voidage, ϵ mf, and particle diameters, Dp are dependent on the sphericity, ϕs, of the particle. This parameter is usually unavailable for flake particles, seriously limiting use of the equations which allow determination of the mass velocity at the onset of fluidization. Equally important is the variation in sphericity as the particle decreases in moisture content, possibly with reduced physical characteristics. In the design of the process stages this becomes of primary concern. This phase of the research has been devoted to the investigation of the sphericity parameter.

Classification of leaves was as stated in the preliminary investigations. Values of sphericity for large, medium, and small alfalfa as well as birdsfoot trefoil, were determined according to the procedure previously described. These were plotted on cartesian coordinates with moisture content as the abscissa shown in Figure 23. Considerable scatter of the data was prevalent, but statistical analysis permitted determination of the regression lines. The equations of the curves are tabulated as follows:

TABLE 5. SPHERICITY RELATIONSHIPS FOR LEAVES AT VARIABLE MOISTURE CONTENTS

Leaf Classification and type	Sphericity, $\phi_s = m(M.C.) + b$	Standard Deviation, $\pm\sigma$
Large alfalfa	0.0000753(M.C.) +.1025	0.0081
Medium alfalfa	0.0000631(M.C.) +.1055	0.0109
Small alfalfa	0.0001305(M.C.) +.1637	0.0314
Birdsfoot trefoil	0.00001 (M.C.) +.1799	0.0215

When considering the magnitudes of the coefficient m, it can be shown that the influence of the moisture content is minor (less than 20%). This influence of itself would have little effect on the process, and the sphericity might be considered nearly constant over the entire moisture content range.

An error analysis of the experimental techniques has been made pointing out certain limitations of the experimental technique. The accuracies of the apparatus were such that the volume of the leaf could be determined to ± 0.001 ml and the area to ± 0.005 in^2. However, because of the natural shrinkage of the leaf, the volumes and areas decreased substantially such that the percentage of error increased sharply as the leaf lost moisture content. Also, when considering the large differential between the sizes of small and large alfalfa leaves, the accuracies were influenced in favor of the larger objects.

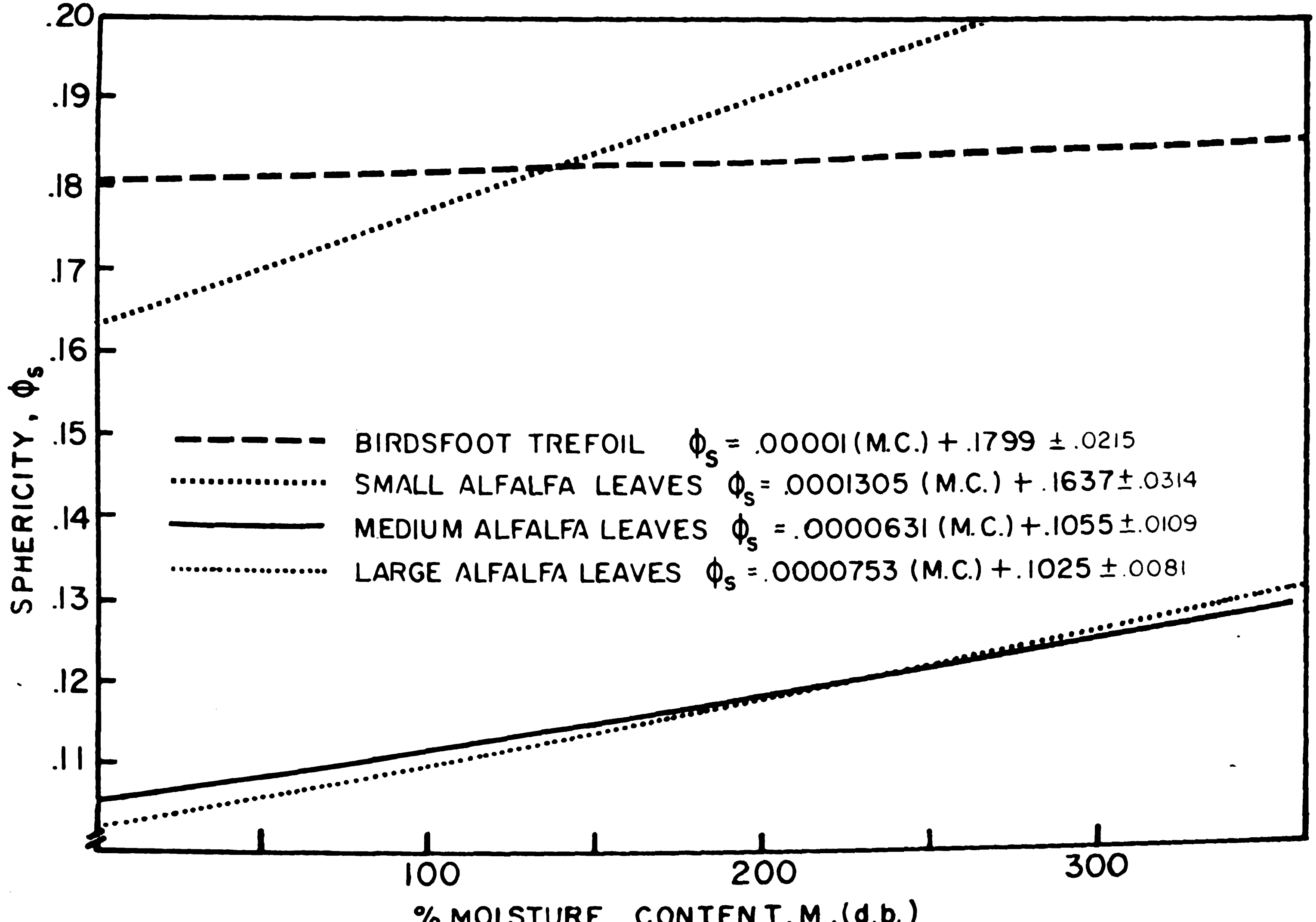


FIGURE 23 SPHERICITY versus % MOISTURE CONTENT (D.B.)

Since $\phi_s = \frac{V^{2/3}}{0.205A}$, the maximum error $\Delta\phi_s$, is:

$$\Delta\phi_s = \frac{\partial\phi_s}{\partial V}(\Delta V) + \frac{\partial\phi_s}{\partial A}(\Delta A)$$

$$\Delta\phi_s = \frac{2/3\ V^{-1/3}}{0.205A}(\Delta V) - \frac{V^{2/3}}{0.205A^2}(\Delta A)$$

The analysis for the results is tabulated as follows:

TABLE 6. ERROR ANALYSIS OF SPHERICITY RESULTS FOR FRESH CUT AND DRIED LEAVES

Leaf Classification	Shrinkage V_d/V_w	Maximum % Error		Statistical Error
		300% m.c.d.b.	0% m.c.d.b.	
Large Alfalfa	.28	± 2.4	± 6.8	± 7.8
Medium Alfalfa	.33	± 3.8	±10.2	±10.3
Small Alfalfa	.35	± 7.6	±17.5	±19.0
Birdsfoot Trefoil	.42	± 5.57	±15.2	±12.0

From this analysis, it is concluded that the error of the experimental technique developed increases as the area and/or volume of the object decreases. Further, error must be expected because of the influence of the hydrostatic pressure in crushing the leaf cells. This can only be analyzed by microscopic inspection by which comparisons can be made of cells before and after stress. However, it was found that the immersion technique was gentle enough not to affect even the most brittle dried leaf. Microscopic verification was not made at this time.

The sphericity determinations indicate that the smaller leaves are more easily fluidized. For all leaves, the voidage ϵ_{mf} can be expected to approach unity. Positive evaluations of voidage could not be determined because of the small scale of the apparatus, but as a result of the tests, the process can be identified as a dilute fluidized bed.

Mass Rate of Flow, Temperature, and Moisture Removal Relationships

Investigation of the fluidized bed drying process has been conducted using laboratory scaled apparatus and techniques described earlier. This has differed considerably from the experimental techniques reported by Schrenk, whereby a continuous pilot process was required to yield meaningful design parameters. The velocity requirements of the drying particle by Schrenk in terms of the mass velocity and the results are presented as a regression line with a dimensionless parameter, $\frac{w_0}{w_1} - 1$ as the ordinate and the mass velocity per unit area as the abcissa. The data available were for inlet temperatures greater than 720°F, considering freshly chopped alfalfa plants as the feed. Provisions were provided to separate out the stems.

It seemed desirable to obtain information which would establish some relationships with the inlet temperature and which would be more appropriate for leaves only. With these

objectives, the tests were conducted at variable inlet temperatures commensurate with the limitations of the small bore laboratory apparatus. The results are superimposed on Schrenk's information to further expand the limits of the available parameters. Regression lines were obtained by statistical analysis and are presented in Figure 24. The tabulation of the relationships follows:

TABLE 7. MASS VELOCITY, TEMPERATURE, AND MOISTURE REMOVAL RELATIONSHIPS

Inlet Temperature °F	$\frac{w_O}{w_1} - 1$	Standard Deviation, $\pm\sigma$
200°	$10^{18.78}(Vmass)^{-5.5242}$	.1535
250°	$10^{14.10}(Vmass)^{-4.3269}$	.1244
300°	$10^{11.85}(Vmass)^{-3.7750}$	.1199
720° (Schrenk 1959 estimated)	$10^{19.5}\ (Vmass)^{-5.5}$	

Analysis reveals a family of curves for which a relationship between the inlet temperatures and the coefficients (or exponent) might be expected. These relationships might be deduced from a plot of the regression line coefficients and Y-intercepts in Figures 25 and 26. Continuity with the established data by Schrenk is not evident, however, the material being considered is substantially

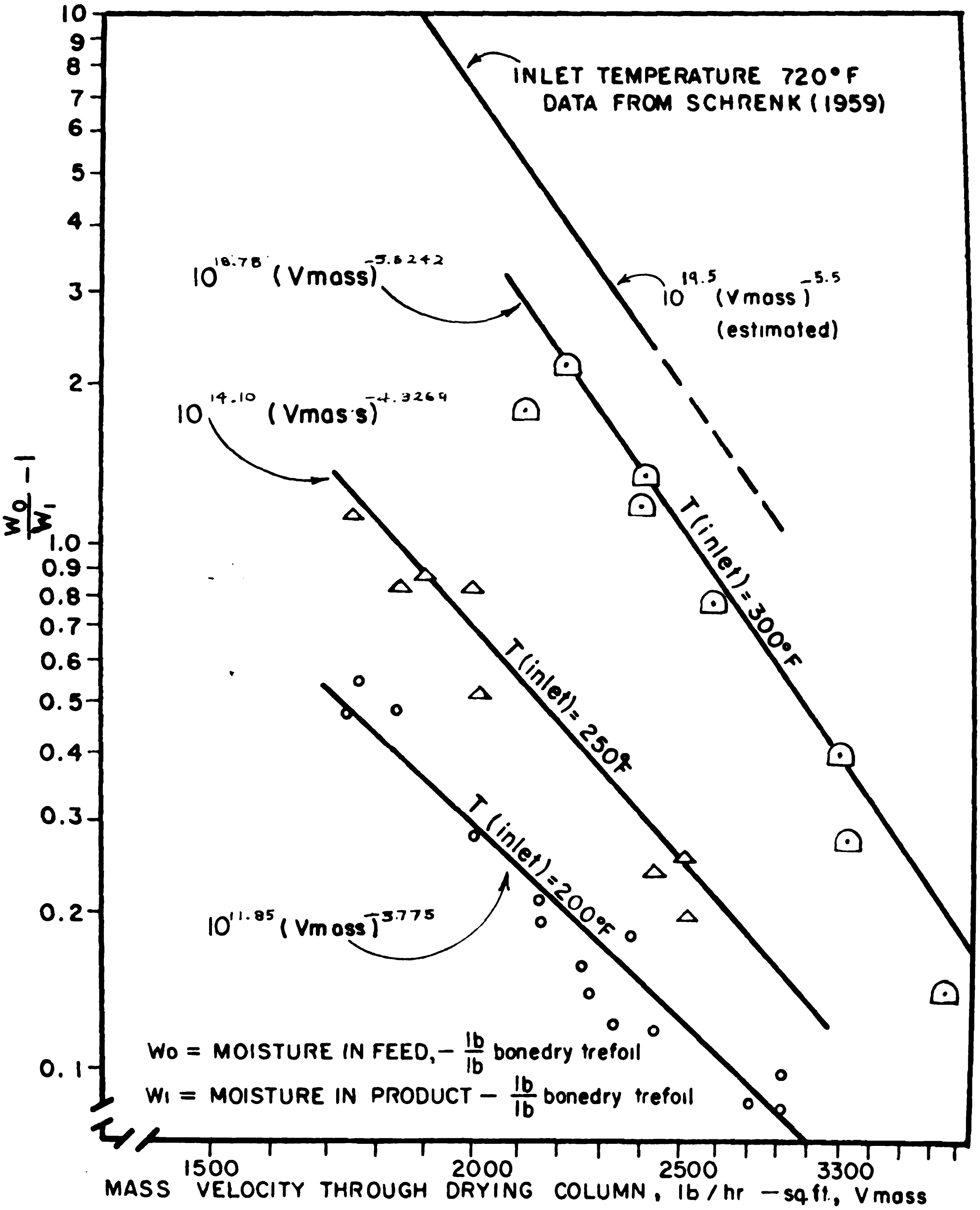


FIGURE 24 RELATIONSHIP BETWEEN FLOW OF HOT AIR AND INITIAL AND FINAL LEAF MOISTURE CONTENT

different and could well account for some of the discrepancy. If the relationship as indicated by three points were acceptable as a straight line, then the expression relating the regression line slope and Y-intercept could be written easily. However, a sufficient range of temperatures was not possible on which to base conclusive statements as to what this relationship is at this stage of the development with the scale of apparatus available.

Sensitivity of the fluidizing velocity to changes in temperature along the length of the tower has been shown. This is well founded upon examination of the differential equation which clearly reveals the existence of a divergent velocity field. This has also been observed and measured. Typical divergence can be seen from an examination of the graphical presentation, Figure 27, where the divergences resulting from natural drafts at various inlet temperatures are obvious. A divergence was detected for all combinations of inlet temperatures and superimposed velocities. The apparatus adequately served as a simulator of the continuous process. A larger scale, with continuous flow of materials would result in heat transfer and evaporation of water vapor with subsequent cooling of the drying gas along the length of the tower, hence a divergence of the velocity field. The divergence would be affected by the mass transfer of plant held water released to the drying

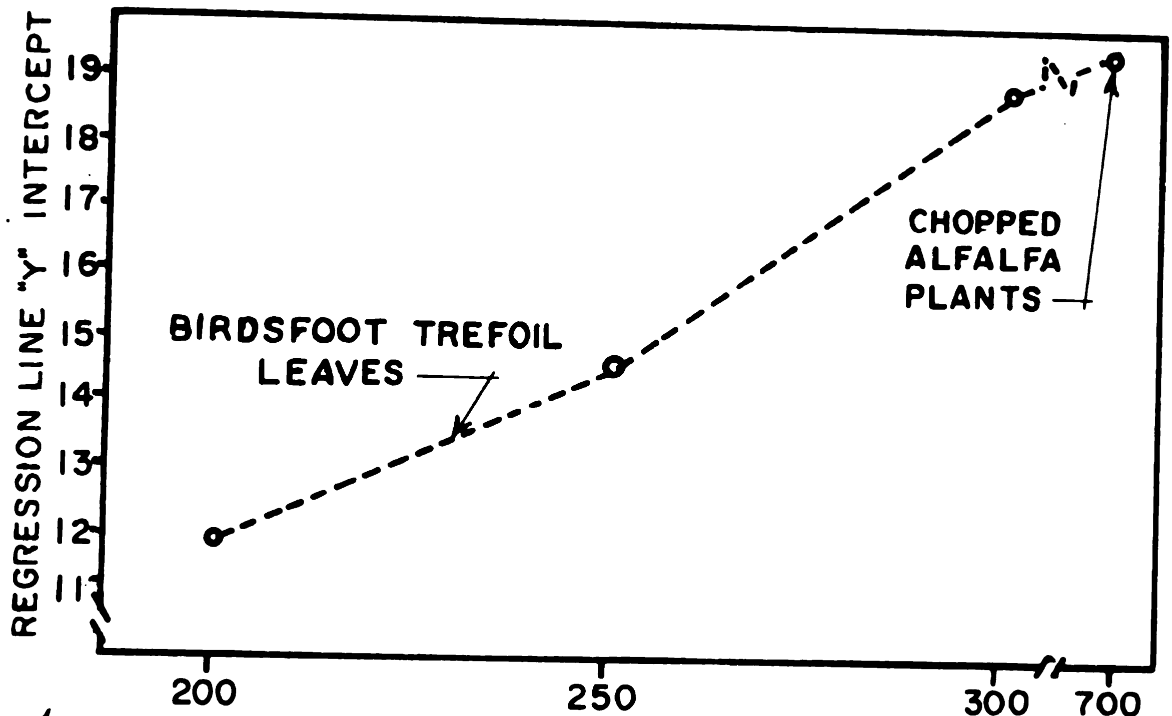


FIGURE 25. REGRESSION LINE "Y" INTERCEPT vs INLET TEMPERATURE (FOR MASS VELOCITY-DRYING DATA)

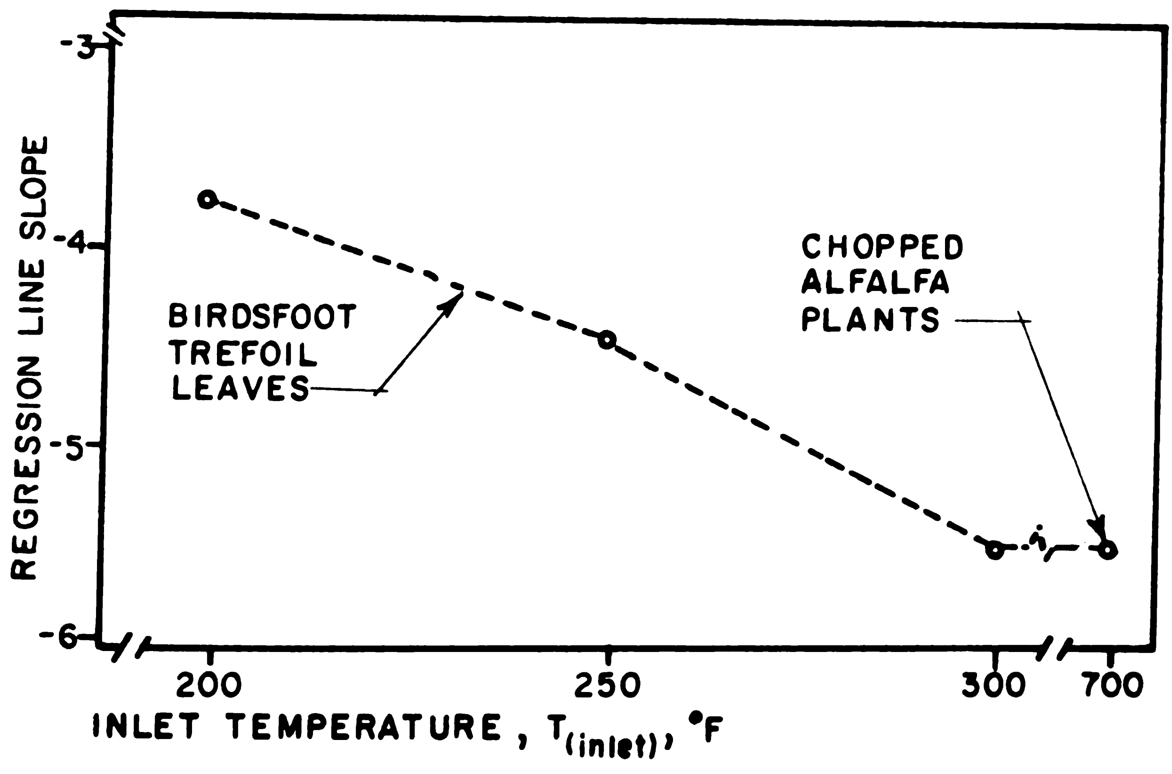


FIGURE 26. REGRESSION LINE SLOPE vs INLET TEMPERATURE (FOR MASS VELOCITY-DRYING DATA)

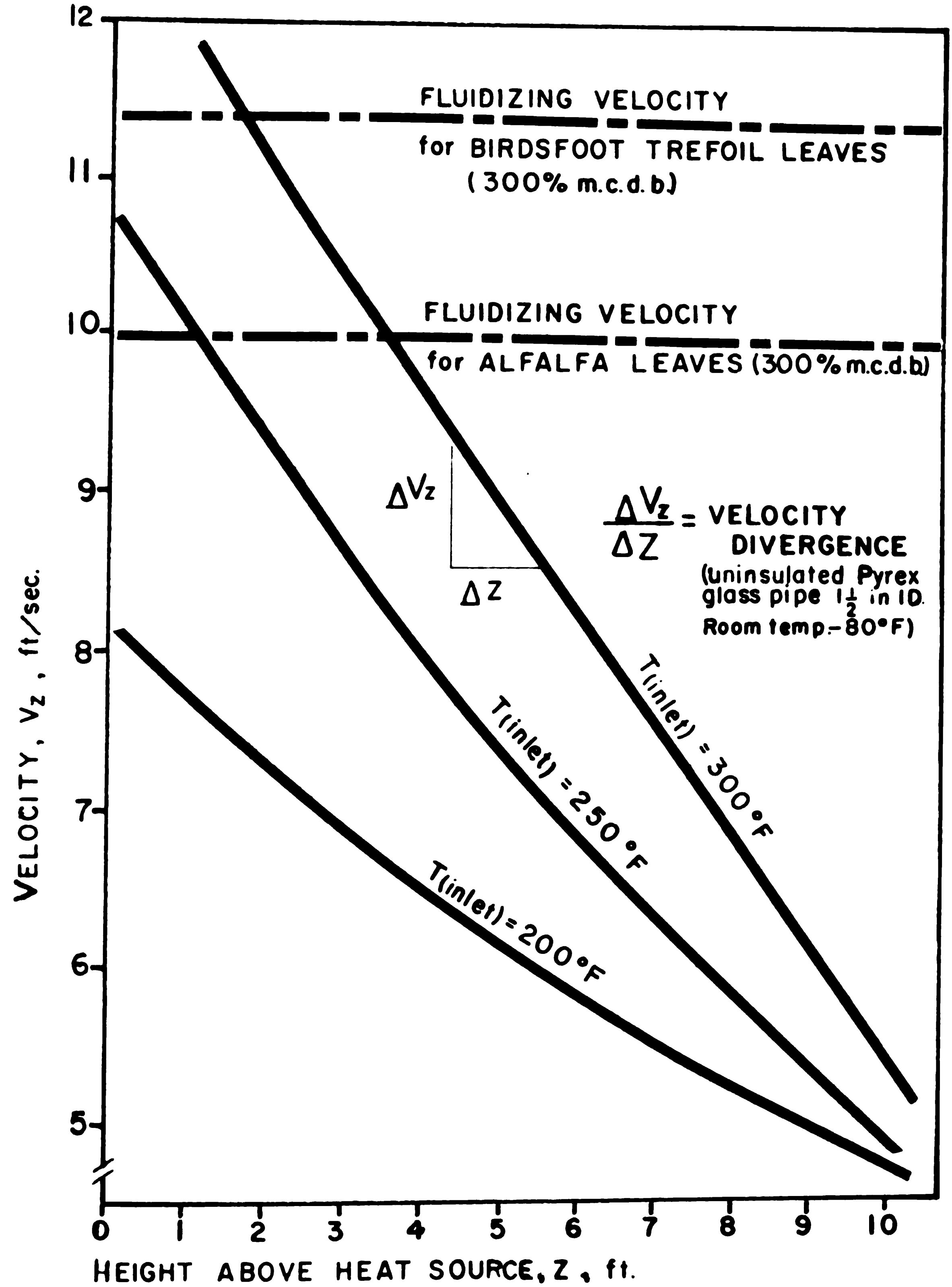


FIGURE 27. VELOCITY VARIATION-NATURAL DRAFTS

gases as water vapor. In order to fully explore this further, a pilot scale observation would be required to further verify the theory.

The significance of this phenomenon is that as the leaf dries, becoming lighter, it does in fact require less velocity to support it. To accomplish this, it might be assumed that a tower needs to be designed smaller at the bottom, so that for a given mass velocity at which fluidization occurs, the absolute velocity would decrease further up the column to accommodate the drying particle. However, the divergence phenomenon in a tower of constant crossection appears to accomplish the same objective, and considerable economics of construction can be obtained for the process under investigation.

SUMMARY AND CONCLUSIONS

The scope of the investigation of an entirely new systems concept of forage harvesting and handling has been such that a detailed study of all the facets uncovered is virtually impossible as a single effort. No pretense is made to imply that this accomplishment has been effected, desirable as it may be. However, the investigations have demonstrated that the system is feasible; that much more research depth is warranted in all facets, and is essential for the complete description of the process.

Results to date can be summarized as follows:

1. Leaf stripping has been demonstrated, and the necessity of such a maneuver has been established as a prelude to the fluidized bed drying process. Whether or not this may be a desirable cultural practice has yet to be established. Even if the plants are cut in a conventional manner and then stripped of leaves, discharging the stems back on to the harvested field area, no increase in present field loss would be experienced and a considerable increase in drying rate and efficiency would be accomplished, making the process desirable from several considerations.

2. The damage point relationships have been definitely established for a specific set of conditions of alfalfa leaves and the results correlate well with those of other

products. Further information is needed to explore the effects of a wider range of plant and culture oriented variables. The damage point relationships can be expressed mathematically.

3. The effects of ultra high temperature on the drying of alfalfa leaves have been explored, largely as a by-product of data taken for another phase. Verification of the mathematical relationships must follow based on statistically designed experiments.

4. Particle behavior can be predicted based on studies of the sphericityof the leaf. Variations in moisture content have been explored and the particles, in spite of substantial shrinkage, exhibit nearly constant characteristics over the entire range of moisture contents. Process design of the mass rate of flow can be made as a result of these studies.

5. The effect of mass velocities on fluidized bed drying have been established showing a definite relationship to work that has been previously reported. Further data is necessary at inlet temperatures higher than those attainable with laboratory scaled apparatus to firmly establish the relationship with the inlet temperature.

6. Divergence of the velocity field has been demonstrated and measured to relate this phenomenon with the needs of a flaked particle drying in free suspension. Refinement of the measuring technique is necessary to provide

for clear cut velocity determinations. Design of the velocity divergence must be a part of the considerations of the process.

In conclusion, fluidization principles have been demonstrated to be well suited to forage harvesting and handling. The limitations relating to the incompatibility of various plant parts in a fluidizing medium have been resolved by the realization that effective separation of the major categories must be accomplished. This may turn out to be the major hurdle in the successful adoption of this system. However, if a practical leaf stripping or stem altering operation can be developed, the system will be competitive with existing ones. The principles could be applied to a process which might conceivably evolve as an alfalfa leaf combine whereby the fresh cut leaf is dried immediately to a moisture content commensurate with safe storage. A forage product could evolve which lends itself to completely automated handling, which has yet to be achieved with forage.

FUTURE INVESTIGATIONS

1. Expansion of the information on time-temperature damage point relationships to correlate the effects of such variables as stage of plant maturity, seasonal variation, plant varieties, location of leaves on plant, etc.

2. Investigation of the drying rate relations for ultra-high drying temperatures by statistically designed experimentation.

3. Evaluation of the sphericities of other forage plants and agricultural products as a prelude to the application of fluidized bed drying principles.

4. Investigation of the change in Young's modulus of plant parts related to the change in moisture content as revealed by observations of the behavior of individual leaves at accelerated drying rates of ultra-high temperatures.

The affect on other hay harvesting and handling processes might be the objective of such a study.

5. Investigation of the feasibility and desirability of stripping leaves from the growing alfalfa plant as a cultural practice. Evaluation should be with the cooperation of crop scientists.

6. Determination of methods to strip leaves mechanically from the alfalfa plant, either standing in the field and/or after mowing.

7. Evaluation of the parameters for fluidized bed drying which will ultimately lead to the design and development of this continuous drying process for alfalfa and other agricultural products as either:

a) farmstead stationary installations, and/or

b) field combines to harvest alfalfa leaves and flash dry them from the fresh cut stage to the safe storage moisture content.

8. Investigation on the effect of stomata behavior on the drying rates of alfalfa leaves.

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APPENDICES

APPENDIX A

TABLE A-1. SUMMARY OF DAMAGE POINT AND DRYING DATA FOR SINGLE ALFALFA LEAVES - TEMPERATURE 281°F.

Leaf No.	Initial M.C. % d.b.	Final M.C. % d.b.	$\frac{M-M_e}{M_o-M_e}$	% H_2O removed	Time, seconds
1	213.2	171.9	0.8063	19.4	10
2	194.2	147.1	0.7575	24.3	15
3	133.7	97.0	0.7255	27.5	17
4	215.8	131.6	0.6098	39.0	20
5	191.3	136.4	0.7130	28.7	22
6	277.5	170.6	0.6148	38.5	25
7	243.6	299.7	0.9429	46.3	27
8	310.3	217.2	0.6999	30.0	30
9	192.5	95.5	0.4961	50.4	32
10	310.1	195.3	0.6298	37.0	35
11	192.8	88.8	0.4606	53.9	37
12	114.9	37.4	0.3255	67.4	40
13	208.6	86.7	0.4156	58.4	42
14	211.5	77.0	0.3641	63.6	45
15	263.1	113.9	0.4329	56.7	47
16	174.5	44.1	0.2527	74.7	50
17	158.7	28.9	0.1821	81.7	55
18	203.0	36.0	0.1773	82.3	60
19	250.8	64.2	0.2560	73.2	65
20	325.8	100.0	0.3069	69.3	70
21	312.3	84.4	0.2703	72.9	75
22	176.4	31.9	0.1808	87.9	80
23	185.0	55.0	0.2973	70.3	85
24	166.7	12.8	0.0768	92.3	90
25	199.4	19.8	0.0993	90.0	95
26	183.0	4.1	0.0224	97.7	100
27	238.2	3.5	0.0147	98.5	105
28	247.2	0.0	0.0	100.0	110

Date: 7/28/62
Air Velocity: 58 fpm @ 80°F
Rotation: 40 rpm

Stage of Maturity: Pre-bloom, 2nd cutting
Equilibrium m.c.: $M_e \approx 0$
No discoloration

TABLE A-2. SUMMARY OF DAMAGE POINT AND DRYING DATA FOR SINGLE ALFALFA LEAVES - TEMPERATURE 296°F.

Leaf No.	Initial M.C. % d.b.	Final M.C. % d.b.	$\frac{M-M_e}{M_o-M_e}$	% H_2O removed	Time, seconds
1	218.7	128.0	0.5853	41.5	20
2	255.7	166.0	0.6492	35.0	25
3	227.1	113.1	0.4980	50.2	30
4	263.9	98.8	0.3739	62.6	35
5	234.4	90.6	0.3865	61.3	40
6	179.3	76.7	0.4278	57.2	45
7	274.4	40.7	0.1483	85.2	50
8	259.2	54.1	0.2087	79.1	55
9	167.5	11.4	0.0681	93.2	60
10	238.6	16.9	0.0708	92.9	65
11	223.4	47.8	0.2140	78.6	70
12	236.5	36.5	0.1543	84.6	75
13	188.3	4.7	0.0250	97.5	80
14	311.8	22.6	0.0725	92.8	85
15	230.0	40.6	0.1765	82.4	85
16	226.3	0	0.0000	100.0	90
17	287.8	2.4	0.0083	99.2	95
18	247.3	7.6	0.0307	96.9	92
19	318.1	0	0.0000	100.0	92

Date: 7/31/62
Air Velocity: 58 fpm @80°F
Rotation: 40 rpm

Stage of Maturity: Pre-bloom, 2nd cutting
Equilibrium m.c., $M_e \approx 0$
No discoloration

TABLE A-3. SUMMARY OF DAMAGE POINT AND DRYING DATA FOR SINGLE ALFALFA LEAVES - TEMPERATURE 311°F.

Leaf No.	Initial M.C. % d.b.	Final M.C. % d.b.	$\frac{M - M_e}{M_o - M_e}$	% H_2O removed	Time, seconds
1	235.9	159.8	0.6774	32.2	20
2	135.5	74.5	0.5498	45.0	25
3	188.3	67.0	0.3558	64.4	30
4	179.5	89.4	0.4981	50.2	35
5	175.2	50.4	0.2877	71.2	40
6	169.9	58.8	0.3461	65.4	45
7	164.6	22.9	0.1391	86.1	50
8	180.7	27.1	0.1500	85.0	60
9	184.8	63.6	0.3442	65.6	55
10	244.4	82.5	0.3580	66.2	65
11	206.3	7.8	0.0378	96.2	70
12	219.8	1.0	0.0045	99.5	90
13	248.6	13.1	0.0527	94.7	75
14	186.7	0.9	0.0048	99.8	80
15	165.8	2.0	0.0121	98.8	82
16	243.6	10.7	0.0439	95.6	85
17	342.2	13.2	0.0386	96.1	90
18	347.5	0.0	0.0000	100.0	95
19	219.5	0.0	0.0000	100.0	100
20	188.9	0.7	0.0037	99.7	105
21	252.1	3.1	0.0123	98.8	90
22	234.0	2.1	0.0090	99.1	95
23	210.9	0.0	0.0000	100.0	100

Date: 7/31/62
Air Velocity: 58 fpm @ 80°F
Rotation: 40 rpm

Stage of Maturity: Pre-bloom, 2nd cutting
Equilibrium m.c., $M_e \approx 0$
No discoloration

TABLE A-4. SUMMARY OF DAMAGE POINT AND DRYING DATA FOR SINGLE ALFALFA LEAVES - TEMPERATURE 379°F.

Leaf No.	Initial M.C. % d.b.	Final M.C. % d.b.	$\frac{M - M_e}{M_o - M_e}$	% H_2O removed	Time, seconds
1	219.5	125.8	0.5731	42.7	20
2	188.9	87.7	0.4643	53.9	25
3	204.1	86.3	0.4228	57.7	30
4	157.1	23.3	0.1483	85.2	35
5	198.3	52.3	0.2637	73.6	40
6	174.8	11.7	0.0669	93.3	45
7	267.9	5.1	0.0190	98.1	50
8	318.2	5.7	0.0179	98.2	55
9	278.7	0	0.0000	100.0	60
10	311.5	0	0.0000	100.0	65
11	268.6	5.9	0.0220	97.8	55
12	168.1	1.1	0.0065	99.4	57
13	237.3	5.9	0.0249	97.5	60
14	139.9	4.7	0.0336	97.7	60
15	130.5	1.7	0.0130	98.7	60
16	135.7	0.8	0.0057	99.4	60
17	169.3	0.0	0.0000	100.0	65
18	141.2	0.7	0.0050	99.5	62
19	215.9	108.4	0.5020	49.8	20
20	196.0	96.8	0.3893	50.6	25
21	168.2	75.4	0.4483	55.1	30
22	237.6	75.2	0.3165	68.3	35
23	233.3	57.1	0.2447	75.5	40
24	218.5	18.5	0.0847	91.5	45
25	216.7	3.1	0.0143	98.6	50
26	215.2	4.3	0.0200	98.0	55
27	211.4	1.9	0.0090	99.1	60
28	243.9	0.4	0.0016	99.6	62

Date: 8/1/62
Air Velocity: 45 fpm @ 80°F
Rotation: 40 rpm

Stage of Maturity: 10% bloom, 2nd cut
Equilibrium m.c., $M_e \sim 0$
No discoloration

TABLE A-5. SUMMARY OF DAMAGE POINT AND DRYING DATA FOR SINGLE ALFALFA LEAVES - TEMPERATURE 455°F.

Leaf No.	Initial M.C. % d.b.	Final M.C. % d.b.	$\frac{M - M_e}{M_o - M_e}$	% H_2O removed	Time, seconds
1	280.4	164.9	0.5881	41.2	10
2	310.6	156.5	0.5042	49.6	15
3	245.9	69.7	0.2834	71.6	20
4	246.2	77.3	0.3140	68.6	22
5	259.8	14.5	0.0751	92.5	25
6	222.7	13.6	0.0611	93.9	27*
7	225.6	11.1	0.0492	95.1	27*
8	268.2	9.4	0.0350	96.5	27
9	277.7	8.5	0.0306	96.9	27
10	285.2	0	0.0000	100.0	30*
11	305.6	0	0.0000	100.0	30*
12	312.1	173.6	0.5562	44.4	10
13	271.4	122.4	0.4510	54.9	15
14	265.5	44.0	0.1657	83.4	20
15	196.3	16.0	0.0815	91.8	25
16	282.7	10.7	0.0385	96.2	27*
17	251.4	0	0.0000	100.0	30*

Date: 8/4/62
Air Velocity: 45 fpm @ 85°F
Rotation: 40 rpm

Stage of Maturity: 10% bloom, 2nd cut
Equilibrium m.c., $M_e \approx 0$
*Discoloration-brown edge

TABLE A-6. SUMMARY OF DAMAGE POINT AND DRYING DATA FOR SINGLE ALFALFA LEAVES - TEMPERATURE 515°F.

Leaf No.	Initial M.C. % d.b.	Final M.C. % d.b.	$\frac{M - M_e}{M_o - M_e}$	% H_2O removed	Time, seconds
1	276.6	64.9	0.2346	76.5	10
2	324.1	10.3	0.0318	96.8	15
3	311.3	1.6	0.0051	99.4	20
4	271.0	104.3	0.3849	61.5	10
5	255.8	34.9	0.1364	86.4	15
6	342.8	0	0.0000	100.0	20*
7	302.2	4.5	0.0149	98.5	17
8	275.0	3.1	0.0113	98.9	18
9	264.2	1.5	0.0057	99.4	20*
10	337.2	2.3	0.0068	99.3	19
11	292.0	2.0	0.0068	99.3	19*
12	264.5	12.9	0.0488	95.1	16
13	283.9	33.3	0.1173	88.3	16

Date: 7/27/62
Air Velocity: 58 fpm @ 80°F
Rotation: 40 rpm

Stage of Maturity: Pre-bloom, 2nd cut
Equilibrium m.c., $M_e \approx 0$
*Discoloration- brown edges

TABLE A-7. SUMMARY OF DAMAGE POINT AND DRYING DATA FOR SINGLE ALFALFA LEAVES - TEMPERATURE 524°F.

Leaf No.	Initial M.C. % d.b.	Final M.C. % d.b.	$\frac{M - M_e}{M_o - M_e}$	% H_2O removed	Time, seconds
1	340.2	146.4	0.4303	57.0	10
2	322.1	142.1	0.4412	55.9	11
3	308.3	98.6	0.3198	68.0	12
4	331.7	115.8	0.3491	65.1	13
5	328.8	57.6	0.1752	82.5	14
6	318.2	56.8	0.1785	82.1	15
7	303.4	44.8	0.1477	85.2	16*
8	320.8	16.7	0.0521	94.8	17
9	307.2	20.3	0.0661	93.4	18*
10	319.7	3.3	0.0103	98.9	18*
11	275.3	5.2	0.0189	98.1	19*
12	319.6	5.4	0.0169	98.3	19*

Date: 8/4/62
Air Velocity: 45 fpm @ 85°F
Rotation: 40 rpm

Stage of Maturity: 10% bloom, 2nd cut
Equilibrium m.c., $M_e \approx 0$
*Discoloration-brown tip, edge

TABLE A-8. SUMMARY OF DAMAGE POINT AND DRYING DATA FOR SINGLE ALFALFA LEAVES - TEMPERATURE 570°F.

Leaf No.	Initial M.C. % d.b.	Final M.C. % d.b.	$\frac{M-M_e}{M_o-M_e}$	% H_2O removed	Time, seconds
1	289.1	79.5	0.2750	72.0	10
2	315.7	61.4	0.1945	80.5	11
3	381.8	122.7	0.3214	67.9	12
4	353.7	75.6	0.2137	78.6	13
5	349.3	54.8	0.1569	84.3	14*
6	350.8	18.6	0.0530	94.7	15*
7	312.9	28.6	0.0914	90.9	14*

Date: 8/4/62
Air Velocity: 45 fpm @ 80°F
Rotation: 40 rpm

Stage of Maturity: 10% bloom, 2nd cut
Equilibrium m.c., $M_e \approx 0$
*Discoloration-brown edges

TABLE A-9. SUMMARY OF DAMAGE POINT AND DRYING DATA FOR SINGLE ALFALFA LEAVES - TEMPERATURE 640°F.

Leaf No.	Initial M.C. % d.b.	Final M.C. % d.b.	$\frac{M-M_e}{M_o-M_e}$	% H_2O removed	Time, seconds
1	298.1	203.8	0.6837	31.6	5
2	331.0	207.0	0.6254	37.5	6
3	284.8	153.8	0.5400	46.0	7
4	306.4	119.4	0.3897	61.6	8
5	374.6	103.2	0.2755	72.4	9
6	244.9	46.1	0.1882	81.2	10*
7	267.1	35.6	0.1333	86.7	10*
8	267.5	58.4	0.2183	78.2	10*
9	328.1	101.0	0.3078	69.2	9*
10	308.5	101.9	0.3303	67.0	9*
11	331.3	91.3	0.2756	72.5	9*
12	292.8	85.7	0.2927	70.7	9*

Date: 8/5/62
Air Velocity: 45 fpm @ 85°F
Rotation: 40 rpm

Stage of Maturity: 10% bloom, 2nd cut
Equilibrium m.c., $M_e \approx 0$
*Discoloration-black edges

TABLE A-10. SUMMARY OF DAMAGE POINT AND DRYING DATA FOR SINGLE ALFALFA LEAVES - TEMPERATURE 661°F.

Leaf No.	Initial M.C. % d.b.	Final M.C. % d.b.	$\frac{M-M_e}{M_o-M_e}$	% H_2O removed	Time, seconds
1	308.0	144.0	0.4675	53.2	5
2	283.1	107.8	0.3808	62.9	6
3	321.8	111.5	0.3465	65.3	7
4	300.0	101.1	0.3370	66.3	8*
5	252.8	46.1	0.1824	81.8	9*
6	289.9	65.2	0.2249	77.5	8*
7	289.2	66.2	0.2289	77.1	8*
8	313.7	102.7	0.3274	67.2	8*

Date: 8/5/62
Air Velocity: 45 fpm @ 85°F
Rotation: 40 rpm

Stage of Maturity: Pre-bloom, 2nd cut
Equilibrium m.c., $M_e \approx 0$
*Discoloration-black tips

TABLE A-11. SUMMARY OF DAMAGE POINT AND DRYING DATA FOR SINGLE ALFALFA LEAVES - TEMPERATURE 761°F.

Leaf No.	Initial M.C. % d.b.	Final M.C. % d.b.	$\frac{M-M_e}{M_o-M_e}$	% H_2O removed	Time, seconds
1	335.2	282.4	0.8425	15.8	2
2	283.3	179.4	0.6333	36.7	3
3	400.0	134.2	0.3355	66.4	4*
4	350.0	215.3	0.6151	38.5	4*
5	318.6	128.6	0.4036	59.6	4*
6	339.4	157.6	0.4644	53.6	5*
7	297.7	71.0	0.2385	76.0	5*
8	295.9	136.5	0.4613	53.9	4*
9	313.8	184.6	0.5883	41.2	4*

Date: 8/5/62
Air Velocity: 45 fpm @ 85°F
Rotation: 40 rpm

Stage of Maturity: Pre-bloom, 2nd cut
Equilibrium m.c., $M_e \sim 0$
*Discoloration-black edge

TABLE A-12. SUMMARY OF DAMAGE POINT AND DRYING DATA FOR SINGLE ALFALFA LEAVES - TEMPERATURE 819°F.

Leaf No.	Initial M.C. % d.b.	Final M.C. % d.b.	$\frac{M - M_e}{M_o - M_e}$	% H_2O removed	Time, seconds
1	296.0	205.3	0.6936	30.6	2
2	330.1	220.4	0.6677	33.2	3*
3	359.6	184.2	0.5122	48.8	3*
4	320.0	36.0	0.2688	73.1	4*
5	208.5	107.3	0.5146	48.5	4*
6	361.8	240.4	0.6645	33.5	3*
7	340.0	173.3	0.5097	49.0	3*

Date: 8/5/62
Air Velocity: 45 fpm @ 85°F
Rotation: 40 rpm

Stage of Maturity: Pre-bloom, 2nd cut
Equilibrium m.c., $M_e \approx 0$
*Discoloration-black edge

APPENDIX B

TABLE A-13. SUMMARY OF SPHERICITY-MOISTURE CONTENT DATA, LARGE ALFALFA LEAVES

Leaf No.	Vol. m.l.	Total surface area in^2	Sphericity Φ_s	Moisture content	Density
1a	0.067	0.934	0.133	359.8	0.906
b	0.058	0.934	0.121	280.3	0.866
c	0.051	0.820	0.127	200.8	0.778
d	0.018	0.566	0.092	0	0.733
2a	0.076	1.094	0.124	287.0	0.784
b	0.067	1.094	0.114	251.3	0.807
c	0.055	0.900	0.122	194.8	0.825
d	0.023	0.626	0.098	0	0.670
3a	0.068	0.986	0.128	346.8	0.913
b	0.062	0.934	0.127	284.2	0.861
c	0.046	0.766	0.127	192.8	0.885
d	0.018	0.434	0.120	0	0.772
4a	0.074	1.100	0.121	341.3	0.853
b	0.063	1.040	0.115	261.5	0.821
c	0.047	0.886	0.111	169.2	0.819
d	0.022	0.606	0.098	0	0.650
5a	0.064	1.066	0.115	350.8	0.902
b	0.054	0.946	0.114	242.2	0.811
c	0.037	0.706	0.119	113.3	0.738
d	0.018	0.560	0.093	0	0.711
6a	0.071	0.980	0.132	316.0	0.879
b	0.065	0.854	0.143	281.3	0.880
c	0.052	0.906	0.116	192.0	0.842
d	0.020	0.546	0.102	0	0.750
7a	0.069	1.074	0.118	336.2	0.872
b	0.062	0.946	0.125	271.7	0.827
c	0.050	0.886	0.116	89.9	0.800
d	0.020	0.586	0.095	0	0.690
8a	0.072	1.066	0.122	313.8	0.914
b	0.062	0.934	0.127	240.2	0.873
c	0.051	0.820	0.127	157.9	0.804
d	0.022	0.580	0.102	0	0.723
9a	0.065	0.960	0.127	344.4	0.862
b	0.056	0.906	0.122	286.5	0.870
c	0.041	0.754	0.119	151.6	0.773
d	0.017	0.534	0.094	0	0.741
10a	0.055	0.874	0.126	298.4	0.884
b	0.048	0.806	0.124	245.1	0.877
c	0.030	0.654	0.112	137.7	0.967
d	0.017	0.460	0.109	0	0.718

TABLE A-13 (Cont.)

Date: 9/12/63
Stage of Maturity: Pre-bloom, 3rd cut

Ave. Volume, Fresh cut, V_w = 0.071 ml.
Ave. Volume, Dried, V_d = 0.020 ml.
Shrinkage, $\frac{V_d}{V_w}$ = 0.28

TABLE A-14. SUMMARY OF SPHERICITY-MOISTURE CONTENT DATA, MEDIUM ALFALFA LEAVES

Leaf No.	Vol. m.l.	Total surface area in^2	Sphericity Φ_s	Moisture content	Density
1a	0.038	0.78	0.1096	291.5	0.845
b	0.030	0.70	0.1046	198.7	0.817
c	0.019	0.56	0.0961	90.2	0.821
d	0.012	0.42	0.0941	3.7	0.708
e	0.012	0.42	0.0941	2.4	0.700
2a	0.040	0.70	0.1258	246.0	0.883
b	0.030	0.58	0.1257	181.4	0.1060
c	0.027	0.54	0.1257	153.1	0.1059
d	0.026	0.52	0.1274	109.7	0.912
e	0.014	0.44	0.0996	19.4	0.964
3a	0.039	0.72	0.1204	180.8	0.864
b	0.025	0.56	0.1231	110.0	1.008
c	0.018	0.50	0.1161	65.8	1.106
d	0.018	0.44	0.1328	19.2	0.794
e	0.012	0.40	0.0987	0.0	1.000
4a	0.035	0.60	0.1350	277.2	0.851
b	0.027	0.54	0.1258	172.1	0.796
c	0.022	0.48	0.1241	118.9	0.786
d	0.018	0.44	0.1328	62.0	0.711
e	0.011	0.36	0.1035	11.4	0.782
5a	0.046	0.88	0.1106	402.3	0.939
b	0.039	0.72	0.1212	296.5	0.874
c	0.031	0.64	0.1166	222.1	0.894
d	0.023	0.58	0.1060	111.6	0.791
e	0.010	0.46	0.0770	0.0	0.860
6a	0.037	0.72	0.1114	254.1	1.043
b	0.026	0.62	0.1073	109.2	0.876
c	0.020	0.48	0.1165	55.9	0.850
d	0.017	0.46	0.1094	21.8	0.759
e	0.016	0.46	0.1049	0.0	0.681
7a	0.046	0.84	0.1158	236.0	0.907
b	0.038	0.74	0.1153	183.9	0.926
c	0.033	0.64	0.1218	147.6	0.930
d	0.025	0.62	0.1046	89.5	0.940
e	0.014	0.50	0.0870	0.0	0.885

TABLE A-14 (Cont.)

8a	0.042	0.82	0.1114	203.0	0.959
b	0.035	0.70	0.1153	157.9	0.980
c	0.030	0.66	0.1108	124.8	0.996
d	0.027	0.62	0.1099	81.9	0.896
e	0.016	0.54	0.0888	0.0	0.831
9a	0.034	0.66	0.1204	245.3	0.965
b	0.027	0.52	0.1317	133.7	0.822
c	0.019	0.44	0.1228	72.6	0.863
d	0.016	0.42	0.1147	20.0	0.712
e	0.011	0.36	0.1035	0.0	0.863
10a	0.047	0.74	0.1337	184.3	0.847
b	0.040	0.70	0.1258	159.3	0.907
c	0.032	0.68	0.1122	120.0	0.963
d	0.027	0.60	0.1135	45.7	0.888
e	0.016	0.48	0.1006	0.0	0.875

Date: 8/16/63
Stage of Maturity: Pre-bloom, 3rd cut

Ave. Volume, Fresh cut, V_w = 0.038 ml.
Ave. Volume, Dried, V_d = 0.013 ml.
Shrinkage, $\frac{V_d}{V_w}$ = 0.33

TABLE A-15. SUMMARY OF SPHERICITY-MOISTURE CONTENT DATA, SMALL ALFALFA LEAVES

Leaf No.	Vol. m.l.	Total surface area in^2	Sphericity Φ_s	Moisture content	Density
1a	0.020	0.314	0.178	272.0	0.930
b	0.017	0.294	0.171	234.0	0.982
c	0.010	0.240	0.147	104.0	1.02
d	0.007	0.186	0.150	0.0	0.714
2a	0.028	0.374	0.186	238.4	0.882
b	0.021	0.380	0.151	212.3	1.09
c	0.010	0.374	0.093	101.4	1.47
d	0.009	0.294	0.112	0.0	0.811
3a	0.023	0.320	0.189	242.6	0.909
b	0.022	0.300	0.196	209.8	0.859
c	0.016	0.300	0.159	80.3	0.688
d	0.008	0.214	0.141	0.0	0.763

TABLE A-15 (Cont.)

4a	0.020	0.260	0.215	264.7	0.930
b	0.015	0.254	0.182	225.5	1.107
c	0.009	0.260	0.127	127.5	1.289
d	0.008	0.194	0.155	0.0	0.638
5a	0.019	0.274	0.197	215.6	0.747
b	0.017	0.274	0.183	173.3	0.724
c	0.012	0.272	0.145	55.6	0.583
d	0.010	0.214	0.163	0.0	0.450
6a	0.022	0.274	0.217	314.3	0.659
b	0.020	0.266	0.208	228.6	0.575
c	0.016	0.240	0.201	42.9	0.313
d	0.007	0.174	0.158	0.0	0.500
7a	0.023	0.240	0.255	290.9	0.748
b	0.019	0.246	0.221	218.2	0.736
c	0.015	0.226	0.206	88.6	0.553
d	0.006	0.174	0.143	0.0	0.733
8a	0.027	0.340	0.199	284.4	0.911
b	0.025	0.314	0.208	228.1	0.840
c	0.025	0.312	0.208	123.4	0.572
d	0.008	0.226	0.135	0.0	0.800
9a	0.020	0.320	0.173	251.8	0.985
b	0.019	0.294	0.184	185.7	0.842
c	0.018	0.294	0.178	78.6	0.555
d	0.008	0.180	0.168	0.0	0.700
10a	0.025	0.300	0.214	290.0	0.796
b	0.022	0.280	0.213	260.0	0.918
c	0.018	0.290	0.181	126.0	0.628
d	0.009	0.174	0.187	0.0	0.555

Date: 9/13/63

Stage of Maturity: Pre-bloom, 3rd cut

Ave. Volume, Fresh cut, V_w = 0.023 ml.

Ave. Volume, Dried, V_d = 0.008 ml.

Shrinkage, $\frac{V_d}{V_w}$ = 0.35

TABLE A-16. SUMMARY OF SPHERICITY-MOISTURE CONTENT DATA, BIRDSFOOT TREFOIL

Leaf No.	Vol. m.l.	Total surface area in^2	Sphericity Φs	Moisture content	Density
1a	0.026	0.320	0.207	387.5	0.900
b	0.023	0.294	0.207	322.9	0.812
c	0.020	0.254	0.205	218.8	0.765
d	0.018	0.240	0.217	100.0	0.533
e	0.012	0.186	0.213	8.3	0.433
f	0.010	0.180	0.195	0.0	0.480
2a	0.028	0.360	0.193	373.7	0.964
b	0.023	0.336	0.182	235.1	0.830
c	0.020	0.334	0.167	133.3	0.665
d	0.018	0.280	0.186	54.4	0.489
e	0.015	0.240	0.192	0.0	0.380
f	0.011	0.226	0.165	0.0	0.518
3a	0.017	0.260	0.192	377.1	0.982
b	0.014	0.260	0.168	294.3	0.986
c	0.014	0.254	0.172	228.6	0.821
d	0.013	0.186	0.224	82.9	0.492
e	0.010	0.166	0.211	2.9	0.360
f	0.009	0.160	0.205	0.0	0.389
4a	0.020	0.386	0.144	358.7	1.055
b	0.018	0.354	0.147	223.9	0.827
c	0.016	0.306	0.157	106.5	0.594
d	0.013	0.246	0.170	28.3	0.454
e	0.010	0.234	0.150	0.0	0.460
f	0.009	0.226	0.145	0.0	0.511
5a	0.024	0.294	0.213	300.0	0.800
b	0.022	0.286	0.208	245.8	0.755
c	0.020	0.286	0.195	204.2	0.730
d	0.018	0.274	0.190	143.8	0.650
e	0.012	0.220	0.180	35.4	0.542
f	0.011	0.200	0.187	0.0	0.436
6a	0.023	0.386	0.158	395.2	0.904
b	0.021	0.340	0.169	316.7	0.833
c	0.019	0.326	0.165	231.0	0.731
d	0.016	0.280	0.172	69.0	0.444
e	0.014	0.214	0.205	2.4	0.307
f	0.014	0.206	0.213	0.0	0.300
7a	0.025	0.320	0.202	395.5	0.872
b	0.021	0.300	0.192	334.1	0.909
c	0.019	0.240	0.225	270.5	0.858
d	0.013	0.226	0.185	143.2	0.823
e	0.008	0.220	0.138	18.2	0.650
f	0.007	0.160	0.185	0.0	0.628

TABLE A-16 (Cont.)

8a	0.028	0.420	0.166	310.9	0.939
b	0.024	0.354	0.177	259.4	0.958
c	0.021	0.346	0.166	215.6	0.962
d	0.018	0.340	0.153	157.8	0.917
e	0.015	0.286	0.161	62.5	0.693
f	0.010	0.226	0.155	0.0	0.640
9a	0.021	0.326	0.176	362.7	1.124
b	0.020	0.306	0.182	311.8	1.050
c	0.016	0.274	0.176	352.9	1.125
d	0.014	0.260	0.181	170.6	0.986
e	0.012	0.242	0.164	54.9	0.658
f	0.010	0.226	0.155	0.0	0.510
10a	0.024	0.340	0.185	475.7	0.888
b	0.022	0.326	0.182	391.9	0.827
c	0.017	0.280	0.178	291.9	0.853
d	0.016	0.274	0.175	172.3	0.631
e	0.013	0.220	0.190	32.4	0.377
f	0.009	0.186	0.176	0.0	0.411

Date: 9/9/63
Stage of Maturity: 10% bloom, 3rd cut

Ave. Volume, Fresh cut, V_w = 0.029 ml.
Ave. Volume, Dried, V_d = 0.01 ml.
Shrinkage, $\frac{V_d}{V_w}$ = 0.42

APPENDIX C

SMOKE POWDER TERMINAL VELOCITY

Smoke powder: Norit "A" (activated charcoal)

Chemical compound: Carbon

Sieve Analysis:

Mesh Size	Particle Dia., D_p, mm	Weight Over Screen, %
60	0.25 or greater	0.29
140	0.10 or greater	1.97
300	0.05 or greater	16.75
Thru 300	less than 0.05	81.00

Density of air at 212°F, 1% R.H.: ρ_f = 0.06 lb. per cu. ft.

Viscosity: μ = 0.0218 centipoises

Density of particle: ρ_s = 33.0 lb. per cu. ft.

$\rho_s - \rho_f = 33.0 - 0.06 = 32.94$ lb. per cu. ft.

Diameter of particle = 0.05 mm = 0.00197 inches

From Figure 28, the terminal velocity U_t can be determined by the following steps of procedure:

1. Start at left hand axis ρ_f = 0.06 ....pt 1
2. Connect with μ = 0.0218 ....pt 2
3. Intercept "a" axis at ....pt 3
4. Also intercept "c" axis at ....pt 3′
5. From pt 3 on "a" axis to (ρ_s - ρ_f) = 32.94 ..pt 4
6. Cross "b" axis at ....pt 5
7. From pt 5 to particle diameter, D_p = 0.00144....pt 6

8. Intersect "d" axis at ....pt 7

9. Follow pattern to "e" axis at ....pt 8

10. Connect 3' with pt 8, intersect "f" axis at ...pt 9

11. Connect pt 6 with pt 9, intersect U_t at ....pt 10

From this analysis, the terminal velocity $U_t = 0.1$ fps. This value checks with observed free fall values within 10%. With the small magnitudes in comparison with the velocity of the fluidizing air, this was neglected in the velocity calculations.

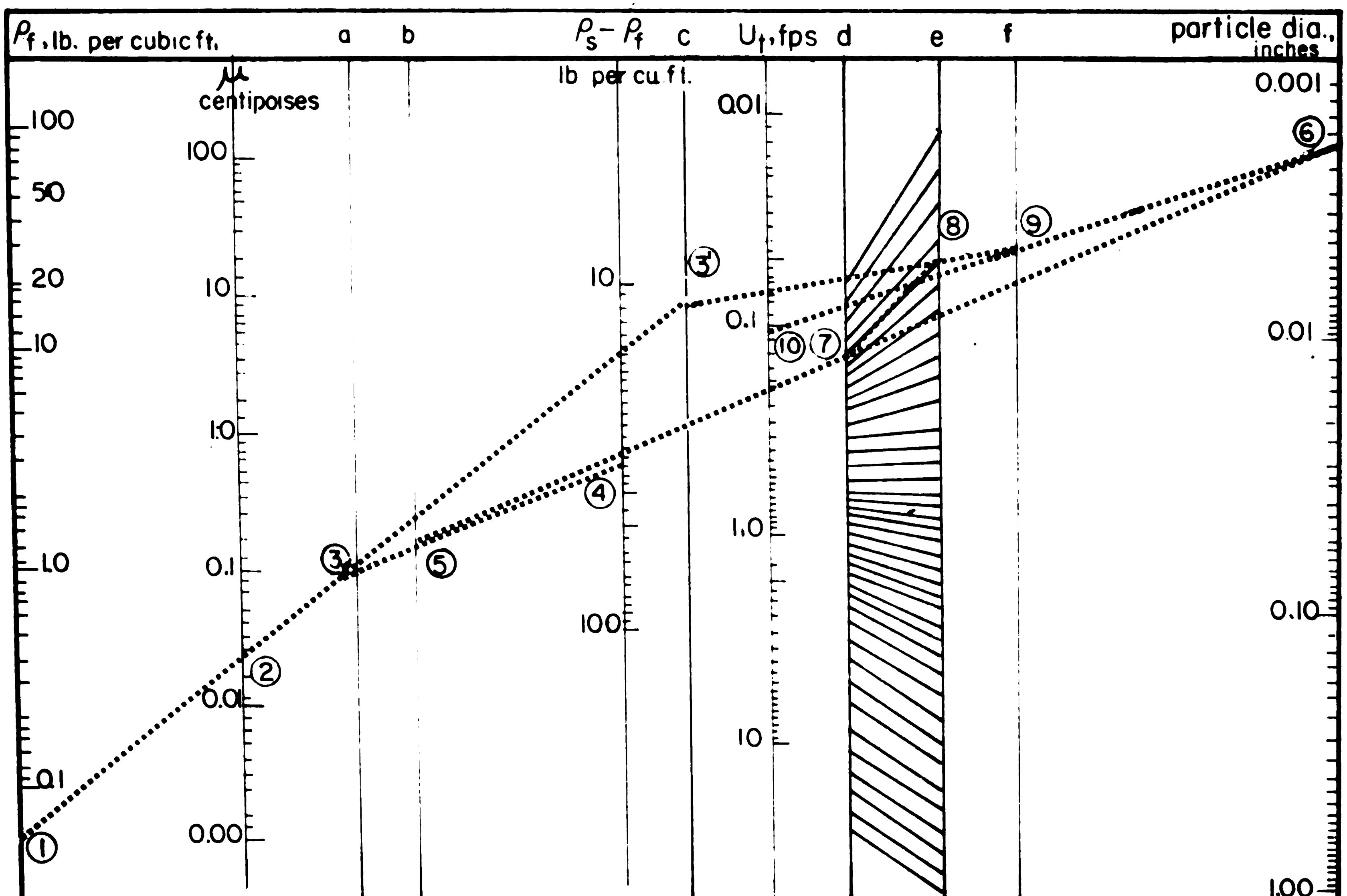

FIGURE 28 NOMOGRAPH FOR EVALUATION OF PARTICLE TERMINAL VELOCITY, LEVA (1959)

THEORETICAL TERMINAL VELOCITY FOR ALFALFA STEMS AND LEAVES

Stoke's Law, Binder (1943), is applied to particles of the following dimensions to determine their terminal velocities;

Quantity	Fresh Stem (1 in.)	Dried Stem 25% (mcdb)	Fresh Leaf	Dried Leaf 25% mcdb
Diameter, d, in.	0.090	0.073	xxx	xxx
Thickness, t, in.	xxx	xxx	0.010	0.009
Projected Area, Ap, $ft^2 x10^4$	6.25	5.07	25.7	16.6
Crossection Area, Ac, $in^2 x10^3$	6.36	4.20	xxx	xxx
Volume, V, $in^3 x10^3$	6.36	420	2.9	.97
Weight, w, $lb.x10^5$	18.3	7.52	9.02	3.15
Density, ρ, lb/cu.ft.	50.20	30.85	54.52	52.85
Area/Weight, ft^2/lb	3.41	6.75	28.38	52.70

Stems are approximated as cylinders, $C_d = 1.7$, $R_e = 50$

Leaves are approximated as disks, $C_d = 1.2$, $R_e = 150$

Sample calculation:

$$U_t^2 = \frac{2\,W}{\rho C_d A}$$

Assume: air entering @ 500°F, $\rho = 4.13 \times 10^{-2}$ lb/ft^3

$\mu = 1.900 \times 10^{-5}$ lb/ft sec.

air leaving @ 300°F, $\rho = 5.23 \times 10^{-2}$ lb/ft^3

$\mu = 1.615 \times 10^{-5}$ lb/ft sec.

For example:

Fresh cut stem, 1 inch long, air entering @ 500°F

$$U_t^2 = \frac{2 \quad (18.3 \times 10^{-5}}{1.7 \quad (4.13 \times 10^{-2})(6.25 \times 10^{-4})} = 8.33$$

$$U_t = 2.89 \text{ ft/sec; } 174 \text{ ft/min}$$

$$R_e = \frac{(4.13 \times 10^{-2})(2.89)}{(1.90 \times 10^{-5})} \frac{(0.09)}{12} = 47$$

Similarly, the following values of U_t can be determined along with Reynolds number, R_e.

Particle	Air Temp. °F	Term Velocity, U_t ft/sec	ft/min	Reynolds Number R_e
Fresh Stem (1 in.)	500	2.89	174	47
Dried Stem (1 in.)	300	1.83	110	36
Fresh Leaf	500	1.19	71	148
Dried Leaf	300	.78	47	117

APPENDIX D

SAMPLE CALCULATIONS FOR MASS RATE OF FLOW AND MOISTURE REMOVAL RELATIONSHIPS

Test No.: 15c
Date: 9/22/63
Material: Fresh Birdsfoot Trefoil Leaves
Quantity: 1.0501 g (89 leaves)
Stage of Maturity: 10% Bloom, 3rd cut
Atmos. Air: Temp. = 85°F; R.H. = 25%; ρ = 0.072 lb/ft^3
Air In: Mean Temp. = 242°F; R.H. = 0.8%; ρ = 0.05 lb/ft^3
Air Out: Mean Temp. = 141°F; R.H. = 6%; ρ = 0.066 lb/ft^3
Fluidization Immediate

Divergence of Velocity Field Data, Test 15c

Photocells,	1-2	2-3	3-4	4-5	5-6
Dist. Between, ft.	2.63	2.42	2.38	2.54	2.08
Oscillograph Chart Output, Units*	4.8	5.1	5.7	6.2	6.0
Time, Secs.	0.19	0.20	0.23	0.25	0.24
Velocity, fps	13.6	11.8	10.4	10.2	8.7

*Oscillograph chart output speed = 25 units/sec., one unit = ½ centimeter.

$$\text{Time} = \frac{\text{No. units}}{\text{units/sec.}} = \frac{6.0}{25} = 0.24 \text{ secs.}$$

$$\text{Velocity} = \frac{2.08}{0.24} = 8.7 \text{ ft/sec.}$$

Mass Velocity, lb/ft^2 hr. = Velocity x Density x 3600

= 8.7 x 0.066 x 3600 = 2060 lb/ft^2 hr.

Moisture Removal Data, Test 15c

Time, Secs.	Initial M.C. % d.b.	No. Leaves Out	Dry M.C. % d.b.	Leaves Out %	Sub Total Leaves out %
10	380.2	17	209.2	19.1	19.1
20	380.2	30	198.0	33.7	52.8
30	380.2	13	173.9	14.6	67.4
40	380.2	4	154.8	4.5	71.9
50	380.2	0	-	-	-
60	380.2	3	156.7	3.4	75.3
70	380.2	2	80.6	2.2	77.5
80	380.2	1	7.1	1.1	78.6
90	380.2	3	22.6	3.4	82.0
100	380.2	-	-	-	-
110	380.2	-	-	-	-
4 min	380.2	16	103.8	18.0	100.0

a) Weight of feed, fresh cut leaves = 1.0501 g
b) Weight of feed, bone dry = 0.2187 g
c) Weight of total H_2O in feed, w_o = 0.8314 g
d) Initial moisture content, % d.b. = 380.2%
e) Weight of H_2O removed in process, $w_o - w_1$ = 0.3729 g
f) H_2O removed %, $\frac{w_o - w_1}{w_o} \times 100 = 44.8\%$

Schrenk's parameter (1959) = $\frac{w_o}{w_1} - 1$

w_o = weight of H_2O in feed lb/lb bone dry

w_1 = weight of H_2O in product lb/lb bone dry

g) $1 - (f) = 1 - \frac{w_o - w_1}{w_o} = \frac{w_1}{w_o} = 0.552$

h) $\frac{1}{(g)} = \frac{w_o}{w_1} = 1.815$

i) $\frac{w_o}{w_1} - 1 = 1.815 - 1 = 0.815.$

TABLE A-17. SUMMARY OF MASS RATE OF FLOW AND MOISTURE REMOVAL DATA, TEMPERATURE = 200°F.

Test No.	Entrance Velocity fps	Exit Velocity fps	Mass Rate of Air Flow, Vmass lb/ft^2 hr.	H_2O Removed %	Moisture Removal ratio, w_o/w_1 -1
6c	14.5	7.2	1735	32.2	0.48
6a	15.5	7.3	1835	32.9	0.49
6b	15.2	7.2	1760	35.4	0.55
5a	13.7	8.4	2021	22.6	0.28
5c	13.9	9.0	2160	15.8	0.19
5b	14.2	8.4	2160	16.9	9.21
7a	16.4	9.3	2270	13.6	0.16
18b	16.3	9.4	2280	12.0	0.14
18a	16.3	9.6	2320	10.9	0.12
7b	15.6	9.8	2400	15.0	0.18
7c	16.3	10.0	2450	10.6	0.12
8c	16.4	11.0	2700	8,4	0.09
8b	16.4	11.5	2830	9.1	0.10
8a	16.8	11.5	2830	7.9	0.09

TABLE A-18. SUMMARY OF MASS RATE OF FLOW AND MOISTURE REMOVAL DATA, TEMPERATURE - 250°F.

Test No.	Entrance Velocity fps	Exit Velocity fps	Mass Rate of Air Flow, Vmass lb/ft^2 hr.	H_2O Removed %	Moisture Removal ratio, w_o/w_1 -1
15a	14.5	8.7	2060	33.9	0.52
15c	13.6	8.7	2060	44.8	0.82
16a	13.6	8.0	1900	45.3	0.83
16b	13.1	7.3	1740	53.1	1.13
16c	13.3	7.8	1840	44.9	0.82
17a	14.9	10.4	2510	23.4	0.31
17b	14.5	10.4	2510	16.2	0.20
17c	15.2	10.0	2410	19.3	0.24

TABLE A-19. SUMMARY OF MASS RATE OF FLOW AND MOISTURE REMOVAL DATA, TEMPERATURE = 300°F.

Test No.	Entrance Velocity fps	Exit Velocity fps	Mass Rate of Air Flow, Vmass lb/ft^2 hr.	H_2O Removed %	Moisture Removal ratio, w_o/w_1 -1
28a	15.2	9.0	2110	64.2	1.79
28b	13.9	9.5	2220	68.7	2.19
26a	17.2	10.4	2440	56.9	1.32
26b	16.8	11.1	2590	43.6	0.77
26c	16.3	12.1	2830	55.0	1.22
27c	18.2	12.7	3020	12.6	0.28
27b	17.2	12.7	3020	28.6	0.40
27a	17.2	14.0	3330	21.8	0.14