# SOME BASIC PROPERTIES OF THE COFFEE FRUIT AND COFFEE BEANS

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Adolfo Eschenwald

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By

ADOLFO ESCHENWALD

AN ABSTRACT

SUBMITTED TO THE COLLEGE OF AGRICULTURE OF MICHIGAN STATE UNIVERSITY OF AGRICULTURE AND APPLIED SCIENCE IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

DEPARTMENT OF AGRICULTURAL ENGINEERING

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## ABSTRACT

The investigation is primarily concerned with the experimental determination of basic engineering properties of the coffee fruit and parchment coffee beans. Little work has been done on this subject. The scant and incomplete information available is only on a limited phase of the problem, namely drying.

A practical means of shipping fresh coffee fruits from Puerto Rico to Michigan State University was worked out so that the green and ripe fruits arrived in perfect condition. Best temperatures and relative humidities for storage in a fresh condition were also determined. The equipment and the working procedure was prepared ahead of time and tested. Shipping schedules were planned carefully.

Data are presented on:

1. Coefficient of friction and angle of repose of coffee fruit and coffee beans
2. Initial rebounding or resiliency studies for coffee fruits
3. Specific gravity and bulk density
4. Air flotation and conveying velocities
5. Air flow relationship
6. Exposed drying rates
7. Equilibrium moisture contents for parchment coffee and
8. Preliminary studies on electronic sorting of green and ripe fruits.

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# SOME BASIC PROPERTIES OF THE COFFEE FRUIT AND COFFEE BEAN

## INTRODUCTION

Coffee is a very important crop in the world market. The economy of several nations in North America, South America, Africa and Asia depend to a great extent on the production, harvesting, processing and marketing of coffee. (World Summaries, 1958) (Guiscafré, 1953). Over 90 percent of the American families serve coffee and more American families use coffee regularly than any other table served item except sugar and salt. Per capita consumption has increased tremendously in the United States of America. (Horn, 1954). A great amount of research work has been done on varieties and cultural practices. Very little basic information is available on processing. The regular routine of hundreds of years is being followed in this important phase of the preparation of the crop for the market. Some of the sparsely available information is contradictory and is based on experiences or observations with little or no research data. This condition is aggravated by the fact that coffee is a product that requires considerable handling and processing on the farm before it is ready for the market. The very poor keeping qualities of the unprocessed product and the susceptibility to rapid deterioration in quality makes the improvement of processing very challenging. (Eschenwald, 1957) (Vivaldi, 1957). It is a well known and accepted principle that a coffee tree, of the right variety, produces top quality coffee. It is also very well known and generally accepted that very little if anything can be done to improve this already present quality. On the other hand quality can be rapidly and permanently impaired without affecting the appearance of the processed product. (Baron Goto, and Fukvnaga, 1956) (Howard, 1954) (Lockhart, 1956).

For years, coffee production and processing has been living in the past and has become static in many of its phases. The picking, handling, sorting and processing of the crop are good examples. Coffee needs scientific research and a logical start is uncovering basic, preliminary data that might serve as basis for future developments. Toward these goals has this work been directed.

A brief summary follows for those who are not familiar with the coffee production. Coffee is produced in the tropical regions of the world under a great variety of conditions ranging from very intensive to very extensive forms of cultivation. It is grown at elevations varying from sea level to as high as 5,000 to 7,000 feet. The lower elevation orchards are usually in the higher latitudes ($22^{\circ}$ to $25^{\circ}$). The optimum temperatures seems to be a minimum of $60^{\circ}$ F. and a maximum of about $80^{\circ}$ F. with very little fluctuations below or above these limits. (Debecca, 1958) (Heyman, 1955).

The general botanical classification of coffee is still confusing when dealing with varieties and species. A general accepted classification follows: (Core, 1955) (Jordan, 1957).

| | |
|---|---|
| Kingdom | - Vegetable |
| Sub-kingdom | - Angiospermae |
| Class | - Dicotyledoneae |
| Sub-class | - Simpetalae |
| Order | - Rubiales |

| | |
|---|---|
| Family | - <u>Rubiaceae</u> |
| Genus | - <u>Coffea</u> |
| Sub-genus | - <u>Eucoffeae</u> |
| Specie | - <u>arabica</u>, <u>liberica</u>, <u>canephora</u>, <u>robusta</u>, and many others |

Under average conditions it takes from four to five years, from the preparation of the seed bed, to the time the trees start bearing fruit. Full production is obtained after the sixth year.

The coffee fruit has been called a cherry or a berry. It is a drupe, normally containing two seeds. Occasionally there occurs three or more seeds as tri-celled or pluri-celled ovaries or through false polyembryony. On the other extreme, a one-seeded fruit is common due to the abortion of an ovule. The fruit, originally green, turns to a yellowish green and finally to a cherry red color on ripening. It is formed by the following layers from the outside to the center: Epicarp or pulp, mesocarp or mucilage, espermoderm, and embryo. Some countries store or export their coffee as parchment coffee and some as hulled coffee. Hulled coffee, when the parchment has been removed, is known as green coffee. Parchment coffee has a longer keeping quality than green coffee. For general calculations of quantity and for statistical data all coffee, either parchment or green, is expressed as green coffee.

The fruit is picked by hand when completely ripe. All efforts, so far, to mechanize the picking has failed due to the flowering and fruiting habits. Some progress has been attained in the efficiency of hand pickers by the application of time and motion studies where the basic movements (Therblings) have been analyzed and simplified (Eschenwald, 1957).

As soon after harvest as feasible, the processing must be started and should not be stopped until the seeds are dried to about 12 to 13 percent moisture content, dry basis. There are two general ways of processing coffee according to the procedure followed. These are known as dry processing and wet processing. Dry processing is practiced only in places where water is scarce or in backward areas of extensive cultivation where quality is not considered. Wet processing is more costly and elaborate. It requires more facilities, equipment, machinery and know-how. The commodity obtained is of far superior quality. This is the method followed in the more intensive and specialized areas of production. Figure 1 shows a wet processing flow chart.

The basic steps in the wet process method are as follows:

1. Pulping - removal of the epicarp. This is done very efficiently by machines of various design. (Baron Goto and Fukunaga, 1956) (Eschenwald, 1957) (Gutierrez and Alvarez, 1957).
2. Demucilaging - removal of the mesocarp. The mesocarp, which consists mainly of pectines is removed by three generally used methods which can be classified as fermentation, chemical and mechanical (Alvarez, 1956) (Blasingame and Eschenwald, 1954) (Carbonell and Vilanoua, 1952) (Eschenwald, 1957) (Hansen, 1952).
3. Washing - once the mucilage is removed, the coffee beans are thoroughly rinsed in clean water.
4. Drying - the drying process must be started immediately or the beans must be kept for short periods of time under circulating water. Drying is done in the sun or by using heated air dryers. The use of indirectly heated air dryers is becoming more and more

a part of coffee production. During all these stages in the processing the fruits and the beans must be handled several times before the product is ready for the market. Basic engineering data are essential for more efficient handling and processing of the coffee crop.

A summary of the world coffee production and export follows. (World summaries, foreign crops and markets, U.S.D.A., 1958).

Table 1. World green coffee production, 1000 Bags a)

| Continent | Year | | | | | Percent of Total Prod. | Percent Increase in Prod. |
|---|---|---|---|---|---|---|---|
| | 1954-55 | 1955-56 | 1956-57 | 1957-58 | 1958-59 Estimated | 1959 | 1954 to 1959 |
| North America b) | 7,489 | 7,823 | 7,750 | 8,575 | 8,525 | 14.5 | 14 |
| South America c) | 26,022 | 31,575 | 26,040 | 32,780 | 37,980 | 65.0 | 46 |
| Africa d) | 7,112 | 8,749 | 8,775 | 8,600 | 9,560 | 16.3 | 34 |
| Asia & Oceania e) | 1,565 | 2,201 | 2,625 | 2,590 | 2,590 | 4.2 | 59 |
| Total World Production | 42,188 | 50,348 | 45,190 | 52,545 | 58,655 | | |

a) 132.276 pounds each

b) Major producers - Costa Rica, Cuba, Dominican Republic, El Salvador, Guatemala, Haiti, Honduras, Mexico and Nicaragua.

Minor producers - Hawaii, Guadalupe, Jamaica, Panama, Puerto Rico and Trinidad.

c) Major producers - Brazil, Columbia, Ecuador, Peru and Venezuela.

Minor producers - Bolivia, British Guiana, Paraguay and Surinam.

d) Major producers - Angola, Belgian Congo, Cameroum, Ethiopia, French West Africa, Kenya, Madagascar, Tanganyika, Togo and Ugnada

Minor producers - Cape Verde, Ghana, French Equatorial Africa, Liberia, Nigeria, Sao Tome, Sierra Leone and Spanish Guinea.

e) Major producers - India, Indonesia and Yemen.

Minor producers - New Caledonia, New Hebrides. North Borneo Philippines, Portugese Timor and Vietnam.

Table 2. World green coffee exportable production
1000 Bags a)

| Continent | Year | | | | | Percent Exportable Production |
|---|---|---|---|---|---|---|
| | 1954-55 | 1955-56 | 1956-57 | 1957-58 | 1958-59 Estimated | |
| North America b) | 5,437 | 5,779 | 5,830 | 6,580 | 6,615 | |
| South America c) | 20,984 | 28,286 | 18,475 | 28,025 | 33,745 | |
| Africa d) | 6,839 | 8,395 | 8,330 | 8,140 | 9,095 | |
| Asia & Oceania e) | 662 | 1,157 | 1,737 | 1,635 | 1,590 | |
| Total World Exportable Production | 33,922 | 43,617 | 34,372 | 44,380 | 51,045 | 87 |

a) 132.276 pounds each

b) Major producers - Costa Rica, Cuba, Dominican Republic, El Salvador, Guatemala, Haiti, Honduras, Mexico and Nicaragua.

Minor producers - Hawaii, Guadalupe, Jamaica, Panama, Puerto Rico and Trinidad.

c) Major producers - Brazil, Columbia, Ecuador, Peru and Venezuela.

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e) Major producers - India, Indonesia and Yeman.

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The United States is the major coffee importer with a total of 2,761,190,000 pounds imported in 1957 which has a cash value of 1,375,736,000 dollars.

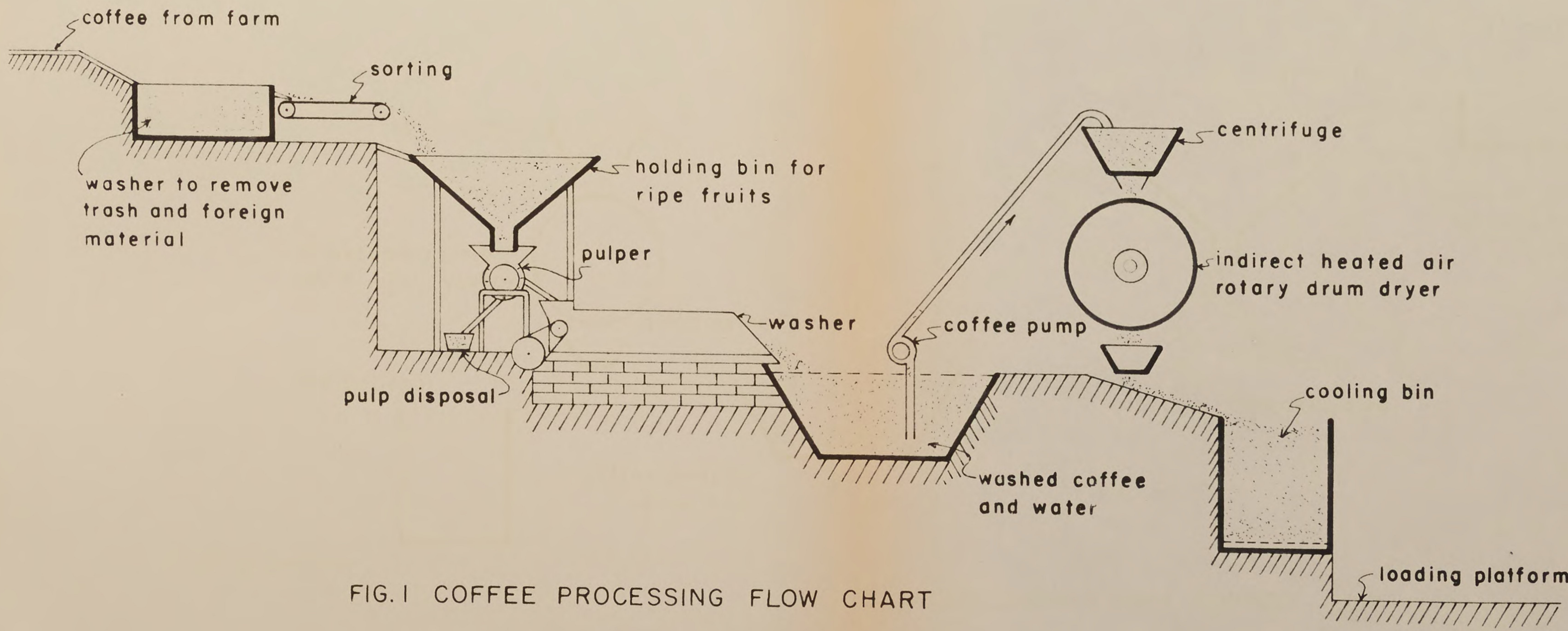



FIG. I COFFEE PROCESSING FLOW CHART

## OBJECTIVE

The main objective was to determine some basic properties of the coffee fruit and coffee beans. The following were evaluated:

1. Coefficients of friction and angle of repose.
2. Rebounding characteristics of green and ripe fruit.
3. Specific gravity and bulk density.
4. Air flotation and conveying velocities.
5. Resistance to air flow.
6. Drying rates.
7. Equilibrium moisture contents.
8. Electronic sorting.

## MATERIAL USED

The coffee fruits (_coffea arabica_, _forma nativa_) used in this study were shipped from Puerto Rico by air freight during 1958 coffee harvesting season. Harvesting starts at the beginning of June in the lower, warmer sections and lasts till November in the higher and cooler parts. Getting the fruits in good condition was one of the most difficult and sometimes discouraging part of the work due to the human element involved. Unlimited cooperation, precise timing, and desire to succeed were essential but not always present and some shipments were a total loss. The complete lack of information as to the storage and transportation of the coffee fruit was also a great handicap to the project. Some small test shipments were sent upon request, by personal friends in the western part of the island. Others were sent by the Puerto Rico Experiment Station, from their Coffee Sub-station located in the central mountainous region. These shipments, 5 in total, amounted to 30 pounds of green and 30 pounds of ripe fruits. Packed in different ways, but not refrigerated, all the ripe fruits in everyone of the shipments suffered some discoloration in the short period required for air transportation. The seeds or beans, however, were not affected since they are very well protected by all the outer layers of the fruit. These were used for some of the preliminary determinations. In order to get a fresh fruit with a natural color a survey of previous work along this line was conducted. Two methods of approach were followed namely: literature and contacts with specialists. The results were negative in both cases since no basic work has been done in coffee fruit storage and transportation. The use of information available for other crops serves as a guide to plan for a carefully well-timed shipment where a combination of cooling, aeriation, and carbon dioxide atmosphere were to be provided (Goetz, 1955) (Guillow, 1958) (Pentzer, and Heinze, 1954). A special box was prepared by the Agricultural Engineering personnel at the College of Agriculture, University of Puerto Rico for a trial shipment. Twenty pounds of green fruits and twenty pounds of ripe fruits, recently picked, were placed loosely in onion bags. These, in turn, were placed in separate, partially insulated, compartments of the wooden box and dry ice was placed in the center. The package was sent immediately by air freight and picked up at the Lansing airport two days after shipment. The correct timing in the picking, packaging and sending enabled receiving fresh fruit in very good condition and with all their natural color. Part of the fruits were taken immediately to the Electronic Sorting Company at Lowell, Michigan. Previous arrangements had been made to run some electronic sorting tests of green and ripe fruit. The rest of the fruit was stored at 50° F. and approximately 90 to 95% relative humidity. The general principle that tropical and sub-tropical fruits and vegetables require a high storage temperature and a very high relative humidity was followed (Biale, 1950) (Rose, et. al., 1954) (Ulrich, 1958) (U.S.D.A, 1953). The equipment and materials needed for the determinations, where fresh fruit was required, has been prepared and tested before-hand. In this way the tests were conducted in the minimum time and when the fruits were in the best condition of freshness. For the rest of the study, periodic samples were taken from storage, processed and used. Under these conditions the fruits, which normally are very perishable, lasted for 6 weeks in good condition.

Color pictures taken after 30 days storage show the fruits are still fresh and of a natural color (Fig. 17). At the end of six weeks the ripe fruits start to soften and develop mold and the green ones were turning yellow and ripening slowly. The beans inside the fruit, however, were normal in appearance.

## REVIEW OF LITERATURE

The review of literature is presented for each of the aspects covered in the study and is therefore composed of eight parts. No work has been reported on coffee or any of the specific fields covered here so the review of literature is based on similar work done for other crops or work done on coffee in related fields.

1. Coefficient of friction and angle of repose.

Wifred (1898) reported results of studies on angle of repose, coefficient of friction and bulk densities for wheat, barley, oats, corn, beans, peas, tares, and flax seed on rough boards, smooth boards, iron and concrete.

Jamieson (1905) coefficients of friction between wheat and various materials of construction were reported.

Ketchum (1911) reported data compiled from experiments conducted by V. Pleissner on the coefficient of friction for wheat and rye and bin wall material. The ratio of the lateral to the vertical pressure exerted by the grain is also discussed as a function of the bin wall material. Values reported for similar materials and grain vary some from the values reported by Jamieson (1905) probably due to variety and moisture content.

Kramer (1944) reported the angle of repose and coefficient of friction for rice and several construction materials. The moisture content of the product was considered.

Hintz and Schinke (1952) determined the coefficient of sliding friction for chopped corn and alfalfa on steel at sliding velocities from 0 to 6000 fpm. Results show that the sliding coefficient of friction above 1000 fpm did not vary much from 0.5. At velocities below 1000 fpm the results vary widely.

Richter (1954) conducted laboratory tests to determine friction coefficients for chopped hay, straw and silage on galvanized steel. Static coefficients were determined by a weight system in which the weight required to start motion gave a measurement of friction force. Sliding coefficients were determined by sliding a surface under the product and recording the pull exerted at different velocities on a spring balance. Polishing of the steel surface reduced the coefficient of dry materials but had a lesser effect on the coefficient for moist material. There was a distinct tendency toward higher static coefficients for moist materials at the lower unit pressures. There were only small effects on the sliding coefficients of any material as a result of varying sliding velocities or unit pressures. Results are summarized as follows:

| | Range | Recommended valves |
|---|---|---|
| **Chopped hay and straw** | | |
| Static coefficient | 0.17 - 0.42 | 0.35 |
| Sliding coefficient | 0.28 - 0.78 | 0.30 |
| **Silages** | | |
| Static coefficient | 0.52 - 0.82 | 0.80 |
| Sliding coefficient | 0.57 - 0.78 | 0.70 |

2. <u>Resiliency or rebounding of coffee fruit</u>.

There is no literature available along this line for any crop. The reason seems to be that any rough handling will seriously damage the product. There is the possibility that this is not the case with coffee fruits since the outer layers protect very well the bean and the outer layers are removed in processing.

3. <u>Specific gravity and bulk density.</u>

Zink (1935) points out that the specific gravity of a product is expressed as the ratio of mass of the body to the mass of an equal volume of water at 4° C. Work on specific gravity and air space in grain and seeds were performed by the use of specific gravity bottle principle. Mercury was used as a fluid. Air entramped in the crevices and brush of some seeds gave an error estimated as 0.1 difference in specific gravity.

Pflug <u>et</u>. <u>al</u>., (1955) designed, constructed and operated at M.S.U. a specific gravity separator for potatoes. It consists of a separating tank, a reservoir tank, two conveyors and a circulating pump. Sodium chloride brine was used as the separating medium. The brine specific gravity was calibrated at 1.080. All potatoes that had 1.080 or higher specific gravity sink to the bottom where they were removed by a conveyor. All potatoes that had less than 1.080 specific gravity value floated and were picked out by a second conveyor located at a higher level. In the fraction separated as floaters 15 to 20 percent were in the specific gravity range of 1.080 to 1.085 with the remainders below 1.080.

4. Air flotation and conveying velocities.

Sturtevant Division of Westinghouse Corporation (1946) developed air velocities and air volume curves for conveying material. The weight used is not the true density of the material but the average bulk weight of a cubic foot of the material in the condition in which it is to be conveyed. This work was reprinted in the Agricultural Engineering Yearbook, 1958.

United States Department of Agriculture, Grain Storage Laboratories (n.d.), worked out air velocities required to cause loose grain to move along the bottom of ducts.

Madison (1949) published some generally used conveying air velocities. The conveying velocity being directly related with the bulk density of the product. He reported that it is easier to convey material in a vertical pipe than in a horizontal one, in that lower velocities may be used to satisfactorily float the material. In a horizontal pipe too low a velocity allows a separation of the material from the air stream.

Rice (1958) found that the particles with dimensions approaching sphere or cubes required the greatest velocity for conveying.

5. Air flow relationships.

Henderson (1943) determined and evaluated the air flow relationships for shelled corn. Information was needed for the design of natural and mechanical ventilating and drying systems. Results of the test were mathematically expressed and the fundamental formula for clean shelled corn developed as follows:

$Q = K P^{c}$ where $Q$ = cfm per square foot

$K$ = function of depth of grain

$c$ = slope of the curve

$P$ = pressure drop in inches of water

Shedd (1945) conducted some work on the resistance of ear corn to air flow. Full size bins were used since ear corn tend to bridge and the smaller the bin the less the compaction. Air flow rates of 10, 20, 30, 40, 50, 60 and 70 cfm per square foot were used. Air flow measurements were done with a pitot tube located in the pipe between the fan and the bin. Data which were plotted on logarithmic scale with air flow, Q, versus static pressure, P, resulted in a straight line. A formula of $Q = aP^{b}$ represents the air flow--static pressure relationship.

Shedd (1951) reports data on the resistance of grain to air flow. The air was supplied by an entirely different mechanism than the one used so far. An inverted bell over a reservoid full of water was used and as the bell was pushed up or down air circulates through the grain in either direction. He found that when drawing air through the grain the minus static pressure was slightly less than the positive static pressure found when forcing air through. The condition of packing, moisture contents and foreign material caused more variations in air flow than had been expected. He observed that in a batch drying operation, a favorable factor would be that the grain shrinks first at the bottom of the bin as it dries. This would cause the grain to be less densely packed after drying has started than at the beginning of the drying operation.

Shedd (1953) stated that if the air flow-static pressure relationship when ploted in logarithmic paper come out as a straight line this relationship could be expressed by the already mentioned formula. $Q = aP^c$ where $Q$ = air flow in cfm per square foot; $P$ = pressure drop per foot depth of grain in inches of water a and c = constants for any one lot and condition of grain. He also found that the general slope of the curve is greater for fine material than for a coarse one. If the material is fine the formula will fit the curve for only a narrow range of rates of air flow. Fine material produce a convex curve when the air flow is plotted versus the pressure drop.

Hall (1955) presents a method for rapidly and accurately determining air-flow values in grain drying structures of non-rectangular cross section. Plotting in logarithmic scale the air-flow in cfm per square foot against the depth of grain in inches for various static pressures a straight line relationship was obtained. These isopressure lines are very easily used to find the resistance of a certain air flow for any depth of the grain.

6. <u>Exposed drying rates</u>.

Madison (1949) published a table of drying temperatures and drying time for different crops. Temperatures from 140° F. to 150° F. for 40 hours are recommended for coffee drying.

Lopez (1952) found that high drying temperatures, from 60° to 105° C. (140° to 221° F.) cause a corresponding increase deterioration in quality until completely ruined from the aroma and flavor point of view. He also reported that the higher the initial water content of the product the lower the initial drying temperature to use. The heating of the water in the product increases its ability to dissolve organic compounds. These compounds move with the water to the outer layers of the bean where the heat volatilizes all the low boiling point aromatic constituents resulting in a very low quality product. As the bean dries out this solvent action is less pronounced and higher than starting temperatures can be used safely.

Llewelyn (1955) states that drying of coffee should be done in three stages, namely:

Stage 1 - fully wet (approx. 54% w.b. moisture content) to skin dry (43%) using sun drying and thin layers of grain until such time as specially-designed dryers become available.

Stage 2 - skin dry to black stage (20-25%) using bed or rotary dryers of conventional design.

Stage 3 - black stage to final stage (about 11% w.b. moisture content) using ventilated silos.

Ives (1955) reports studies conducted in Turrialba, Costa Rica since 1949 trying to find a method of drying coffee without processing. No practical results have been attained due to the stale, vinegar like flavor of the final product. In 1952 the studies were modified. A fast means of drying processed coffee was then the main goal. When a temperature of 180° F. was attempted for fast drying the coffee beans show a very marked bleaching which makes them unsuitable for the market. When the initial drying is done at low temperatures higher final drying temperatures could be used safely. As pointed out by Lopez (1952) fast drying with high temperatures, independent of previous processing, always produce low quality coffee.

Hall (1956) stated that the exposed drying rate of a product can be used for determining the effect of temperature and air flow on drying. Data on drying sugar beet seeds in single layers and in four inch layers are presented.

McCloy (1956-57) reports that the experiments started by Llewelyn, (1955) were continued in an effort to find a mechanical means of drying arabic parchment coffee, which cause little or no loss of quality. Fifty-eight field scale experiments on bed driers and sixteen on radial flow and flow-ventilated silos have shown that the suggested method by Llewelyn avoids the severe damage known to be caused by simple single-stage drying in about 24 hours, but may cause overall damage decreasing the coffee by one market class and thus the value. The damage occurs principally during Stage 2 with coffee which has first been skin-dried in the sun and then mechanically dried in conventional dryers in a 24-hour cycle with an air-inlet temperature of 120° F. Damage is somewhat more pronounced if fully wet coffee is put into the dryer. The Stage 2 process has been extended to a 48-hour cycle using temperatures of 100° F., but damage has not been eliminated. Two practicable methods for immediate use which should not cause any more damage to quality than would occur with sun-drying under difficult conditions are recommended as follows:

1. Sun-dry to the black stage and finish-dry in a conventional dryer using a temperature around 100-120° F. in a 24 hour cycle.
2. Sun-dry to the skin-dry stage and machine-dry at about 120° F. in a 24-hour cycle to the black stage and finish in the sun.

Coffee damaged by incorrect methods of drying develops a characteristic brown-yellow color and a sour and unpleasant liquor results.

Laboratory experiments have confirmed the field-scale findings and investigations aimed at determining the circumstances under which losses of quality occur, have given the following tentative findings:

1. Fully wet coffee will be severely damaged by a single-stage drying at any temperature over 100° F.
2. The lower the initial moisture content at which mechanical drying is started, the less is the damage, at any temperature over 100° F.
3. Sunlight is probably not an essential factor.
4. Severe damage to quality caused by mechanical drying is probably associated with damage to viability.
5. It is possible that a critical temperature below 100° F. exists, below which fully wet coffee can be dried in one stage without damage.

Hall (1957) presents fully the theory of drying and points out that there is a difference between common drying and mechanical drying of farm products. He points out the effect of drying temperature on viability and on the chemical structure and composition. Results obtained by other researchers in a specific crop like coffee are actually confirming this statement.

McCloy (1958) reported that the use of artificial radiation has shown that color development during drying of coffee beans is photo-sensitive. To avoid loss of quality, machine drying at low temperatures, should be combined with sun-drying. He recommends that coffee beansbe stored at less than 15% moisture content, w.b., and points out that coffee deterioration during bin storage may be reduced by the use of perforated floors and small cold air fans.

Ulrich (1958) found that when plotted the water lost by a crop (transpiration) versus the time element gives a straight line. The linearity obtained is a function of the vapor pressure gradient difference and the slope of the curve is due to the nature of the cuticle or surface.

7. <u>Equilibrium moisture content</u>.

Coleman and Fellows (1925) determined the moisture contents for cereal grains and flax seed exposed to 15, 30, 45, 60, 75, 90 and 100 percent relative humidity and 25° C. (77° F.) temperature.

Burton (1941-42) found that equilibrium moisture in static chambers was attained in 29 days for onions, tomatoes, pine flax, lettuce and peanuts when exposed to atmospheres of 35, 55 and 76 percent relative humidity and 30° C. (86° F.). Fluctuations after that period of time were attributed to weighing errors. Variation in the absorption of water by seeds of the same variety under same relative humidities, but at different temperatures, which were not expected were observed. The explanation of this phenomena must be sought not only on the physical conditions of the atmosphere surrounding the seed but in the physical condition of the seed itself. Similar variations were observed in the parchment coffee beans.

Johnston and Foote (1951) pointed out that the coffee curing process to produce good quality depends on the substitution of controlled pectic enzyme action for spontaneous fermentation and substitution of rapid drying for slow and inefficient drying.

Barton and Goenga (1952) studied the reliability of a tester for measuring the moisture present in "coco" coffee. "Coco" coffee is defined as a heterogenous mixture of whole fruits, broken fruits, clean seed and fruit coats. They found that when the moisture content is in the range of 10 to 23 percent of the dry weight of the "coco" coffee the moisture tester can be used satisfactorily if a small correction factor of -1.75 percent was applied. There is no application for this data where clean, high quality coffee is produced.

Lopez (1952) reported equilibrium moisture contents for parchment arabic coffee as determined from different storages. The objective was to find out how coffee fluctuates in its moisture contents with changing atmospheric conditions. Data obtained show that parchment coffee responds very slowly to relative humidity and temperature fluctuations as affecting its water contents. He points out that more detail and controlled research is needed.

Goetz (1955) presents a technical discussion of living matter as affected by temperature an water contents. He classifies the state of living matter as active or inactive and applies the term biokinetic range for the first condition and biostatic to the second.

Hall (1956) determined the equilibrium moisture content for sugar beet seeds for 90, 75 and 53 percent relative humidity and temperatures of 40°, 60°, 80° and 100° F.

Hall (1957) discusses fully the equilibrium moisture contents of crops and explains its determination, practical uses, representation and relations with vapor pressure, moisture content and temperature.

Hall and Arias (1958) desorption isotherms covering a wide range of relative humidities and temperatures were worked out for corn. A complete analysis was given of the drying theory and the discussion and adaptability of the existing formulae in the light of the information gathered.

8. Electronic sorting.

Curtis (1953) reported an installation of a battery of electronic sorting machines in California for the sorting of green coffee before being inspected by the U.S. Customs.

Curtis (1956) (1958) reported on the progress attained in green coffee commercial sorting and its effect on quality of the final product.

## PROCEDURE

1. Coefficient of friction and angle of repose.

The coefficient of friction for coffee fruit and coffee beans at different stages during the processing was determined for several of the most commonly used building materials. A conventional tilting table was used, as shown in Fig. 2. The fruits or beans were placed in bottomless, three inch diameter, one inch high galvanized iron containers. Due to the weight of the container it was impossible to raise it so that there will be no contact with the surface being tested. After several unsuccesful tests these were discarded and cardboard containers of the same shape and size were used. After placing the product in the container, and with the tilting table in a horizontal position, the container was raised until only the product came in contact with the surface. The table was slowly tilted until the seed slid on the surface. The angle was measured with a protractor. The tangent of the angle at which the product slid is the coefficient of friction. All tests where the product tilts or rolls were discarded. The data in Table 3 are the average of four successful tests where the product slid over the surface without rolling and the holding frame did not come in contact with the surface.

The angle of repose of the product, or that is, when fruit or seed slides over itself was determined only for the ripe fruit, green fruits and parchment coffee. The limited amount of material available did not permit determinations during other stages in the processing. To perform these determinations would have meant the simultaneous processing of all the product at once so the other tests could not have been performed.

The angle of repose or the coefficient of friction of the fruit over itself was performed as follows: A box twelve inches wide, twelve inches long and six inches high was prepared with a round orifice two inches in diameter in the center of the bottom. A sliding gate on the underside of the bottom permits the opening to be closed or opened without moving or disturbing the box or the contents. The box was level on top of two blocks leaving the orifice free. The fruits were placed in the box and the gate opened. As the fruits flow out freely they come to their normal angle of repose. This angle was measured with a protractor, and also calculated by the function of the angle.

2. <u>Resiliency of green and ripe fruits</u>.

The rebounding characteristics of the fruit when dropped or projected against a surface were studied. The objective was to observe if the fruit, upon collision with another body, will respond as an inelastic, elastic or intermediate type collision. The information might be of interest for mechanical picking or sorting of the crop. A wooden frame four feet by four feet was built. A piece of commercial wrapping paper was fastened to the frame and a one inch hole cut in the center. This frame was placed level over the surface to be tested which was also level. An adjustable height arm mounted on a firm base was prepared with a clip on the end to hold the fruit lightly. The clip could

**Fig. 2. Tilting Table Used for Coefficient of Friction Determinations.**

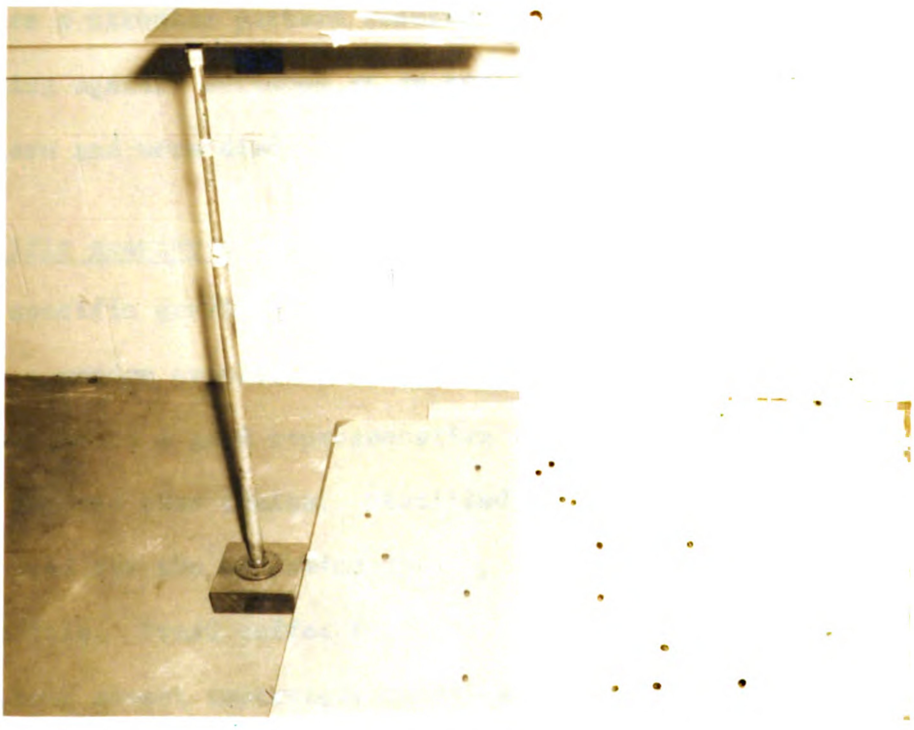


**Fig. 3. Equipment Used for Resiliency Studies.**

be opened to drop the fruit when desired. In this way a uniform height of drop was assured with the least human intervention. The arm was adjusted for height, the clip centered on the hole in the paper and the fruits dropped one at a time against the surface being tested. Baby powder was spread over the paper so that the fruits left a clear spot in the place where they hit after rebounding from the surface, as illustrated in Fig. 3. The place where the fruit hit in the first bounce from the surface was marked. A minimum of 500 fruits were projected in each test. The rebounding distances were measured from the center of the paper. Due to the lack of uniformity on the shape of the fruits a circular pattern resulted. For this same reason projecting against surfaces at an angle did not show any definite pattern and were discontinued.

3. Specific gravity and bulk density.

The specific gravity of the green and ripe fruits was determined from a random sample. A Boerner sampler was used to assure the selection of a good representative set of one hundred green and one hundred ripe fruits. Distilled water at known temperatures was used for the determinations by the conventional Archimides principle. Fresh coffee fruits do not absorb water readily due to their almost impervious covering and due to the fact that the intra-cellular space is saturated so there is no water vapor pressure gradient at a uniform temperature and under saturation conditions. The average density for ripe and green fruits was calculated. The fruits that floated in the water were discarded for upon checking them they exhibited aborted embryos.

$$\text{Specific gravity} = \frac{\text{weight of fruit in air}}{\text{apparent loss of weight in water}}$$

The bulk density for green and ripe fruits and the pulp were obtained by weighing a certain quantity of the product and then measuring the volume this same amount occupies when in a normal state.

$$\text{Bulk density} = \frac{\text{weight}}{\text{volume}}$$

4. <u>Air flotation and air conveying velocities</u>.

The air flotation velocities were determined for the green and ripe fruit, fresh pulp, and pulped washed wet coffee beans. A pitot tube installation in a 1 5/8 inch plastic tube was used. The pressure difference ($P_2$-$P_1$) between the static pressure tap and the impact pressure tap was measured with an inclined tube type manometer (Type C Micro-Manometer) so as to expand the scale and be able to read more accurately low pressure differentials. A screen placed above the pitot tube installation and at 12 inches from the top of the tube was provided to hold the sample being tested. Air was supplied by a Type P, electrically powered, ¼ h.p., 3400 rpm fan manufactured by the Electric Ventilating Company. The volume of flow and the velocity of flow in the plastic tube were controlled by a sliding gate installed on the inlet opening of the fan. The air velocity for flotation was determined for fifty samples in each case taking the average of five readings. Flotation velocities required, in fpm, were calculated using the pitot tube formulae adjusted to the room air conditions (Eckman, 1957). The conveying air velocity was figured by adding 30 fps or 1800 fpm to the flotation velocity. The results obtained fit very closely on the conveying velocities in fpm curve, developed by the Sturtevant division of the Westinghouse Electric Corporation in 1946 and reproduced in the 1958 Agricultural Engineering Handbook (page 86 Fig. 8). The equipment used is shown in Fig. 4.

5. Air flow relationships.

Information on the resistance of coffee fruits and coffee beans to air flow is essential for the storage of the fruit previous to processing, for drying the processed beans and for keeping the dried beans in storage. To perform the determinations a centrifugal, radial flow, electrically powered fan was used to supply the air. The outlet of the fan was connected to an air-tight plywood box with a three and one-half inch inside diameter galvanized piping. A sliding gate was provided at the entrance to the box and another at the outlet side to obtain the desired flow. The inlet and outlet to the box were located at a 90° angle. This box served to eliminate the air turbulence and provided a uniform steady air flow. From this setting box the air passed through a three inch inside diameter galvanized iron pipe into a smaller box that served as the base for the coffee beans holding tower. A three inch inside diameter pipe, five feet long was prepared to hold the sample. A flange with four equally spaced holes was welded to the bottom of the pipe to mount it on top of the receiving box and directly on top of a three inch bore. A screen was soldered to the lower end of the pipe to hold the sample. One quarter inch taps were soldered to the pipe at one foot intervals from zero, immediately over the screen, to four feet in height.

Fig. 4. Equipment Used to Determine Air Flotation Velocities.

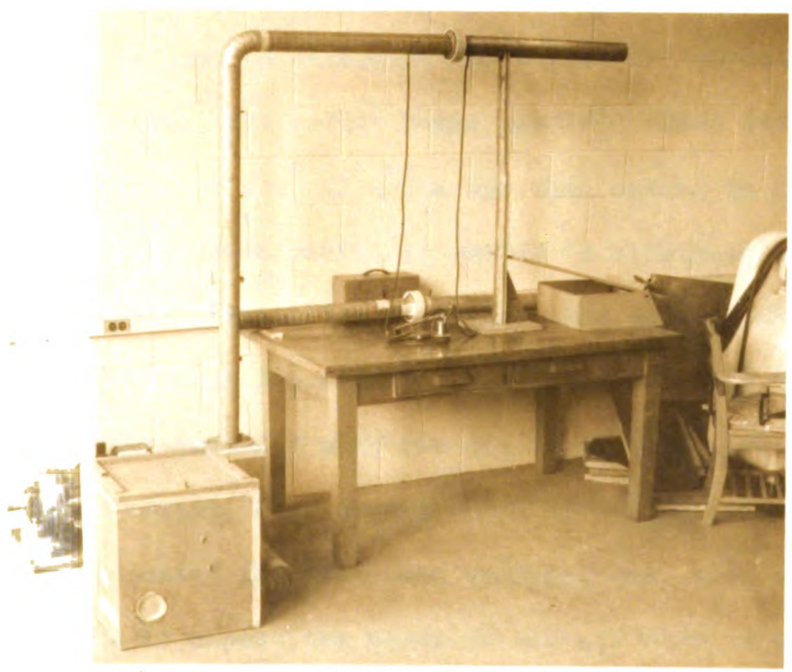


Fig. 5. Equipment Used for Air Flow Relationship Studies.

A vena contracta, orifice type, flow meter was built and installed on top of the tube containing the sample to measure the air flow. A slanting tube manometer as described under Procedure-Air flotation was used to measure the pressure differences. Fig. 5 shows the installation used. Air flow rates varying from 10 to 70 cfm per square foot were used. The air flow rates were calculated from air flow pressure drop curves, Fig. 8, and also from data provided by Fan Engineering Handbook, Fig. 9.

6. Exposed drying of washed coffee beans.

Exposed drying, also called thin layer drying, refers to the drying of a product in a thin layer of one unit thickness so that the whole unit is exposed to the air moving around it. The information can be used to determine the effect of temperature and air flow on drying. The coffee beans used for these tests were hand peeled, fermented for 12 hours and then washed in distilled water. The fermentation period is needed to eliminate the mucilage covering the beans. Distilled water was used to wash the samples so as to avoid mineral deposits on the outside coating of the beans which might interfer with the drying process. To supply the heated air for drying, hair dryers which have a resistance coil which can be adjusted for different temperatures, were used. To provide a place to expose the beans to the air flow, a three and one-quarter inch inside diameter piece of pipe was connected to the hair dryer outlets. All junctions were sealed so no air leaked out through the sides. A three inch inside diameter, tray with wire mesh (window screen) bottom was built for each one of the units to hold the samples. Tape was wrapped around each tray so no air escaped through the sides. A thermometer was inserted immediately below the trays to obtain the temperature of the incoming air. The desired temperature was regulated with a variable resistance. The air flow was measured with a one inch vena contracta type orifice in a three inch pipe. The pressure differential across the restriction was measured with a slant tube Type C micromanometer as described previously. The samples were weighed in an analytical balance at the beginning of the test and periodically afterwards as shown in Tables 13 to 18. The final drying was done in an air oven at 100° C (212° F) for 96 hours. The temperatures used were: 85° F, 100° F, 120° F, 140° F, 160° F and 180° F. The air flow was 92 fpm or 4.5 cfm per square foot. The average relative humidity of the incoming air was 35%. Three independent determinations were averaged to get the results for each temperature used. The equipment used for the tests are shown in Fig. 6.

7. <u>Equilibrium moisture content for parchment coffee</u>.

The hygroscopic equilibrium of a product can be determined either by a static or dynamic method. In the first case the product comes to equilibrium with the surrounding atmosphere without agitation of air or product. In the second case either the atmosphere surrounding the product or the product itself are moved or agitated in relation to each other. The static method requires longer periods of exposure to reach equilibrium but is simple to do. Care was taken so that the total surface area of the sample does not exceed the surface area of the liquid used to regulate the relative humidity. The individual beans were kept separated so there

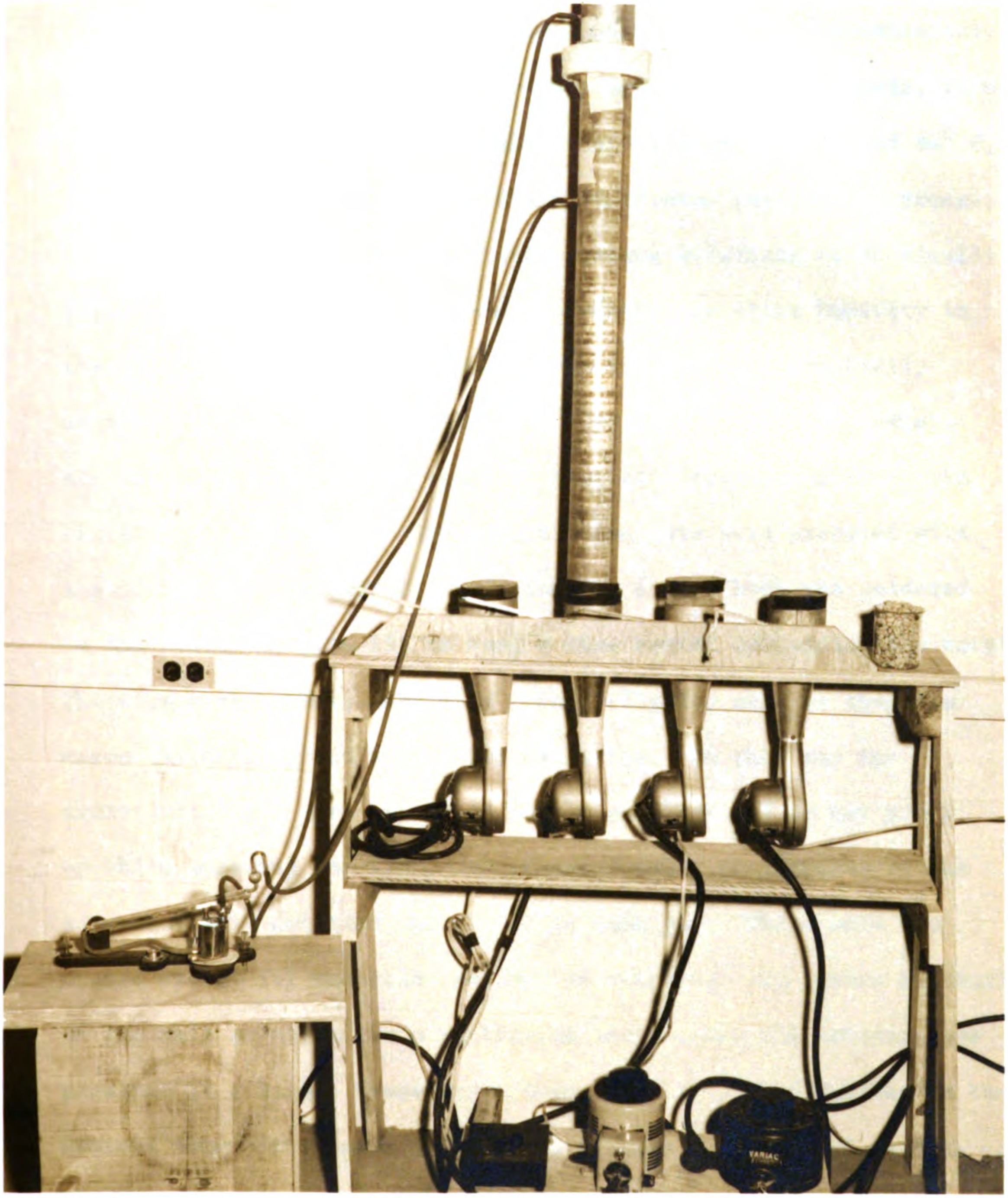


**Fig. 6. Equipment Used for Parchment Coffee Drying.**

was no direct contact between them while exposed to the treatment. These precautions are not so critical in the dynamic chamber determinations. In the equilibrium moisture content determinations for parchment coffee, both the dynamic and the static methods, were used independently. For the higher temperatures, 100° F and 86° F, a dynamic chamber available in the Agricultural Engineering processing laboratory was used. Saturated aqueous solutions of chemically pure salts were used to maintain the desired relative humidity in the thermostatic chambers. Above room temperatures are easily maintained in the dynamic chambers. For lower than room temperatures, where the dynamic chambers present a cooling problem, the static method was used. One gallon mason jars were prepared with a good sealing threaded lid and gasket. A wire hook was soldered in the center of each lid to hang a wire basket containing the sample. The wire mesh baskets were made round, slightly smaller than the mason jar opening and with a convex bottom. In this way the individual beans were scattered in the perifery and do not group up while screwing the lid. One thousand cubic centimeters of the saturated salt solution was placed in each jar. These were not opened except for the brief periods of weighing. To insure saturation of the salt solution for a particular temperature the solution was prepared at a higher temperature than required. Upon cooling to the desired temperature some salt crystalization was observed in each case. The temperature was maintained within $\pm$ 1° F. either by adjustments of the rehostats in the dynamic chambers or by placing the Mason jars used in the static determinations in temperature controlled coolers.

Ripe coffee fruits were pulped, fermented for 12 hours, washed in distilled water, weighed and placed in the controlled chambers or jars. Periodical weighing in an analytical balance were taken until a uniform weight was obtained. This was considered the equilibrium moisture content for the conditions under consideration. The dynamic chamber determinations were carried on for 624 hours and the static ones for 2200 hours so as to be sure equilibrium had been reached. The final drying, to calculate the moisture contents of the coffee beans during different stages of the test, was done in an air oven at 100° C for 96 hours. The product was placed into the controlled conditions immediately after washing off the mucilage at a moisture content which varies from 53 to 55%, w.b. The curves obtained in this way are therefore of the desorption type and being for a fixed temperature are called desorption isotherms.

8. Sorting of green and ripe coffee fruits.

Ripe coffee fruits are picked by hand. No matter how careful the picker is, a variable number of green or partially ripe fruits are always present in the product. The percent of unripe fruits present varies considerably during the harvesting season. The last picking includes all the fruits left on the tree and the amount of green fruits present is considerable. If these are not sorted out before processing a dual problem results. First the quality of the whole batch will be ruined and second, there is considerable loss involved. Sorting, so far, is done by hand. A simple, efficient way of separation needs to be developed. Information on the physical properties of the fruit is very helpful for mechanical sorting. Separation by color using the principle of a photo-sensitive cell also offers posibilities.

Proper feeding, photometric principles and electronic controls are the three fundamentals to consider in this type of sorting. A mixed sample of green and ripe fruits were run several times through a Gunson's Electronic Separator installed by the Sortex Company of North America at Lowell, Michigan. The general principle on which this machine works are as follows: The commodity is fed from the hopper by means of a vibrating chute so as to align on a grooved belt. As the belt moves forward the product is projected in a single stream to a point in the optical unit where each component is evenly illuminated and viewed from two nearly opposite sides against a background. Any variation from the bulk color will produce a variation of light received as compared with the steady reflection given by the background. The point of observation is focussed onto a scanning slot behind which is situated a light sensitive device (photo-cell). Any variation of color will cause a pulse to be given by this photo-cell which, after amplification according to control setting, raise the voltage in a pair of needle terminals to about 20,000 volts. The passing particles are electrically charged by these needles as they fall through. The product being sorted continue to fall in their natural trajectory into an electric field created by deflectors which only act upon the charged particles. The deflection caused is enough to change the trajectory and the charged particle falls to one side of a dividing edge. The non-charged particles follow a normal trajectory and fall to the other side of the divider. One stream consists of uncharged particles falling naturally and the other of the charged and deflected ones, of different color.

## RESULTS AND DISCUSSION

Coffee is a crop which requires considerable handling and processing in the farm before it is ready for the market. During this processing period, which includes numerous steps, the product is moved several times. In the design of the structures and equipment the main problem encountered is the lack of basic information about the crop itself and how it behaves in relation with construction materials. Most coffee in Puerto Rico is grown on hilly land where the slope of the terrain could be very well used to advantage for a gravity flow system. Fig. 1 shows a proposed plan for a simplified processing system in which the product is moved through the plant mainly by gravity, saving considerable labor and power.

To construct the necessary facilities for such an installation the angle of repose and the coefficients of friction between the product, at different stages of processing, and the construction materials must be known. Table 3 gives the results obtained for the angle of repose and coefficient of friction as determined by the tilting table method for the main construction materials used in coffee processing. Values for materials that are not adaptable to be used at certain stages of processing are not included. Higher values obtained for wet surface product on wood are expected since the grain of the wood upon soaking water becomes rougher. The removal of the excess free water immediately after washing and before drying, in a simple continuous process, is a challenging problem. Coefficients of friction for perforated steel and wire mesh were determined only for washed wet coffee beans where the excess water could probably be sieved out while the beans slide over a surface. Research work similar to that conducted in Hawaii for the passion fruit juice extraction might be the solution (Kinch, 1958).

Table 3 Coefficient of Friction of Coffee Fruit and Coffee Beans

| Treatment | Ripe Fruits | | Green Fruits | | Pulped Unwashed Beans | Pulp | Washed Wet Beans | Dry Beans |
|---|---|---|---|---|---|---|---|---|
| | D.S. a | W.S. b | D.S. a | W.S. b | c | c | d | e |
| Concrete (Wood Floated) | 0.64 | 0.59 | 0.64 | 0.62 | 0.94 | 0.70 | 1.03 | 0.55 |
| Concrete (As taken from forms) | 0.68 | 0.55 | 0.59 | 0.59 | 0.93 | 0.62 | 0.98 | 0.51 |
| Rough Wood (With Grain) | 0.61 | 0.75 | 0.77 | 0.85 | | | | |
| Rough Wood (Across Grain) | 0.68 | 0.74 | 0.59 | 0.66 | | | | |
| Planed Wood (With Grain) | 0.61 | 0.70 | 0.51 | 0.67 | 0.90 | 0.75 | 1.07 | 0.42 |
| Planed Wood (Across Grain) | 0.61 | 0.66 | 0.59 | 0.67 | 0.93 | 0.81 | 1.15 | 0.49 |
| Plywood (With Grain) | 0.59 | 0.69 | 0.50 | 0.60 | | | | 0.47 |
| Plywood (Across Grain) | 0.64 | 0.71 | 0.55 | | 0.62 | | | 0.53 |
| Galvanized Iron | 0.57 | 0.47 | 0.50 | 0.47 | 0.54 | 0.60 | 0.87 | 0.40 |
| Aluminum | 0.58 | 0.52 | 0.54 | 0.47 | 0.49 | 0.58 | 0.78 | 0.40 |
| Stainless Steel | 0.64 | 0.55 | 0.49 | 0.45 | | | 0.65 | 0.34 |
| Steel | 0.59 | 0.49 | 0.59 | 0.58 | 0.65 | 0.73 | 0.90 | 0.53 |
| Steel-Perforated 1/16 Diam. 8/sq. in. | | | | | | | 0.90 | |
| Steel-Perforated 1/8 Diam. 16/sq. in. | | | | | | | 0.90 | |
| Steel-Perforated 5/32 Diam. 16/sq. in. | | | | | | | 0.90 | |
| Steel-Perforated 3/16 Diam. 13/sq. in. | | | | | | | 0.75 | |
| Window Screen 14x18 Mesh | 0.78 | 0.79 | 0.65 | 0.65 | | | 1.11 | |
| Green Fruit | | | | 1.33 | | | | |
| Ripe Fruit | | 1.15 | | | | | | |

a Dry surface
b Wet surface
c Immediately after pulping
d Immediately after washing
e 12% moisture d.b.

The results of the preliminary rebounding test for ripe and green coffee fruit show some possibilities of obtaining a definite pattern. The ripe fruits, being covered by a mucilagenous substance which makes them softer, rebound, in general, a shorter distance than the green, harder fruits. The results of a single series of tests with limited amount of material should not be considered conclusive. This phase of the test is postponed to be continued at a latter date during the following coffee crop season.

Projecting the fruits against surfaces at an angle to the path was not satisfactory. The great variation in shape of the fruit and the form in which these hit the surface resulted in a very scattered pattern. Best results were obtained when the fruit and the surface being tested meet each other at a 90$^{\circ}$ angle. Steel, concrete and wooden surfaces were tried at different dropping heights. Results will not be published until enough replications are performed to insure a dependable statistical analysis. Fig. 3 shows the equipment used for these preliminary tests. In the samples studied very little difference was found in the average specific gravity and density of green and ripe fruits. The specific gravity for the green fruits varied from 1.0063 to 1.1163 and for the ripe fruit from 1.0072 to 1.0884. Contrary to expectations the green fruits showed a higher average specific gravity than the ripe fruits. The higher average value in specific gravity and density of the green fruit seems to be due to some physio-chemical changes that occurs on ripening. The result of one hundred individual determinations of green and ripe fruits fluctuate so much that there is no way of expressing any significant difference for green and ripe fruits. The values obtained for specific gravity, bulk density and void space for coffee compares with the values obtained for wheat, oats, corn, buckwheat and millet by Zink (1935) and by the U.S.D.A. (n.d.) Table 4 and 5 show the results of these tests.

Table 4. Specific Gravity and Density of Green and Ripe Coffee Fruits

| Fruits | Specific Gravity a | Temp. of Water °F. a | Weight Density a | |
|---|---|---|---|---|
| | | | Grams/cu. cm. | Pounds/cu. ft. |
| Green | 1.0722 * | 79° F. | 1.0687 | 66.76 |
| Ripe | 1.0454 ** | 80° F. | 1.0415 | 65.07 |

Table 5. Bulk Density of Coffee Fruits and Coffee Pulp

| Fruits or Pulp | Number of Fruits b | | Weight Density b | | Void Space Percent b |
|---|---|---|---|---|---|
| | Per cu. cm. | Per cu. ft. | Grams/cu. cm. | Lbs/cu. ft. | |
| Green | 0.546 | 15,460 | 0.601 | 37.54 | 44 |
| Ripe | 0.361 | 10,222 | 0.596 | 37.24 | 43 |
| Pulp c | | | 0.248 | 15.48 | |

a Average of 100 determinations

b Average of 20 determinations

c Freshly removed pulp

* Ranges from 1.0063 to 1.1163

** Ranges from 1.0072 to 1.0884

The preliminary work by other researchers on pneumatic conveyance of material was done on ensilage cutters and blowers. In 1946 the Sturtevant Division of the Westinghouse Corporation developed a general curve for conveying velocities based on the bulk weight of the material being conveyed. The basic equation for a pitot tube fluid velocity measurement is as follows: $V = C_{pt} \sqrt{(d_m - d_f)\, v} \;\; \sqrt{2gh}$ (Eckman, 1957) where

$V$ = Velocity of flowing fluid, feet per second

$C_{pt}$ = Velocity coefficient, a constant, approx. 1

$d_m$ = Density of manometer fluid, pounds per cubic foot

$d_f$ = Density of fluid over the manometer fluid, pounds per cubic foot

$v$ = Specific volume of the flowing gas, cubic feet per pound

$g$ = Acceleration due to gravity, feet per second per second

$h$ = Manometer differential, feet

Since

$C_{pt}$ = Approx. 1 $\qquad d_m = 62.4$

$d_f = 0 \qquad g = 32.2$

Then

$$V = \sqrt{(62.4)\ (64.4)\ vh}$$

As h is measured in inches of water let $h = \frac{h'}{12}$

And

$$V = \sqrt{\frac{(62.4)\ (64.4)\ vh'}{12}}$$

$$V = \sqrt{334.2\ vh'}$$

Using

$$v = 14.5$$

$$V = \sqrt{(334.2)\ (14.5)\ h'}$$

$$V = 69\sqrt{h'} \quad \text{in feet per second}$$

$$V' = 4140\sqrt{h'} \quad \text{in feet per minute}$$

The generally accepted pneumatic conveying velocity is the flotation air velocity plus from 30 to 50 feet per second. The values obtained for coffee fruit, pulp and beans are presented in Table 6. When these values are calculated with the above formulae they come very close to the values for conveying velocities obtained by using the Sturtevant air conveying curve as shown in Table 6 and Fig. 7. The Buffalo Forge Co. (1949) published some generally used conveying air velocities based on the following formula:

$$V = 1030\sqrt[3]{w}\ \sqrt{d} + 582.5\sqrt{w}$$

V = Air velocity, feet per minute

w = Bulk weight of material, pounds per cubic foot.

d = Diameter of equivalent cross-section of particle, inches.

Using the same bulk densities obtained and the average diameter of the coffee fruit, which is about one-half inch, the results are also very close to the ones obtained by the previously discussed methods.

Table 6 Average Air Velocities for Conveying Coffee Fruits, Pulp and Beans ft/min.

| Material | Pressure Inches Of Water | Flotation Velocity a | Conveying Velocity b | Bulk Density c | Sturtevant Conveying Velocities d |
|---|---|---|---|---|---|
| Green Fruits | 0.881 | 3,883 | 5,683 | 37.54 | 5,600 |
| Ripe Fruits | 0.910 | 3,950 | 5,750 | 37.24 | 5,550 |
| Fresh Pulp | 0.572 | 3,125 | 4,925 | 15.48 | 4,100 |
| Pulped Washed Beans | 0.786 | 3,655 | 5,455 | | |

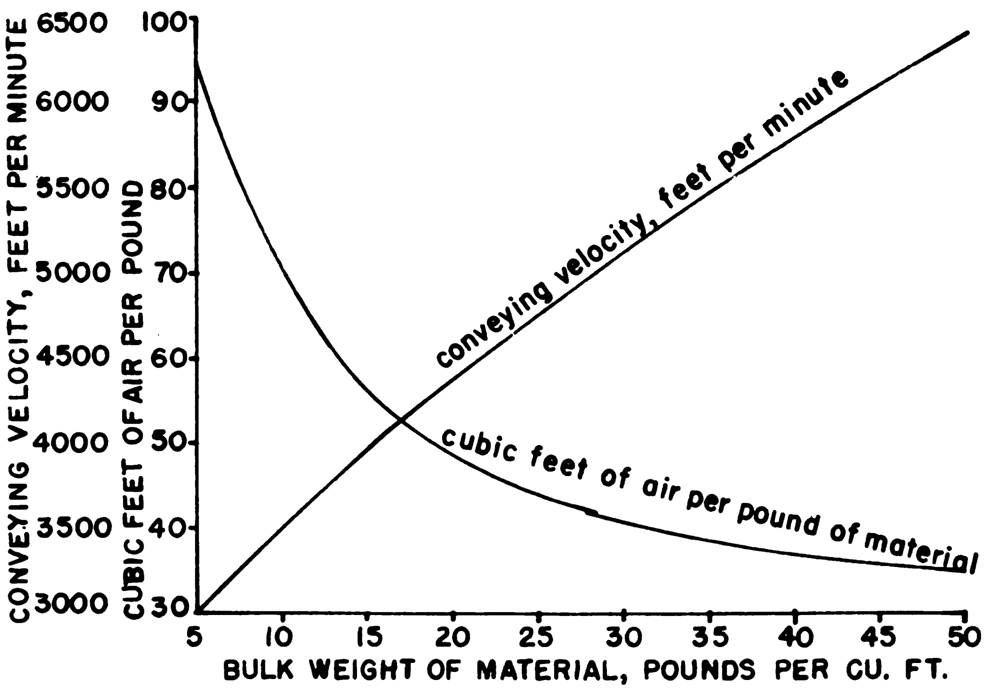



Fig. 7. Average velocities and air volumes for conveying material. Reproduced by permission of the Sturtevant Division, Westinghouse Corp.

a Calculated by formula 4140 $\sqrt{h'}$

b Flotation velocity $+$ 1800 fpm

c From specific gravity determinations

d From Sturtevant conveying curve

The data obtained for the resistance of air flow per each foot depth of coffee fruits and coffee beans during different stages of processing are presented in Tables 7 to 12 and Fig. 10 to 13.

Hall (1957a) points out that the static pressure varies directly as the depth of the product, with a linear relationship between the static pressure and depth. When the static pressure versus air flow data are plotted on logarithmic paper a nearly straight line results which can be expressed by the following formula:

$$Q_a = a_1 P'^{b_1}$$

$Q_a$ = Air flow, cubic feet per minute per square foot

$a_1$ = Constant

$P'$ = Static pressure drop, inches of water

$b_1$ = Exponential value which represent static pressure relationships in crop drying.

Shedd (1953) states that the resistance to air flow is increased if foreign material finer than the product is present and reduced if the foreign material is coarser. The tests were performed with coffee fruits or coffee beans completely free from foreign material. Air flow versus pressure drop relationships in coarser material gives a straighter line, when plotted logarithmically, than finer material for coffee fruits or beans. The volume of air flowing through the product was converted from inches of water to cubic feet per minute and then to cubic feet per minute per square foot of area for a 3 inch inside diameter pipe used for the determinations. Calculations following the Fan Engineering Handbook data and formula, as presented in Fig. 9; and following the air flow pressure drop curves shown in Fig. 8, come very close. Anyone of these could be used to calculate the air flow if the pipe diameter and pressure drops are known.

Ripe coffee fruits offer a higher resistance to air flow than the green fruits. In ventilating or cooling a batch of mixed or partially ripe fruits this must be taken into consideration. In the washed parchment beans the higher the moisture content the higher the resistance to air flow in general. Dryers must be designed on the maximum resistance to take care of the initial drying period.

Table 7 Resistance of Green Coffee Fruits to Air Flow

| | Pressure Drop - Inches of Water | | | |
|---|---|---|---|---|
| cfm/sq. ft. | 1' | 2' | 3' | 4' |
| 46 | 0.102 | 0.204 | 0.306 | 0.418 |
| 62 | 0.170 | 0.332 | 0.497 | 0.680 |
| 84 | 0.276 | 0.536 | 0.804 | 1.104 |
| 103 | 0.382 | 0.746 | 0.940 | 1.530 |
| 118 | 0.495 | 0.962 | 1.442 | 1.980 |
| 133 | 0.601 | 1.168 | 1.752 | 2.405 |

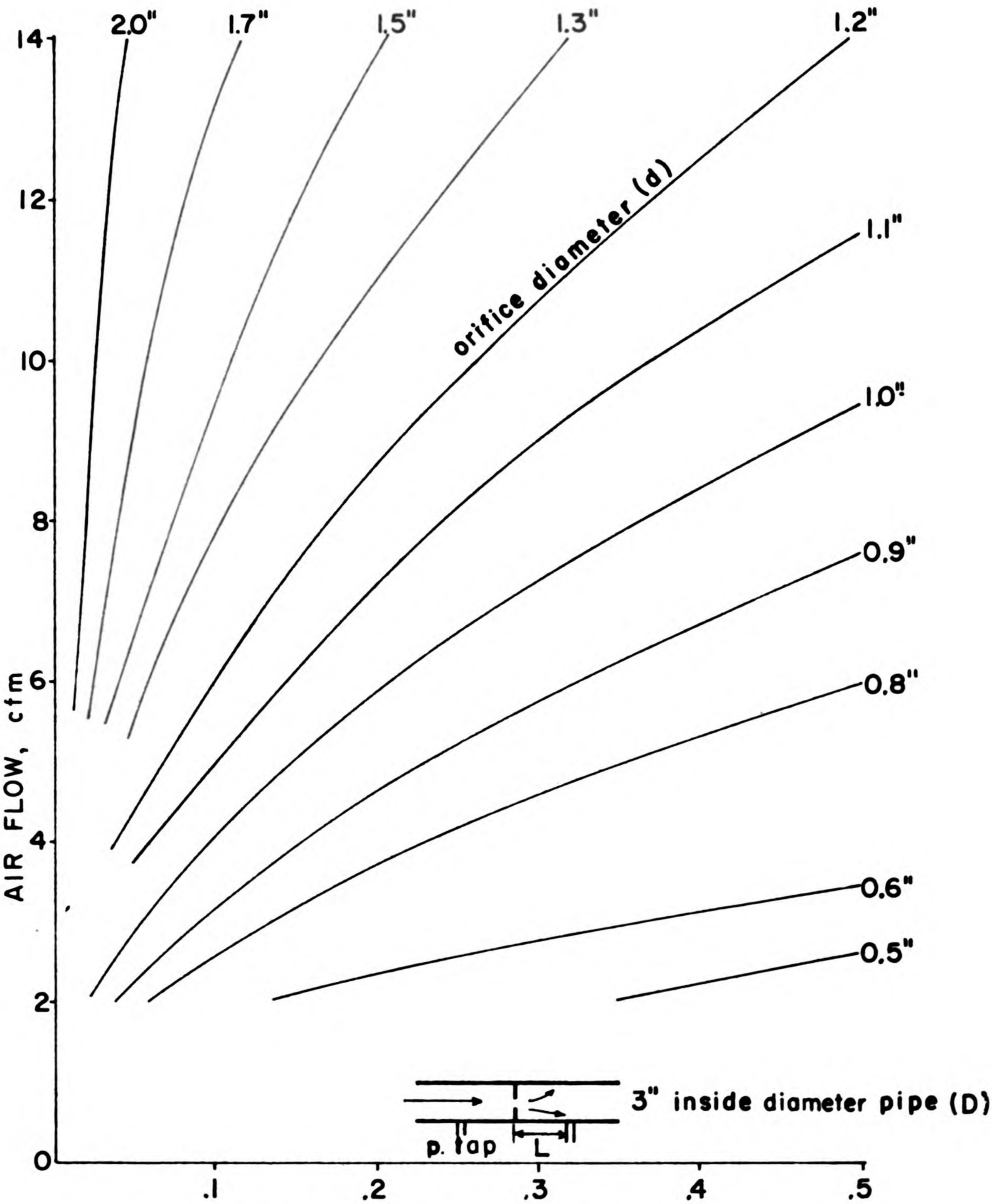



FIG. 8 PRESSURE DROP THROUGH ORIFICE, INCHES OF WATER

$$L = 0.90\,D\left[1-\left(\frac{d}{D}\right)^2\right] \qquad Q = 4005\,C\,A\sqrt{p}$$

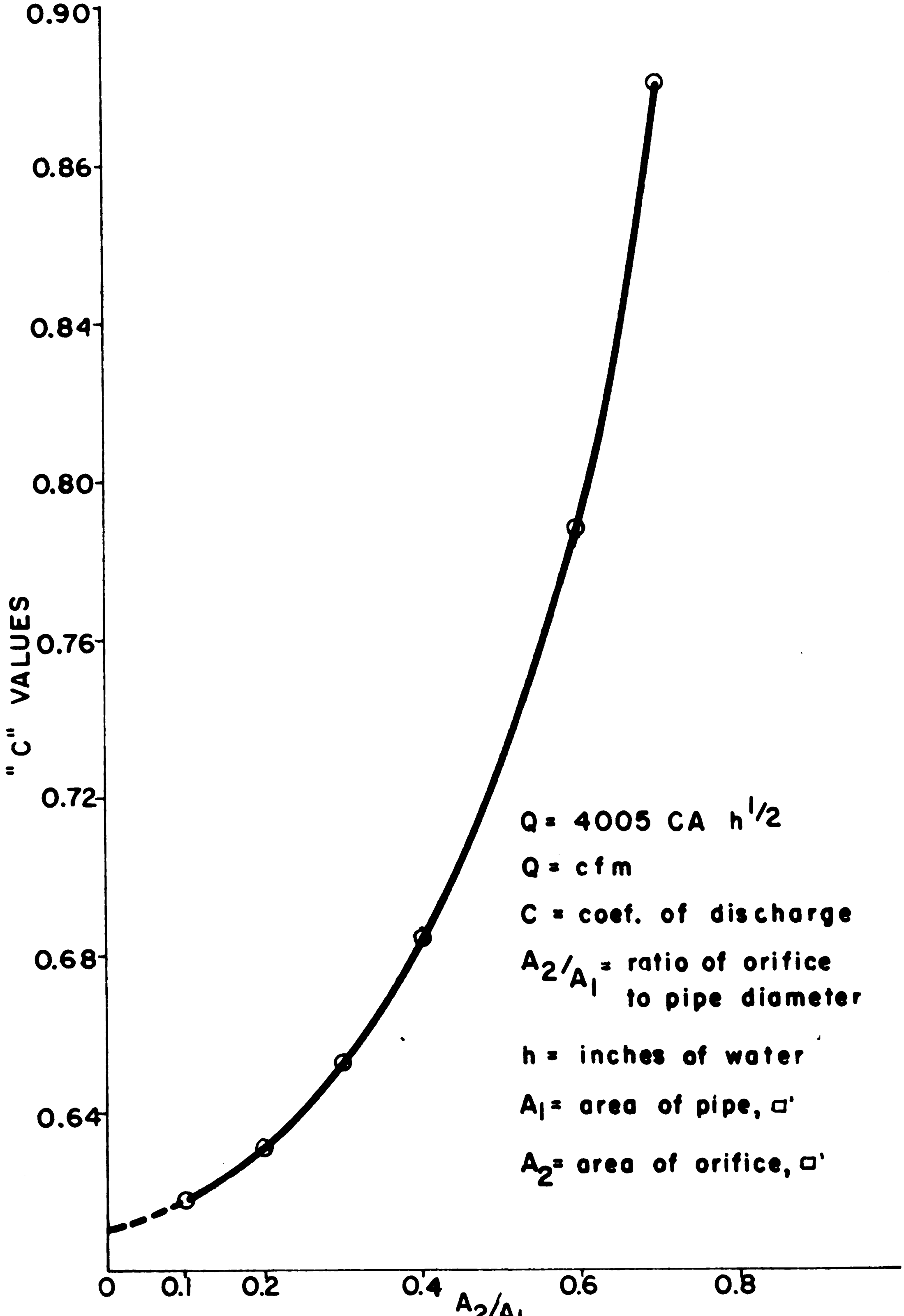



FIG. 9 COEFFICIENT OF DISCHARGE "C" FOR A 1/2" VENA-CONTRACTA ORIFICE IN A 3" PIPE (FROM FAN ENGR. HANDBOOK)

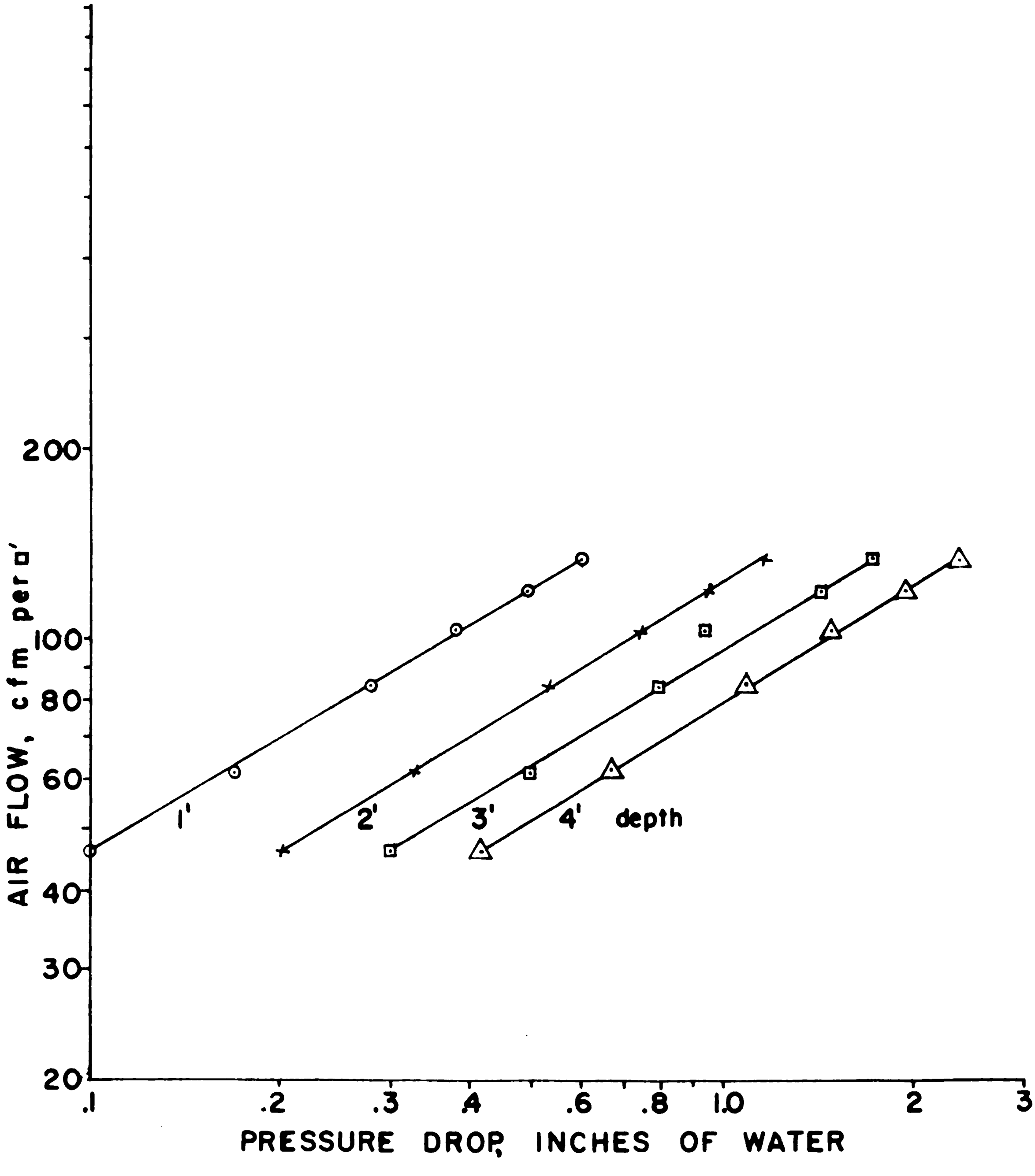



FIG. 10 RESISTANCE OF GREEN COFFEE FRUIT TO AIR FLOW

Table 8 Resistance of Ripe Coffee Fruits to Air Flow

| cfm/sq. ft. | Pressure Drop - Inches of Water 1' | 2' | 3' | 4' |
|---|---|---|---|---|
| 46 | 0.170 | 0.354 | 0.530 | 0.680 |
| 58 | 0.264 | 0.562 | 0.842 | 1.075 |
| 84 | 0.496 | 0.970 | 1.250 | 1.850 |
| 103 | 0.657 | 1.378 | 2.067 | 2.630 |
| 112 | 0.761 | 1.590 | 2.385 | 3.043 |

Table 9 Resistance of Washed Wet Parchment Coffee Beans to Air Flow [a]

| cfm/sq. ft. | Pressure Drop - Inches of Water 1' | 2' | 3' | 4' |
|---|---|---|---|---|
| 11.0 | 0.067 | 0.136 | 0.204 | 0.268 |
| 14.0 | 0.105 | 0.208 | 0.312 | 0.418 |
| 20.0 | 0.188 | 0.378 | 0.567 | 0.754 |
| 30.0 | 0.335 | 0.677 | 1.015 | 1.340 |
| 45.0 | 0.508 | 1.014 | 1.521 | 2.032 |
| 60.0 | 0.760 | 1.607 | 2.411 | 3.240 |

a Immediately after washing
Percent Moisture, w.b.
At Beginning of Test 55.6
At End of Test 53.5

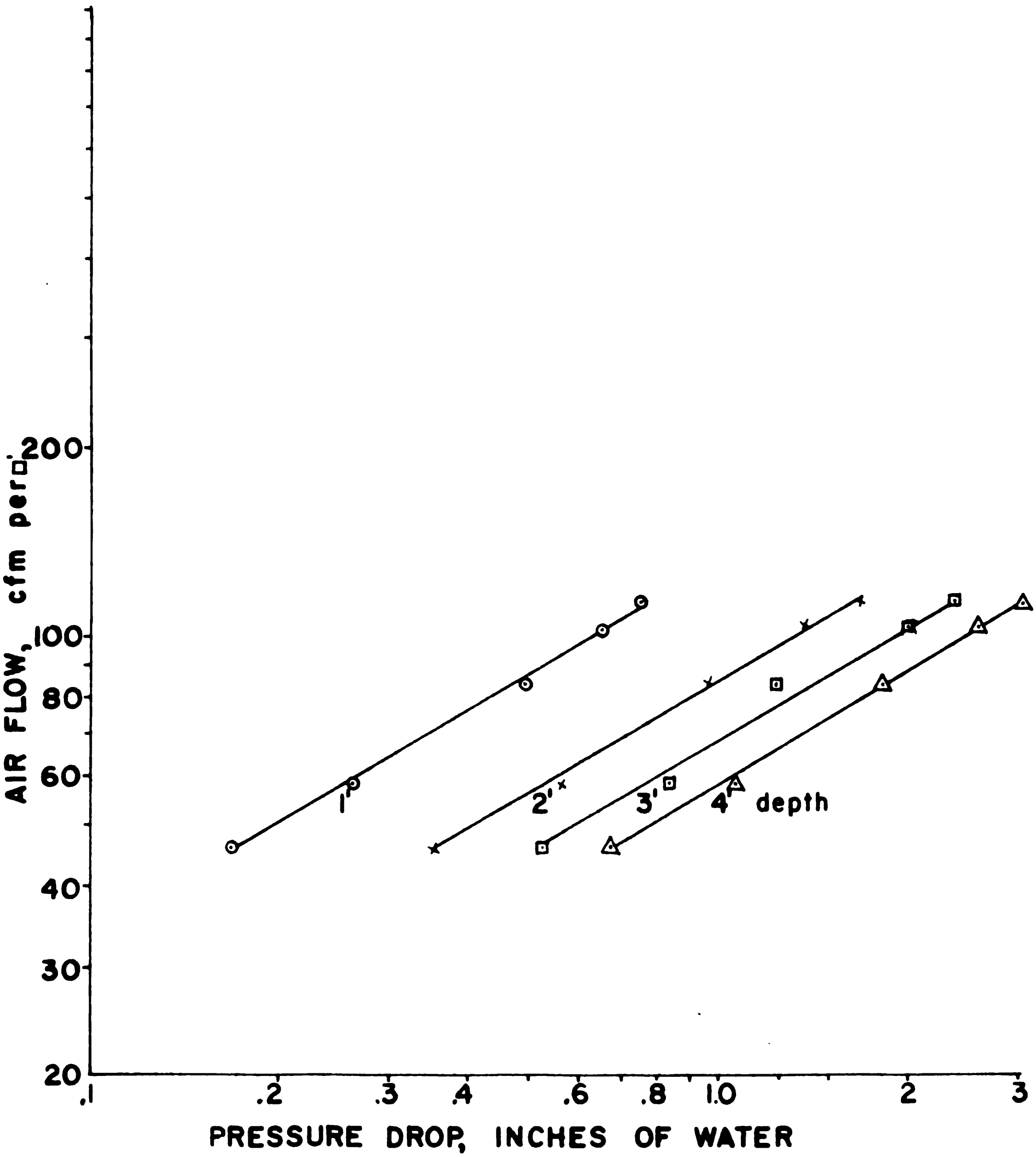



FIG. 11 RESISTANCE OF RIPE COFFEE FRUIT TO AIR FLOW

Table 10 Resistance of Washed Parchment Coffee Beans to Air Flow [a]

| | Pressure Drop - Inches of Water | | | |
|---|---|---|---|---|
| cfm/sq. ft. | 1' | 2' | 3' | 4' |
| 11.0 | 0.058 | 0.107 | 0.175 | 0.220 |
| 21.7 | 0.146 | 0.293 | 0.440 | 0.585 |
| 31.3 | 0.259 | 0.532 | 0.796 | 1.025 |
| 40.7 | 0.386 | 0.765 | 1.147 | 1.535 |
| 48.0 | 0.467 | 0.943 | 1.415 | 1.870 |
| 67.5 | 0.683 | 1.354 | 2.031 | 2.733 |
| 72.0 | 0.770 | 1.537 | 2.305 | 3.080 |

a Air dried for 6 hours
Percent Moisture, w.b.
At Beginning of Test 52.0
At End of Test 49.1

Table 11 Resistance of Washed Parchment Coffee Beans to Air Flow [a]

| | Pressure Drop - Inches of Water | | | |
|---|---|---|---|---|
| cfm/sq. ft. | 1' | 2' | 3' | 4' |
| 11.0 | 0.086 | 0.165 | 0.250 | 0.335 |
| 21.7 | 0.196 | 0.393 | 0.590 | 0.785 |
| 31.3 | 0.326 | 0.643 | 0.965 | 1.305 |
| 40.7 | 0.456 | 0.910 | 1.435 | 1.825 |
| 48.8 | 0.556 | 1.102 | 1.653 | 2.225 |
| 60.6 | 0.782 | 1.560 | 2.340 | 3.130 |

a Air Dried for 24 hours
Percent Moisture, w.b.
At Beginning of Test 45.4
At End of Test 45.0

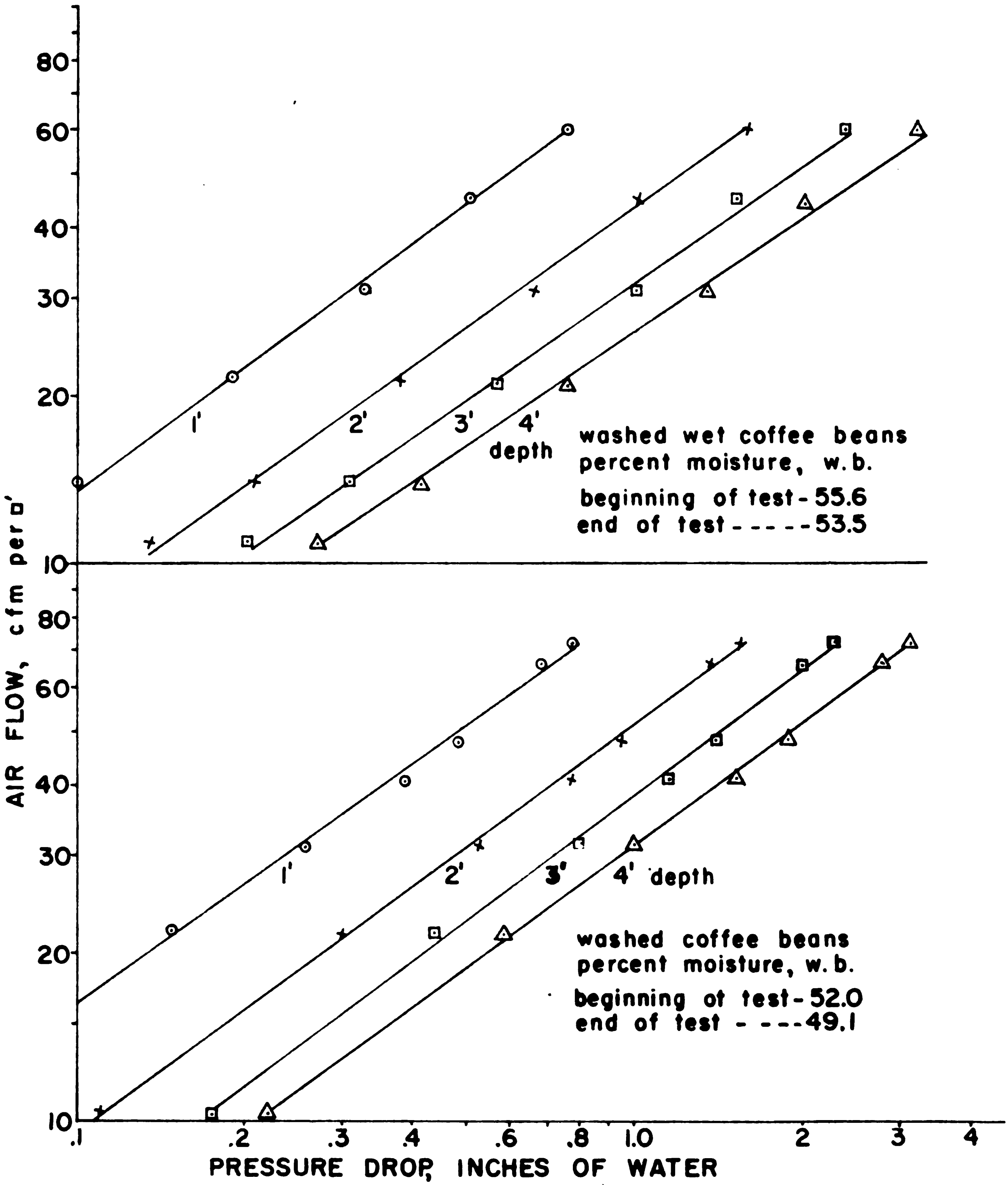



FIG. 12 RESISTANCE OF PARCHMENT COFFEE TO AIR FLOW

Table 12 Resistance of Dried Parchment Coffee Beans to Air Flow [a]

| cfm/sq. ft. | Pressure Drop - Inches of Water | | | |
|---|---|---|---|---|
| | 1' | 2' | 3' | 4' |
| 15 | 0.111 | 0.220 | 0.330 | 0.443 |
| 21.7 | 0.180 | 0.363 | 0.534 | 0.730 |
| 31.3 | 0.305 | 0.607 | 0.910 | 1.220 |
| 40.7 | 0.420 | 0.837 | 1.255 | 1.680 |
| 48.8 | 0.536 | 1.082 | 1.622 | 2.145 |
| 60.6 | 0.741 | 1.476 | 2.214 | 2.965 |

a Air Dried for 10 Days
Percent Moisture, w.b.
At Beginning of Test 13.3
At End of Test 11.7

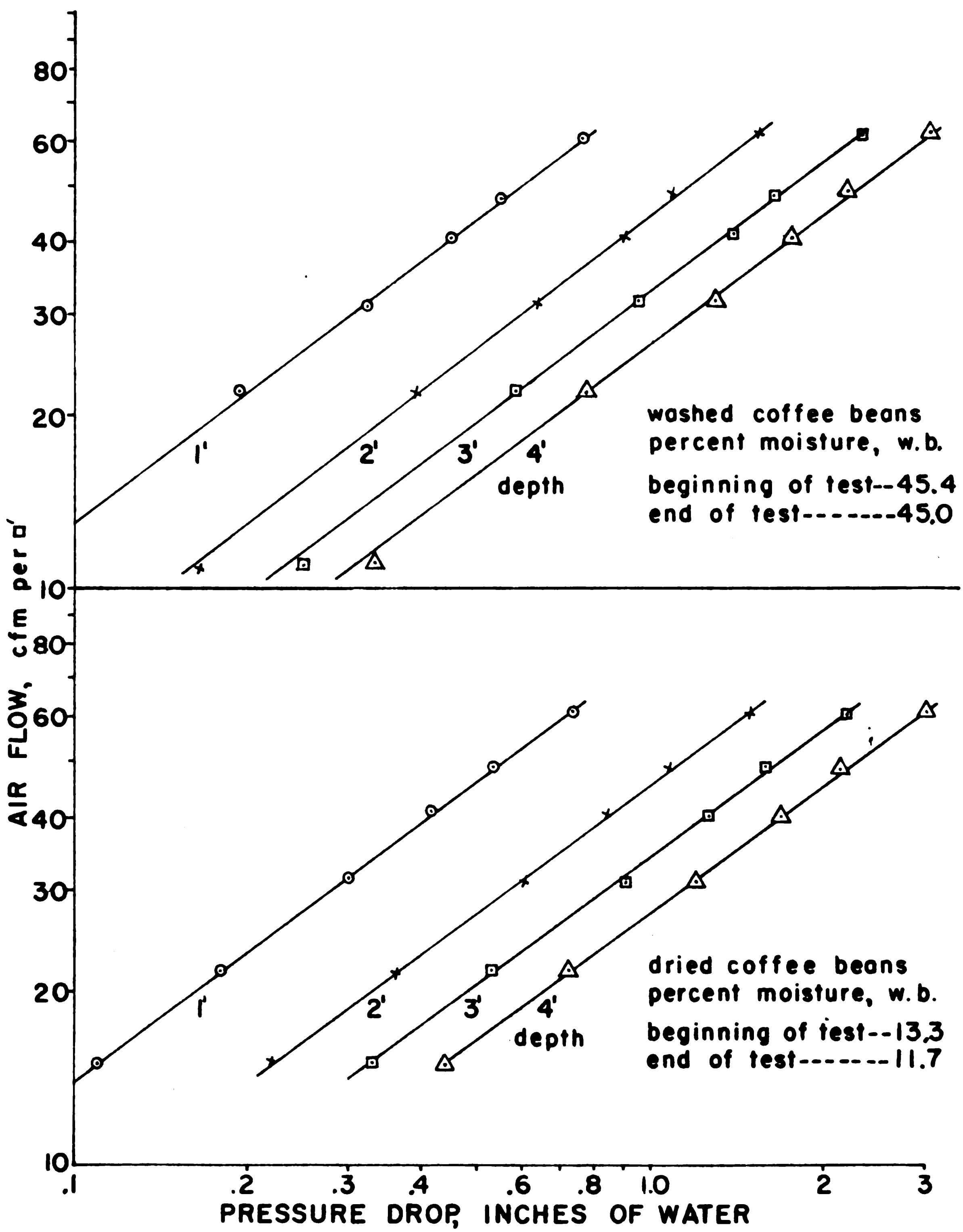



FIG. 13 RESISTANCE OF PARCHMENT COFFEE TO AIR FLOW

Drying is the bottleneck in the processing of the coffee for the market today. The fermentation period required for the removal of the mucilage used to be the main problem in a continous operation. With the development of the caustic soda or chemical method by Carbonell, and Vilanova, (1951-52) at El Salvador and with the recent development of mechanical scrubers and washers this problem was solved. The drying problem is, however, still present and when the harvest season is in its peak the farmer must find a way to dry the coffee to a safe storage moisture content as rapidly as possible without damaging quality. Coffee must be dried immediately after washing or store for very short periods of time under running water. Sun drying was the common practice some years ago. This requires considerable space, facilities and labor. Heated air drying is becoming the common practice today on all farms. Basic drying data for coffee is lagging behind instead of being ahead of the dryer's design. Dryers specifically built for other crops have been and are utilized for coffee drying with considerable disadvantages. The only organized research in coffee drying of which there is any available information was conducted in Peru by Ives (1955) the results of which has been fully discussed.

The coffee bean, after washing, is surrounded by two layers of tissues and an air space between them. This condition greatly hinders the movement of water from the inside towards the surface unless a great vapor pressure gradient is created or long periods of drying are considered. Another important point to consider in drying coffee is the quality of the final product. Temperatures above 120° F. has repeatedly proven detrimental to the coffee quality as discussed previously. The effects of temperature on the color of the outside coating of coffee beans can be observed on color pictures, Fig. 17. The exposed drying curves for the range of temperatures from 85° to 180° F. shows the required drying time for fixed air flow rate and relative humidity. The rate of drying presented in Fig. 15 and 16 also gave an indication which can be used as basis for better drying methods.

Vacuum drying will probably be the answer to rapid, efficient, quality conserving drying of coffee.

Table 13 Exposed Drying Rate for Coffee Beans [a]

| Temp. °F. | Time Minutes | Percent Moisture, d.b. | $\frac{dm}{d\theta}$, %/hr. |
|---|---|---|---|
| | 0 | 120.6 | |
| | 2 | 115.9 | 141.0 |
| | 4 | 113.0 | 114.0 |
| | 6 | 110.7 | 99.0 |
| | 8 | 108.7 | 89.2 |
| | 10 | 107.2 | 80.4 |
| | 12 | 106.0 | 73.0 |
| | 14 | 105.0 | 67.0 |
| | 16 | 104.2 | 62.3 |
| | 18 | 103.5 | 56.4 |
| 85 | 20 | 102.8 | 53.4 |
| | 25 | 101.7 | 45.4 |
| | 30 | 100.9 | 39.4 |
| | 40 | 99.6 | 31.5 |
| | 60 | 98.0 | 22.6 |
| | 90 | 95.9 | 16.5 |
| | 120 | 93.9 | 13.3 |
| | 240 | 86.8 | 8.4 |
| | 360 | 78.8 | 7.0 |
| | 540 | 67.1 | 6.0 |
| | 720 | 50.5 | 5.8 |
| | 1440 | 27.0 | 3.9 |
| | 2160 | 11.9 | 3.0 |
| | 3000 | 8.8 | 2.2 |

a Air Flow 92 fpm, 4.5 cfm per sq. ft.
Average Relative Humidity 35%
Average Three Determinations

Table 14 Exposed Drying Rate for Coffee Beans [a]

| Temp. °F. | Time Minutes | Percent Moisture, d.b. | $\frac{dm}{d\theta}$, %/hr. |
|---|---|---|---|
| | 0 | 120.5 | |
| | 2 | 115.2 | 159.0 |
| | 4 | 111.8 | 130.5 |
| | 6 | 109.1 | 114.0 |
| | 8 | 106.9 | 102.0 |
| | 10 | 105.2 | 91.8 |
| | 12 | 103.9 | 83.0 |
| | 14 | 102.7 | 76.5 |
| | 16 | 101.7 | 71.4 |
| | 18 | 100.9 | 64.7 |
| | 20 | 100.2 | 60.9 |
| | 25 | 98.7 | 52.3 |
| 100 | 30 | 97.7 | 45.6 |
| | 40 | 96.1 | 36.6 |
| | 60 | 93.2 | 27.3 |
| | 90 | 89.5 | 20.6 |
| | 120 | 86.8 | 16.8 |
| | 240 | 71.5 | 12.2 |
| | 360 | 59.4 | 10.2 |
| | 540 | 41.8 | 8.8 |
| | 720 | 29.1 | 7.6 |
| | 1440 | 9.7 | 4.6 |
| | 2160 | 7.4 | 3.2 |
| | 3000 | 6.4 | 2.3 |

a Air Flow 92 fpm, 4.5 cfm per sq. ft.
Average Relative Humidity 35%
Average of Three Determinations

Table 15 Exposed Drying Rate for Coffee Beans [a]

| Temp. °F. | Time Minutes | Percent Moisture, d.b. | $\frac{dm}{d\theta}$, %/hr. |
|---|---|---|---|
| | 0 | 120.7 | |
| | 2 | 113.8 | 207.0 |
| | 4 | 109.5 | 168.0 |
| | 6 | 106.5 | 142.0 |
| | 8 | 104.4 | 122.3 |
| | 10 | 102.4 | 109.8 |
| | 12 | 100,3 | 102.0 |
| | 14 | 98.3 | 96.3 |
| | 16 | 97.1 | 89.7 |
| | 18 | 95.7 | 82.5 |
| | 20 | 95.4 | 75.9 |
| | 25 | 93.2 | 66.0 |
| | 30 | 91.7 | 58.0 |
| 120 | 40 | 88.7 | 48.0 |
| | 60 | 80.7 | 40.0 |
| | 90 | 68.2 | 35.0 |
| | 120 | 64.7 | 28.0 |
| | 240 | 32.7 | 22.0 |
| | 360 | 24.7 | 16.0 |
| | 540 | 23.5 | 10.8 |
| | 720 | 22.3 | 8.2 |
| | 1440 | 5.5 | 4.8 |
| | 2160 | 5.2 | 3.2 |
| | 3000 | 5.0 | 2.3 |

a Air Flow 92 fpm, 4.5 cfm per sq. ft.
Average Relative Humidity 35%
Average Three Determinations

Table 16 Exposed Drying Rate for Coffee Beans[a]

| Temp. °F. | Time Minutes | Percent Moisture, d.b. | $\frac{dm}{d\theta}$, %/hr. |
|---|---|---|---|
| | 0 | 119.6 | |
| | 2 | 111.7 | 237.0 |
| | 4 | 107.0 | 189.0 |
| | 6 | 103.0 | 166.0 |
| | 8 | 100.0 | 147.0 |
| | 10 | 97.5 | 132.6 |
| | 12 | 95.2 | 122.0 |
| | 14 | 93.6 | 111.8 |
| | 16 | 92.2 | 104.1 |
| | 18 | 90.9 | 94.7 |
| | 20 | 89.8 | 89.4 |
| | 25 | 87.3 | 77.5 |
| | 30 | 85.3 | 68.6 |
| | 40 | 80.9 | 58.0 |
| 140 | 60 | 72.7 | 46.9 |
| | 90 | 59.6 | 40.0 |
| | 120 | 50.2 | 34.7 |
| | 240 | 19.9 | 24.9 |
| | 360 | 10.5 | 18.2 |
| | 540 | 7.1 | 12.5 |
| | 720 | 6.0 | 9.5 |
| | 1440 | 4.4 | 4.8 |
| | 2160 | 3.9 | 3.2 |
| | 3000 | 3.3 | 2.3 |

a Air Flow 92 fpm, 4.5 cfm per sq. ft.
Average Relative Humidity 35%
Average of Three Determinations

Table 17 Exposed Drying Rate for Coffee Beans [a]

| Temp. °F. | Time Minutes | Percent Moisture, d.b. | $\frac{dm}{d\theta}$, %/hr. |
|---|---|---|---|
| | 0 | 116.1 | |
| | 2 | 107.2 | 267.0 |
| | 4 | 102.0 | 211.5 |
| | 6 | 98.7 | 174.0 |
| | 8 | 96.0 | 150.7 |
| | 10 | 93.6 | 135.0 |
| | 12 | 91.7 | 122.0 |
| | 14 | 89.9 | 112.6 |
| | 16 | 88.0 | 106.8 |
| | 18 | 86.3 | 98.3 |
| | 20 | 84.7 | 94.2 |
| | 25 | 80.5 | 85.4 |
| | 30 | 76.0 | 82.7 |
| 160 | 40 | 69.2 | 70.4 |
| | 60 | 56.6 | 59.5 |
| | 90 | 40.6 | 50.4 |
| | 120 | 28.7 | 43.7 |
| | 240 | 10.7 | 26.3 |
| | 360 | 7.6 | 18.1 |
| | 540 | 5.7 | 12.3 |
| | 720 | 4.8 | 9.3 |
| | 1440 | 3.5 | 4.7 |
| | 2160 | 2.7 | 3.2 |
| | 3000 | 2.3 | 2.3 |

a Air Flow 92 fpm, 4.5 cfm per sq. ft.
Average Relative Humidity 35%
Average of Three Determinations

Table 18 Exposed Drying Rate for Coffee Beans [a]

| Temp. °F. | Time Minutes | Percent Moisture, d.b. | $\frac{dm}{d\theta}$, %/hr. |
|---|---|---|---|
| | 0 | 125.7 | |
| | 2 | 115.8 | 297.0 |
| | 4 | 109.0 | 250.5 |
| | 6 | 104.2 | 215.0 |
| | 8 | 100.2 | 191.3 |
| | 10 | 96.0 | 178.2 |
| | 12 | 92.4 | 166.5 |
| | 14 | 89.0 | 157.8 |
| | 16 | 85.6 | 152.4 |
| | 18 | 82.6 | 142.2 |
| | 20 | 79.5 | 138.6 |
| | 25 | 70.8 | 131.8 |
| 180 | 30 | 64.0 | 123.4 |
| | 40 | 53.4 | 108.5 |
| | 60 | 34.5 | 91.2 |
| | 90 | 19.9 | 70.5 |
| | 120 | 12.4 | 56.6 |
| | 240 | 6.6 | 29.8 |
| | 360 | 5.0 | 20.1 |
| | 540 | 4.2 | 13.5 |
| | 720 | 3.5 | 10.2 |
| | 1440 | 2.3 | 5.1 |
| | 2160 | 1.9 | 3.4 |
| | 3000 | 1.5 | 2.5 |

a Air Flow 92 fpm, 4.5 cfm per sq. ft.
Average Relative Humidity 35%
Average of Three Determinations

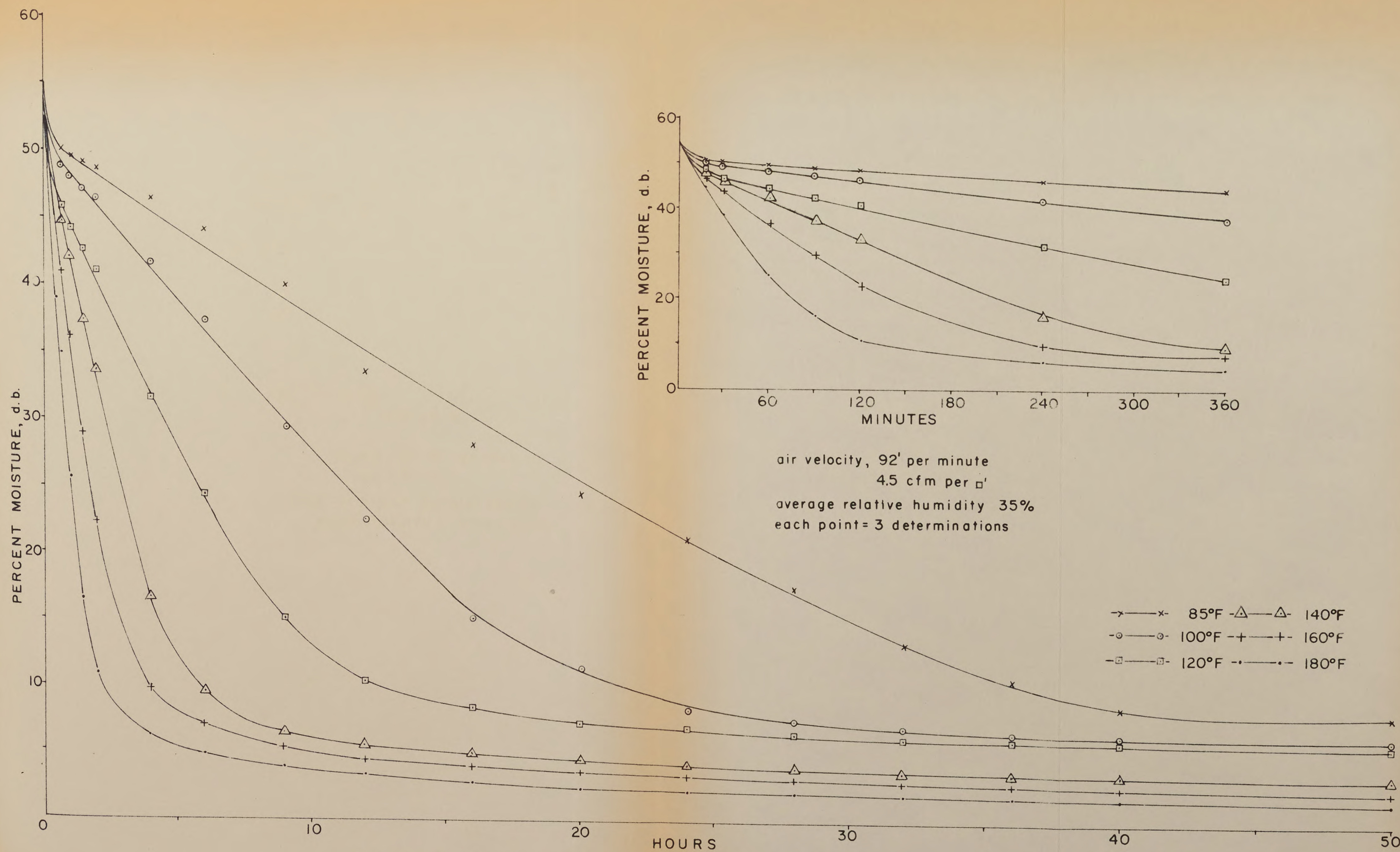
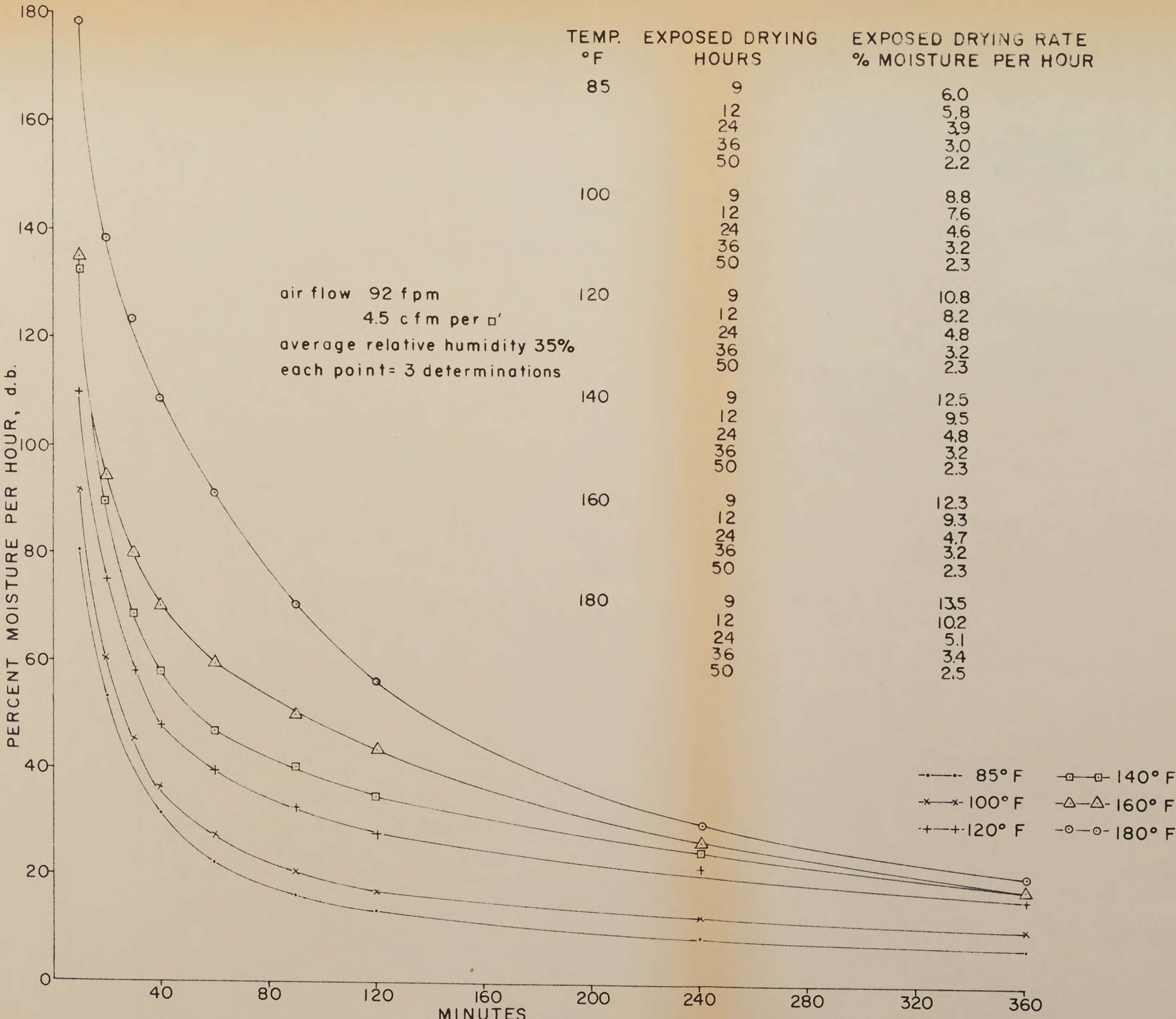



FIG. 14 EXPOSED DRYING OF PARCHMENT COFFEE




| TEMP. °F | EXPOSED DRYING HOURS | EXPOSED DRYING RATE % MOISTURE PER HOUR |
|---|---|---|
| 85 | 9 | 6.0 |
| | 12 | 5.8 |
| | 24 | 3.9 |
| | 36 | 3.0 |
| | 50 | 2.2 |
| 100 | 9 | 8.8 |
| | 12 | 7.6 |
| | 24 | 4.6 |
| | 36 | 3.2 |
| | 50 | 2.3 |
| 120 | 9 | 10.8 |
| | 12 | 8.2 |
| | 24 | 4.8 |
| | 36 | 3.2 |
| | 50 | 2.3 |
| 140 | 9 | 12.5 |
| | 12 | 9.5 |
| | 24 | 4.8 |
| | 36 | 3.2 |
| | 50 | 2.3 |
| 160 | 9 | 12.3 |
| | 12 | 9.3 |
| | 24 | 4.7 |
| | 36 | 3.2 |
| | 50 | 2.3 |
| 180 | 9 | 13.5 |
| | 12 | 10.2 |
| | 24 | 5.1 |
| | 36 | 3.4 |
| | 50 | 2.5 |

FIG. 15 EXPOSED DRYING RATES OF PARCHMENT COFFEE

FIG. 17 COFFEE FRUITS AND BEANS AT DIFFERENT STAGES OF PROCESSING

The equilibrium moisture content for a product, as the name implies, is the state of balance in moisture content to which the product arrives under certain atmospheric conditions. Equilibrium is obtained when the rate of moisture loss from the product to the surrounding air is equal to the rate of moisture absorbed (Hall, 1957a). It is, therefore, also known as hygroscopic equilibrium.

It is a well known fact that water is a major constituent of all plant tissue. It serves as a vehicle for the transportation of organic and mineral matters, as a concentration regulator and as a shock absorber for sudden changes in atmospheric conditions.

The hygroscopic equilibrium is very useful to predict whether a product will gain or lose moisture under certain conditions of temperature and relative humidity. This is very significant when dealing with a product that requires drying and storing for considerable time as coffee. Once the equilibrium moisture content is known the drying process is somewhat simplified and loss caused by over-drying avoided. As pointed out on the discussion of exposed drying, the coffee bean (endosperm) after processing, drying and storage is still covered by a thin layer of cells commonly known as silver skin, an air space and another thicker layer of cells known as the endocarp as shown in Fig. 18. The presence of these, practically impermeable layers, with an air space between them makes drying more difficult and response to varying atmospheric conditions very slow.

Desorption isotherms for parchment coffee for temperatures of 40°, 68°, 86° and 100° F. are presented in Fig. 19 as obtained for three determinations for the 86° and 100° F. and two determinations for the 40° and 68° F.

temperatures.

During the tests it was observed that the samples reached half-way to equilibrium moisture contents fast. To reach equilibrium, however, they took a much longer time. In the higher temperatures, when the product was near equilibrium moisture content, considerable fluctuations started to occur. This is probably due to the severe cracking observed in the endocarp of the beans.

The tests conducted with the Gunson's Electronic sorting machine at Lowell, Michigan shows the following results:

1. The feeding mechanism is not appropriate to handle coffee fruits. The vibration is too violent and the fruits jumped out of the vibrating hopper.
2. The ripe coffee fruit, no matter how gently it is handled, always suffer some bruises or scratches through which the mucilage oozes and the fruits being sorted stick to the feeding belt. This results in an erratic projection which in turn affects the efficiency of the optical unit in scanning the fruit.
3. A machine that sorts truly by color and not by shades and one that scans the fruit more completely is needed. There are instances when a fruit which is ripe enough for processing still have some areas of green tissue on the outside.
4. In order to be able to continue the electric sorting studies, negotiations between the Sortex Company of North America and the Puerto Rico Agricultural Experiment Station have been arranged. One unit, under a loan agreement, is to be installed in Puerto Rico for further studies on color sorting of coffee fruits previous to processing.

Fig. 14—Mature fruit cross section showing the pericarp (pe) greatly reduced in thickness (32 X).

cot.=cotyledon
en.=endocarp
ex.=exocarp
m=mesocarp
s.sk.=silver skin

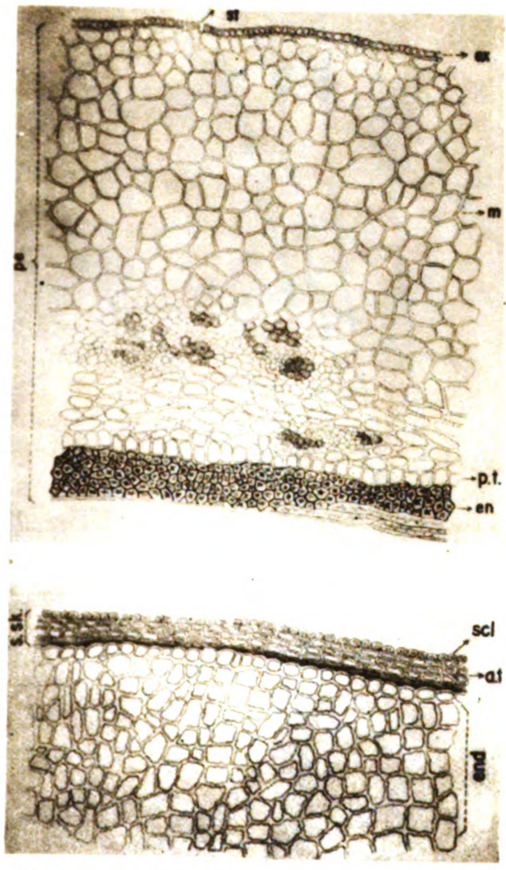



Fig. 15—Mature fruit cross section, illustrating the pericarp and seed histological constitution. (100 X).

a.t.=amorphous tissue
en.=endocarp
end.=endosperm
ex.=exocarp
m=mesocarp
pe.=pericarp
p.t.=palisade tissue
scl.=sclereids
s.sk.=silver skin
st.=stoma

**Fig. 18. Cross Section of a Mature Coffee Fruit. Reproduced by permission of Coffee and Tea Industry Magazine.**

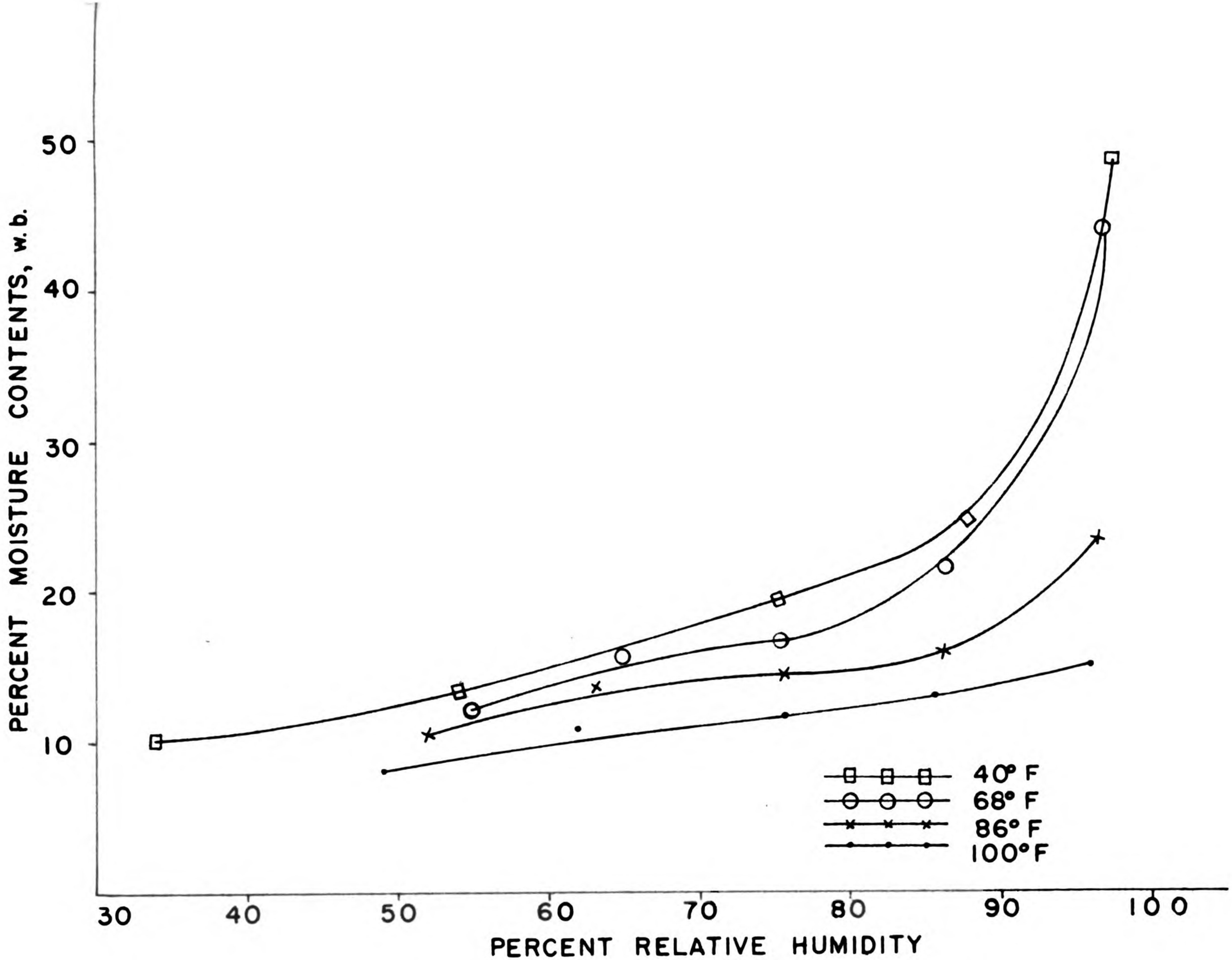



FIG. 19 EQUILIBRIUM MOISTURE CONTENTS OF PARCHMENT COFFEE

# SUMMARY

The coefficients of friction between coffee fruit, coffee beans and different construction materials were determined by the tilting table method. Determinations were performed for dry surface and wet surface fruits, pulp, pulped unwashed, pulped washed wet and pulped washed dry beans.

When the coefficients of friction obtained for wet or dry surface fruits are compared, they show a consistently lower value for wet surface fruits on all metal surfaces and a higher value on all wooden surfaces. The pulped washed, wet beans show the highest coefficient of friction when compared with fruits, pulp, pulped unwashed or pulped washed dry beans for all materials of construction. Values range from 0.65 for stainless steel to 1.15 for planed wood. The washed dry beans (12 percent moisture content, d.b.) showed the lowest coefficient of friction when compared with fruits, pulp, pulped unwashed or pulped washed wet beans. The values obtained vary from 0.34 for stainless steel to 0.55 for concrete and are similar to the values obtained by Kramer (1944) for rough rice on the same materials. The results of the preliminary rebounding tests for ripe and green coffee fruits show possibilities of obtaining a definite pattern for separation. When projected perpendicularly against a rebounding surface the ripe fruits show a form of inelastic collision response while the green ones rebound in what can be classified as an elastic form. Projecting the fruits against a surface at an angle does not show any regular pattern due to the fruits' surface irregularities.

The specific gravity for green fruit varied from 1.0063 to 1.1163 and for the ripe fruits from 1.0072 to 1.0884. No consistent difference was found between green and ripe fruits which could be used to advantage in sorting. The values obtained for specific gravity, bulk density and void space for coffee are similar to the values obtained by Zink (1935) and by the U.S.D.A. (n.d.) for wheat, oats, buckwheat and millet.

The air velocities required for flotation were determined with a pitot tube installation. The conventional pitot tube formula (Eckman, 1957) was used to calculate these values. Generally from 30 to 50 feet per second are added to the flotation velocity to obtain the conveying velocity. The conveying velocities obtained by calculation came very close to the required conveying velocities as determined by the Sturtevant air conveying curve developed by Westinghouse in 1946.

Exposed or layer drying of coffee from approximately 54%, w.b. to below storage moisture contents (12% w.b.) showed that the coffee bean follows the general drying rate pattern as found for other grains. Temperatures of 85°, 100°, 120°, 140° 160°, and 180° F. were used with an air flow of 92 fpm in a 3 inch tray which gave a flow rate of 4.5 cfm per square foot. Drying at high temperatures (over 160° F.) caused an undesirable coloring of the bean and temperatures over 120° F. cause endocarp cracking. So far no practical way of quality maintenance with mechanical drying has been worked out.

Desorption isotherms for parchment coffee beans exposed to temperatures of 40°, 68°, 86° and 100° F. were determined. Due to the nature of the outer layers, parchment coffee is very slow on its reaction to varying atmospheric conditions.

Electronic sorting of the fruits before processing offers good possibilities. Tests performed, using a Gunson's Electronic Separator, shows that the mechanical feeding, and the scanning system need to be modified for successful separation.

## CONCLUSIONS

1. <u>Coefficient of friction.</u>

   During the different stages of coffee processing, the highest coefficient of friction of the product on all materials of construction corresponds to the pulped washed wet beans. Values obtained range from 0.65 for stainless steel to 1.15 for planed wood. This is considerably higher than the values determined for other crops on the same materials. The washed dry beans showed the lowest values. These varied from 0.34 for stainless steel to 0.55 for concrete which compare with results obtained for rough rice on the same materials.

2. <u>Resiliency</u>.

   Ripe and green fruits rebound differently when dropped perpendicular to a surface. A definite pattern can be obtained. Green fruits rebound farther in general than the softer ripe ones.

3. <u>Specific gravity and bulk density</u>.

   No significant, consistent difference was found in the specific gravity of ripe and green fruits. Values obtained for green fruits varied from 1.0063 to 1.1163 and for ripe fruits from 1.0072 to 1.0084.

4. <u>Air flotation and conveying velocities</u>.

   Air flotation and conveying velocities for coffee fruit, pulp and beans determined and calculated using the conventional pitot tube installation and formula, with normal air conditions, compare favorably with work done for other crops. Air velocities of 5,447, 5,567, 4,168 feet per minute were obtained for green fruit, ripe fruit and pulp respectively when determined and calculated with a pitot tube installation and formula as compared with 5,600, 5,550 and 4,100 feet per minute when taken from the Sturtevant conveying curve.

5. Resistance to air flow.

Ripe coffee fruits offer a higher resistance to air flow than the green ones. In parchment coffee, the higher the moisture content the higher the resistance to air flow. A linear relationship resulted when the static pressure in inches of water as plotted logarithmically versus the air flow for coffee fruits and beans.

6. Drying rates.

Fast drying at high temperatures (180° F.) affects the color of the coffee bean.

Exposed drying of coffee beans follows the same general drying rate pattern as for other grains. Severe cracking of the endocarp was observed when beans were dried at temperatures above 120° F. The temperatures being used for coffee drying are too high for quality maintenance.

7. Equilibrium moisture contents.

Parchment coffee responds very slowly to changes in atmospheric conditions requiring long periods of exposure to reach equilibrium:

During the tests, mold growth was not present even when the product was exposed to seemingly favorable conditions. At high temperature and relative humidity considerable fluctuations in moisture content were observed when the product was near equilibrium moisture content. Data shows that overdrying has been a common practice.

8. Electronic sorting.

Oozing of the mucilage greatly hinders the machine feeding of ripe fruits for sorting. Green areas on ripe fruits require a machine that scans the fruit better.

Sorting by shades is not a very effective way of separating the green from the ripe fruits.

## FURTHER STUDIES

Further rebounding or resiliency studies for green and ripe coffee fruits.

Pull needed to remove a ripe and a green fruit from the tree.

Resistance to penetration of a sharp point (needlelike) in ripe and green fruits.

Sliding and rolling coefficients of friction.

Drying studies.

Perforation of the parchment previous to drying.

Measurements of inside temperature of a coffee bean exposed to direct sunlight.

Effects of intermitent drying periods.

Surface water removal studies.

Use of solar energy for drying.

Vacuum drying studies.

Respiration rate studies.

Storage studies.

Ripe fruits.

Pulped wet parchment coffee.

Partially dried and dried parchment coffee.

Further electronic sorting studies.

Studies on the effect of ethelene, 2-4D, or other growth regulators on the color of the coffee fruit as a help in their sorting.

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