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Drying cut fruits with recirculated air for energy savings

Terry Hill. Walker

To the Graduate Council:

I am submitting herewith a thesis written by Terry Hill. Walker entitled "Drying cut fruits with recirculated air for energy savings." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Biosystems Engineering.

Luther R. Wilhelm, Major Professor

We have read this thesis and recommend its acceptance:

John B. Wilkerson,Rabindra N. Biswal

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Vice Provost and Dean of the Graduate School

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To the Graduate Council:

I am submitting herewith a thesis written by Terry Hill Walker entitled "Drying Cut Fruits with Recirculated Air for Energy Savings." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Agricultural Engineering.

Luther R. Wilhelm

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We have read this thesis and recommend its acceptance:

John Wilkerson

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Date 12-3-92

DRYING CUT FRUITS WITH RECIRCULATED AIR FOR ENERGY SAVINGS

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Terry Hill Walker

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DEDICATION

This thesis is dedicated to my parents,

George E. Walker and Pamela P. Walker,

for their truly appreciated support in making

my educational opportunities possible.

The dedication is also extended to my loving wife,

Laura, who has endured much of the time

and effort in completing this project.

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ABSTRACT

The main focus of this study was to test the feasibility of saving energy while drying fruit by recirculating drying air at a constant rate. Four recirculation rates (0, 25, 50, and 75%) were used to dry peaches and apples. For these treatments, the amount of energy consumed, the moisture removed, and the total drying times were measured. Three quantitative parameters (color, shelf-life, and sugar content) were used to determine the final quality of the dried fruit.

For both fruits tested, total energy consumption showed very significant differences among recirculation rates (with 75% recirculation requiring the least energy). The 75% recirculation rate produced an energy savings over no recirculation of approximately 53% for drying peaches and 46% for drying apples. The total processing times, however, were nearly the same for all recirculation rates. In general, no substantial losses occurred in the product quality for fruits subjected to the higher recirculation rates as compared to those subjected to no recirculation. The results of this experiment helped to decide an optimal fixed recirculation rate for maximizing the energy savings without causing destruction in the product quality. By optimizing the energy saved, fruit dehydrators may be improved to produce dried fruits at a lower cost.

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INTRODUCTION

I. DRYING OF FRUITS

The practice of drying fruits has existed since the beginning of recorded history. Until the early eighteen hundreds, however, fruits were exposed to outside air and dried with energy provided by the sun. The first recorded drying of cut fruits in a heated room occurred in 1870 (Hayashi, 1989). This dryer operated by adding heat to the air below the fruits. The heat (provided artificially by burning fuel as a direct heat source) caused moisture to evaporate from the surface of the fruit. This dryer was termed a natural-draft dryer or *evaporator* because the heat rising within the room caused air to circulate over the fruit naturally without the aid of a mechanical device such as a fan.

Later, forced-draft dryers were introduced and became increasingly popular. This type of dryer, known as a *dehydrator*, applies a forced current of air across the product and controls important parameters in drying such as temperature, relative humidity, and air velocity (Cruess and Christie, 1921).

Advantages of Drying Fruits

The four important advantages of drying food are:

- Lower shipping costs
- Longer shelf-life
- Less packaging requirements
- Concentrating solids

Shipping

Reduction of water content lowers product weight, especially in high moisture foods such as fruits. Therefore, shipping much larger quantities of the product is possible with the same labor force. Lower costs can be attributed mostly to a tremendous cost savings for transportation and labor. Even though the process of drying may have a high energy cost, the reduction in transportation and labor costs will usually exceed all other costs when shipping large amounts of the product.

Shelf-life

Removal of moisture in food products reduces the *water activity* (a measure of the availability of water within the product to allow for biological and chemical activity). Low water activities associated with dried fruits that have moisture contents between 18 and 25% causes high osmotic pressures of the sugars, which are present in high concentration. The high osmotic pressure collapses the delicate cell walls of viable microorganisms, therefore suppressing any growth (Brockmann, 1970).

Packaging

The shelf-life of dried fruits depends, to a large extent, on the packaging. With the availability of new packaging materials, only minimal packaging need to be applied to dried fruits. Often polyethylene bags (2-4 millimeters thick) serve as an adequate packaging material when most of the air within the bags is expelled. The fruits remain stable over long periods because, under ordinary conditions, the fruits dried to a moisture content of 24% obtain approximate equilibrium with an atmosphere at 75% relative humidity (Somogyi and Luh, 1986).

Concentrating Solids

By decreasing the amount of water in a fruit product, the other constituents of the dry matter will consequently become more highly concentrated, possibly producing a more desirable product. In the case of fruits, the primary dry matter constituents are sugars (approximately 65% of the total solids) and acids such as ascorbic acid. As compared to fresh fruit, the higher sugar and acid concentrations in dried fruit produce a more candy-like product.

Problems with Drying in Tennessee

Fruit growers and processors in Tennessee may find it difficult to dry fruits simply by sun drying because of the high-humidity conditions common to the area. Because the solar-drying process is long, the possibility of irreversible microbial damage to the fruit (spoilage, decreased sugar content, etc.) may occur. Also, insect populations are usually high in areas associated with high relative humidity. Insects infest the fruits causing sanitation problems. Because of these problems with sun drying in the Southeast, other means of dehydration become necessary to successfully dry fruit products in high humidity regions.

Alternatives for Drying Fruits

Several alternatives exist for drying high moisture fruit products. By using a fan to move air across heated coils in a closed system containing the fruit product, high air temperatures can be achieved to hasten drying conditions. Heating the air to a temperature much higher than the outside air (ambient condition) allows the air to hold much more moisture. In other words, the relative humidity of the air decreases as the temperature of the air rises. Therefore, on a typical, hot summer day in Tennessee, the fan draws high moisture air into the system; heat added to the incoming air then causes a decrease in the relative humidity even though the same amount of moisture still exists. As the heated air passes over the surface of the cut fruit, it draws more moisture from the fruit. This moisture is removed from the fruit because the heated air has a greater capacity to hold moisture than it would if not heated. Thus, the thermal energy in the air hastens the evaporation of moisture from the surface of the fruit.

Drying Applications in Tennessee

Some fruit growers in Tennessee have expressed an interest in drying a portion of their total fruit yield to provide alternate markets for a part of their production. Many small-scale fruit growers operate under tight economic constraints. Follis (1982) mentioned that factors behind these problems often include high equipment costs, high energy costs, and low availability of productive land. Because many of these growers operate on a small scale, a batch-type system seems appropriate for their needs. However, a large amount of energy would be required to operate the dryer. Energy costs are thus a key factor in any decision involving small-scale dehydration.

The high energy cost for operating the batch dehydrators results, to a great extent, from the loss of a large amount of available heat to the surroundings. The losses come primarily from the heated air exiting the dehydrator. Heat loss also occurs, to a lesser extent, through the walls of the dryer. By recirculating some of the heated air and sufficiently insulating the dehydrator, the system could potentially save a considerable amount of energy.

II. OBJECTIVES

The objective of this research was to find an optimum recirculation rate of drying air among the four rates tested (0%, 25%, 50%, and 75%) to save energy during the dehydration process. Any differences in the quality of the dried fruits subjected to each recirculation rate were to be documented. Tests included peaches, a slow drying product, and apple slices, a fast drying product.

CHAPTER II

LITERATURE REVIEW

I. FRUIT DRYING

History of Drying

The process of drying foods may be one of the oldest known activities demonstrated by man. Hayashi (1989) reported that inhabitants of regions that are now part of the Soviet Union practiced drying meats as early as 20,000 BC. Around 4,000 BC, American Indians preserved potatoes by drying them using sunlight and wind. Other processes included the drying of sea water to obtain salt (9,000 BC), sun drying fruits on pads in the Near East (7,000 BC), and drying apples by cutting them into slices and hanging them (2,000 BC). Since fish was a major source of food to cultures existing as early as 500 BC around the Mediterranean Sea, 'salting' (a type of osmotic dehydration) became an important technique used for drying. This technique was significant because early fishermen needed a way to prevent fish from spoiling.

The people from these early times may not have understood how drying affects foods, but they did realize the benefits of drying foods. The main benefit is that dried foods do not spoil as quickly as the same undried foods. Today, it is realized that dried foods do not spoil readily because they lack the water to support growth of microorganisms (Hayashi, 1989; Nichols and Christie, 1930; Foods and Nutrition Encyclopedia, 1983).

For many years, foods were dried only by natural means (such as energy supplied by the sun and wind). Hayashi (1989) stated that the first drying of fruits in a heated room (e.g. kiln drying) occurred in 1870. Gould (1907) reported that the drying of apples by 'evaporation' first took place in western New York State. At this time, a distinction was made between 'dried' apples (apples dried by the sun) and 'evaporated' apples (apples dried by natural-draft evaporators).

With the arrival of natural-draft evaporators, apples ceased to be dried by the sun. The switch to natural-draft evaporators occurred mainly because apples tend to mature late in the season (Nichols and Christie, 1930). With shorter days and cooler weather, the conditions are unfavorable for sun drying. Because of their lightly colored flesh, apples, more so than other fruit, are damaged from exposure to dirt and dust associated with sun drying.

Although evaporators were an improvement over sun drying apples, Wiegand and Powers (1922) and Wiegand (1923b, 1924) found many inefficiencies in them. However, they did suggest adding a forced draft to convert the natural-draft evaporator into a dehydrator.

New Technology for New Needs

Today, commercially dried fruits have received greater attention from consumers because of the demand for healthy, dried food-snacks (Hayashi, 1989). Until recently, the demand for dried fruits increased only in response to needs during military conflicts (Somogyi and Luh, 1986). The lack of proper food storage facilities (freezers, etc.) during war times required other means for preserving foods (e.g. drying). Somogyi and Luh (1986) stated that new technology has brought an important innovation in fruit dehydration. Progress in dehydration has been stimulated by higher transportation costs, rapidly improving drying technology, and revolutionary new package materials.

Sun-dried fruits constitute most of the dried fruit consumed in the world today. Mechanically dehydrated fruits are produced in relatively small amounts. Because of recent technological advancements, production of mechanically dehydrated fruits has rapidly increased in the last decade. Although dehydrated fruits proved to be invaluable during previous wars throughout the world, the technology for making a dehydrated product attractive to the consumer has only recently emerged (Somogyi and Luh, 1986).

Drying fruits is a major form of processing in states, such as California and Washington, that produce high fruit yields each year. California commercially dries massive amounts of fruit each year, leading the world in the production of raisins and prunes (USDA, 1990). Because of the strong emphasis on processing fruits in California, many of the technological improvements in drying can be attributed to research conducted at California experiment stations.

Economic Importance

The fruit drying industry serves as an important commodity to certain countries such as Greece, Chile, Iran, Turkey, and Australia (Van Arsdel and Copley, 1964). Both dried fruits and dehydrated fruits play an important role in the agricultural industry of the United States, especially in the state of California. In the United States, California produces more than 90 percent of all dried and dehydrated fruits. Washington and Oregon also dehydrate large amounts of fruit. Arizona, Idaho, New York, and Virginia contribute to a lesser extent to the production of dried and dehydrated fruits. Table II-1 shows the production of dried fruit in California in the past decade.

Table II-1. Dried fruit production (dry basis), California, 1980-89.

Year	Apples	Apri-cots	Dates	Figs[1]	Peach-es[2]	Pears[3]	Prunes	Grapes[4]	Total
	Tons	*Tons*	*Tons*	*Tons*	*Tons*	*Tons*	*Tons*	*Tons*	*Tons*
1980	2,140	3,600	22,400	14,450	2,200	1,500	168,000	310,550	524,840
1981	1,400	3,800	22,300	12,200	2,050	1,440	159,500	258,000	460,690
1982	1,000	4,800	23,900	12,200	2,600	1,200	126,000	295,300	467,000
1983	1,000	4,100	17,000	11,050	2,000	1,080	145,000	398,500	579,730
1984	2,050	3,520	22,200	11,500	1,550	780	148,000	335,350	524,950
1985	4,700	2,000	28,900	10,400	2,050	1,310	141,000	347,940	538,300
1986	1,950	1,400	17,800	16,200	1,800	1,410	99,000	278,900	418,460
1987	2,900	2,980	19,400	16,850	3,900	1,130	229,000	357,950	634,110
1988	17,800	2,640	22,000	13,450	5,000	1,220	151,000	366,500	579,610
1989	17,650	3,280	22,000	14,000	3,400	1,119	215,000	433,200	709,649

1 Standard and substandard
2 Freestone only.
3 Bartlett only.
4 Raisin and table type.
Source: Economic Research Service (USDA, 1990)

Drying Environments

The best method for drying fruits depends on factors such as the environment and the type of fruit. Often, the choice between mechanical dehydration and sun drying depends heavily on the environmental conditions associated with the drying location. Drying environments vary considerably from one region to another in the United States. Because of the sunny, dry conditions associated with much of the California fruit growing region, fruits can be easily sun-dried there. An average day in southern California will have a low relative humidity and a high temperature, a combination that speeds up the drying process. However, Tennessee and similar regions in the southeastern United States often experience high relative humidities associated with warm air, making the conditions for sun-drying much less favorable.

Advantages and Limitations: Dehydration vs. Evaporation

Perry *et al.* (1946) and Cruess and Christie (1921) identified several advantages and limitations for mechanical dehydrators as opposed to natural-draft evaporators.

Advantages

When done properly, dehydration of fruits has several advantages over natural-draft evaporation (e.g. sun drying). The drying of fruits by evaporation on trays in the sun (placed in the outside air) may cause contamination by dirt, dust, and microorganisms as opposed to a dehydrator (a process that controls the environment). A dehydrator controls such factors as infestation by insects and damage associated with animals and bad weather conditions (Perry *et al.*, 1946). A dehydrator also has the advantage of requiring less space than that needed for sun drying.

The longer drying times associated with natural-draft evaporation often allow enough time for the growth of microorganisms, such as molds and yeasts, that can cause fermentation and spoilage. Chase *et al.* (1941) stated that microbial growth does not occur when the soluble solid content (sugars, in particular) of the fruit is concentrated by the removal of water. A dehydrator eliminates the potential for any significant microbial growth by concentrating the soluble solid content of the fruit before any considerable growth occurs. On the other hand, evaporation often takes a long time, allowing for microbial growth to occur before the soluble solids become sufficiently concentrated.

Dehydrated fruits and sun-dried fruits show differences in both nutritional value and general appearance. Cruess and Christie (1921) claimed that dehydrated fruit resembled fresh fruit in color and flavor more than sun-dried fruit after both were cooked. Bhardwaj and Lal Kaushal (1990) noted that the retention of both ascorbic acid (vitamin C) and carotene (pro-vitamin A) content was greater in dehydrated apples than in sun-dried samples. Large losses of carotene in sun-dried apples, however, may explain why lighter colors are observed in the sun-dried fruit as compared to the dehydrated fruit (Desrosiers and Desrosiers, 1982).

Limitations

Although many advantages exist for dehydration, some limitations exist that may make the dehydration process more cumbersome than evaporation. Perry *et al.* (1946) noted several limitations, primarily concerning the quality of the dried product. For instance, improper dehydration may result in an inferior product that is cracked, scorched, or discolored from the effects of high temperatures and case hardening. These adverse effects may be caused by a combination of excessive temperatures, lack of humidity control, and periodic variations of moisture content in the fruit.

Dehydrators: Batch vs. Continuous

Dehydration systems are either continuous-type or batch-type. The continuous system (used for large industrial dehydrators) represents the fastest way to dry large quantities of fruit. These dehydrators were introduced on the West Coast to produce prunes in large quantities over a short time. Continuous dryers should be kept running for long periods without shutdowns (Beavens, 1944). In Tennessee (where the total yield of fruit produce is far less than that of California), smaller batch-type systems appear more useful for small scale processes. Generally, the batch-type systems cost much less than the larger, industrial, continuous systems. Therefore, in most cases, the batch systems are more economical for small crop farmers than the larger continuous systems.

Selecting the type of dryer depends on the nature of the fruit to be dried and the desired product (Franzen *et al.*, 1987). A schematic suggested by Van't Land (1984) for selecting the appropriate dryer (for drying fruits) is depicted in Figure II-1. The selection scheme of continuous dryers also applies to batch dryers, although the dryer's design may be altered.

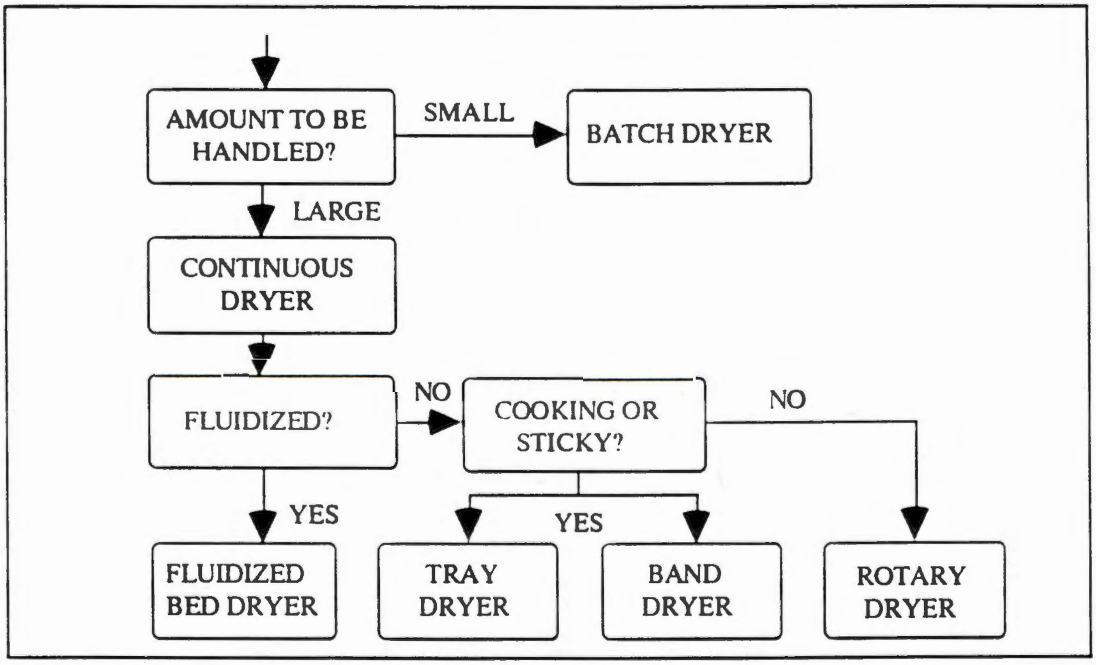

Figure II-1. Selection schematic for dryers applied to fruit products.

Source: Van't Land (1984)

Cabinet Dryers

A cabinet dryer is a batch-type tray dehydrator. This dryer takes the shape of a box containing perforated shelves. A fan is located near the back of the cabinet with a heating element (e.g. steam coils and electrical resistance units) placed immediately in front of the fan (Hall, 1989). The air is heated and moves across the product, which is placed on one or more stacks of trays.

Beavens (1944) noted two important purposes for selecting cabinet dryers:

1. Experimental operations could be easily performed to determine drying parameters which apply to commercial-scale operations.
2. Small amounts (1-20 tons per day) of fruit may be dehydrated where operations require either short or long periods.

Cabinet Dryers: Construction

The design of cabinet dehydrators varies mostly in how the heated air is circulated through the trays and the type of heater used (Beavens, 1944). Typically, continuous tunnel dehydrators employ large centrifugal or rotary fans that blow air across the surface of fruit. This is called *cross circulation.* Some cabinet dehydrators contain either small centrifugal or rotary fans, but often employ propeller or radial fans. Cabinet dehydrators usually contain perforated trays that allow the air to flow through the trays. This is called *through circulation.* Through circulation dries larger pieces of material faster than cross circulation. With through circulation, air moves past all surfaces of the fruit, allowing for moisture to quickly move from all surfaces.

A wide variety of heaters may also be used in a forced air cabinet system. The type of heater used depends on (1) fuel use and availability, (2) the cabinet design, and (3) the availability of materials. The source of heat may be applied as either direct heat or indirect heat. Fuel combustion (a form of direct heat) efficiently heats the incoming air. The maximum amount of heat in the fuel is transferred to the drying air (Van Arsdel, 1973a). Fuel combustion, however, may occur as incomplete combustion that produces injurious byproducts (e.g. carbon monoxide and sulfur dioxide). Indirect heating (e.g. furnaces, steam pipes) eliminates the problems associated with direct fuel combustion because the byproducts of the heating fuel does not make direct contact with the drying air. However, indirect heat sources are less efficient because only 50-75 percent of the heat is made available for drying (Beavens, 1944).

Drying Uniformity: Problems and Solutions

Drying uniformity in the product is very important to the fruit drying industry (Adams and Thompson, 1985). Moyls (1985) reported that nonuniform airflow presented the main problem encountered with commercial batch dehydrators. Mrak (1938) stated that drying uniformity in the product depended on uniform airflow. Nonuniform airflow causes the fruit on some trays to dry much faster than the fruit located on other trays that get less air flow. The final product of each batch varies in moisture content because some fruits do not dry to the extent of others in the same batch. Therefore, the incompletely dried fruit may contain enough moisture to support microbial growth.

Christie and Nichols (1929) recognized that nonuniform airflow occurred near the frontal area of the trays in a continuous, concurrent, tunnel dehydrator for prunes. The compactness of the batch dryers causes nonuniform airflow because the air cannot be distributed evenly before reaching the drying trays. Employing a longer section between the blower and drying trays would allow a more uniform distribution of air.

However, this addition would eliminate the original compactness of the unit, making it less economical, and requiring more floor space.

A possible solution to the problem of nonuniform airflow may be to modify the drier by adding a flow diverter and turning vanes. The flow diverter would push the air flow in the direction toward the turning vanes. The vanes would allow the airflow to become more uniform by forcing the flow to disperse equally at the frontal area before passing over the fruit. Adams and Thompson (1985) reported that this type of modification significantly reduced the range in final moisture content (wet basis) of prunes by approximately 40 percent (99% confidence level) compared to the output of conventional tunnel dehydrators. The range of moisture contents, before the modification, averaged approximately 12 percent. An average range of seven percent was observed in the modified tunnels.

Moyls (1985) introduced a moving-vane batch dehydrator that would continuously vary airflow over the drying product for the duration of the process. The results from this experiment showed that the moving-vane model dried more evenly than a similar batch dehydrator equipped with fixed vanes. This study also implied that loading the trays with equal amounts of fruit and rotating the trays 180° near the middle of the process helped obtain a product with uniform moisture content.

Drying Time and Energy Considerations

The total drying time can be reduced by (1) applying heated air of given velocity and (2) directing the air to allow sufficient contact with all surfaces of the fruit. The reduced drying time decreases the chance for microbial spoilage and may result in less energy consumption.

In the past, energy considerations did not influence the processing of foods (Kefford, 1982). Now, however, the large increase in the price of fuel oils has become a major concern to the food processing industry (Crawford and Elson, 1982). Energy costs now govern many of the decisions made for designing and purchasing food processing equipment. Olabode *et al.* (1977) noted that drying requires the highest energy input among all operations examined in processing potatoes. The processes in this study included hot-air drying and freeze drying, canning, retorting, and freezing. However, for the complete system (including processing, storage, and distribution) the drying process reduced the total consumption of energy with less stringent packaging requirements and reduced transportation costs.

Although dehydrators reduce the total cost of processing and distributing dried fruits, the feasibility of dehydrator use may still be disputed by fruit growers with small crops. Small fruit growers may not be able to afford the initial investment of adding dehydrators if the operating cost becomes high. Therefore, for these small fruit growers to profit by drying part of their total fruit yield, reducing the operating costs would be necessary .

Recirculating Drying Air

Recirculating some of the heated air through the dryer allows for significant energy savings (Wiegand, 1923a; Mrak, 1938; Beavens, 1944; Thompson *et al.*, 1981; Strumillo and Kudra, 1986), thus reducing the operational costs. From early experiments with fruit dehydration, Wiegand (1923) discussed five main advantages associated with recirculating the air:

> (1) *Saving Heat and Fuel.* Nearly two-thirds of the heat is lost if air is not recirculated.

(2) *Adding Moisture to the Air.* Humid air prevents case hardening.

(3) *Decreasing Drying Time.* Humid air is a better heat conductor than dry air, and it keeps the surface of the fruit pliable, thus allowing for better moisture transfer to the drying air.

(4) *Lowering Drying Cost.* Cost lowered significantly from energy savings.

(5) *Increasing Quality.* Quality is increased by lowering the temperature and increasing the airflow rate and amount of recirculation.

II. PRODUCT QUALITY

The quality evaluation of dried fruits relies primarily on sensory stimuli (Pattee, 1985). Until recently, sensory evaluation depended upon highly trained persons (a sensory panel). With rapidly increasing technology, however, techniques have been developed to accurately analyze some of the sensory properties. These basic sensory properties include sight, taste, touch and hearing. From these properties, human judgment (which is not always consistent from one person to the next) may be imposed on a food product (Campbell *et al.*, 1979).

Through technological advancements, instruments can now measure parameters such as color differences, texture, and chemical changes in processed foods. These advancements have allowed for a more quantitative approach in determining sensory properties. Together with the quantitative output from these instruments and the qualitative assessment from a sensory panel, a reasonably accurate description of the dried fruit quality is now possible.

Effects of Recirculated Air on Fruit

Studies of the effects of dehydration on fruits are important to both improving the processing of dried fruits and obtaining better quality control. Parameters such as texture and color measure quality attributes of the dried-fruit product. The exit air from the recirculation dryer contains moisture and heat (not used in evaporation) that is partially circulated back through the system. This leftover heat helps evaporate more moisture from the fruit, thus requiring less energy. At the same time, recirculated moisture increases the humidity of the drying air. The increase in humidity may slow the drying process a little because the higher vapor pressure associated with higher humidity air reduces evaporation rates (especially during the early portion of the dehydration process when most of the moisture is removed).

A slower rate of moisture removal from the fruit may, however, eliminate the effect of "case hardening," where the surface of the fruit flesh becomes leathery and substantially impermeable to water (Van Arsdel *et al.*, 1973a). This hard layer forms when moisture is removed too rapidly from the surface of the flesh. The case hardened layer then impedes further moisture removal from the center of the fruit, resulting in an undesirable product. While the outside layer remains hardened, the inside of the fruit may contain too much moisture, thus contributing to the growth of microorganisms.

Storage Stability

The development of shelf-stable products is important to developing countries and in situations where refrigeration and thermal processing are inadequate (Brockmann, 1970; Kaplow, 1970). Storage stability in dried fruits can be described by the ability of the fruit to retain acceptable flavor, color, nutrients, and overall appearance (Stafford and Guadagni, 1977). Nutrient losses and other chemical changes, such as enzymatic browning and changes in flavor, are the primary factors affecting storage stability. Other quality factors that determine the storage stability may include microbial spoilage and nonenzymatic browning. Many of these changes are caused largely by environmental factors. Some of these factors include light, temperature, water activity, oxygen partial pressure, and package permeability's (Singh *et al.*,1983).

Nutrient Retention

Factors involved in the changes in the nutritional quality during dehydration and storage have become very important for determining the storage life of dried fruits (Kirk *et al.*, 1977). Limited information exists on effects of dehydration and storage on the kinetics of nutritional losses in dried fruits (Labuza, 1972; Resnik and Chirife, 1979). Much of these losses occur during the preprocessing stages, which involve sorting, washing, cutting, peeling and often blanching to destroy enzymes. During both the preprocessing stage and dehydration process, nutrients are depleted by either a physical manner or a combination of physical-chemical reactions. For instance, washing and peeling the fruits would physically remove some valuable nutrients.

Blanching destroys enzymes that are responsible for both depleting nutrients and browning (Phaff *et al.*, 1945). However, the high blanching temperatures increase rates of some reactions that break down important nutrients. The effect of dehydration on fruits causes the nutrients to become concentrated as the water is removed. Dehydration also requires the addition of heat to supply energy for the evaporation. The combination of adding heat and concentration of nutrients accelerates the physical-chemical interactions that depletes the nutrients, often producing less favorable compounds (Labuza, 1972).

The retention of both water-soluble and fat-soluble vitamins accounts for much of the research done on nutrient retention in relation to the dehydration of fruits. Destruction of ascorbic acid (vitamin C), and ß-carotene (provitamin A) have been studied extensively because of their sensitivity to heat and other factors.

The most labile of all vitamins is most likely ascorbic acid (Labuza, 1972). Lee and Labuza (1975) studied the destruction of ascorbic acid in various dehydrated foods as a function of moisture content, water activity, and storage temperature. The study found an increased rate of destruction of ascorbic acid as the moisture content and water activity increased. The increase in reaction rate was attributed to decreased viscosity that resulted in the increase of mobility of reactants.

Muller and Tobin (1980) discussed losses of ascorbic acid by heat destruction and leaching. Desrosiers *et al.* (1985a) found that only 26.7 percent of the ascorbic acid remained after the home dehydration of fresh peaches. The peaches were pretreated with an ascorbic acid dip that increased the total ascorbic acid by twenty fold. After six months of storage at ambient temperature, the ascorbic acid content further decreased to 9.1 percent. Mrak and Phaff (1947) found that only 10 percent of the ascorbic acid remained in peaches after sun drying and 20 percent remained after tray drying.

Hurt (1979) estimated that 50 percent of the vitamin A in the western diet was derived from plant materials (e.g. carrots, green pepper, and peaches). In plants, the precursor to vitamin A exists in the form of provitamin A carotenoids (e.g. ß-carotene). Desrosiers *et al.* (1985b) found that degradation of carotene occurs in peaches and green peppers in a commercially available home dehydrator (Equi-Flow Dehydrator System).

However, after two months of storing the dried peaches at room temperature, no significant additional losses in carotene content occurred.

Due to its highly unsaturated structure, ß-carotene degrades by either oxidative degradation or cis/trans isomerization (Stefanovich and Karel, 1982). Arya (1979) reported that carotene degrades by an oxidation mechanism that depends on water activity, temperature, and the presence of reactants (e.g. oxygen, enzymes, and lipid hydroperoxides). Cis/trans isomerization can occur in the absence of oxygen, especially when exposed to heat, light, or acid (Schadle *et al.*, 1983). Marty and Berset (1990) showed that prolonged heating at 180° C caused limited destruction of the ß-carotene. However, the combination of mechanical agitation in the presence of common food constituents (e.g. water and starch) permitted greater oxygen transfer that increased the oxidative degradation of carotene.

Microbial Spoilage

The presence of microorganisms on the surface of dried fruit indicates the quality of the raw materials and the sanitation practiced during production (Somongyi and Luh, 1986). The USDA established that dried, cut fruits (e.g. apples, peaches and pears) contain very little growth of bacteria, yeast, and molds. The low microbial counts were partially attributed to the fact that most dried fruits have a low pH and contain a high level of sugars (King *et al.*, 1968). The high concentration of sugar causes a high osmotic pressure, which inhibits the growth of microorganisms. Furthermore, King *et al.* (1968) determined that microorganisms do not grow on dried fruit that have an 18 to 25 percent moisture. From the results of this experiment, Table II-2 summarizes the aerobic bacteria, yeast, and mold counts for various dried fruit based upon King's experiment. Dates had the highest bacteria counts of all dried fruits.

Table II-2. Aerobic bacteria, yeast, and mold counts per gram of processed dry fruit.

	Apples	Other cut fruits	Dates	Figs	Prunes	Raisins
Bacteria						
Average	274	835	6,487	662	3,718	2,542
90% of counts less than	730	757	21,000	93	4,600	8,200
Range	0-2,600	0-11,000	0-50,000	0-7,700	0-50,000	0-60,000
Yeasts and molds						
Average	261	23	2,478	17	851	3,934
90% of counts less than	730	50	720	110	6,000	20,000
Range	0-1,500	0-210	0-30,000	0-120	0-7,100	0-30,000

Source: King *et al.* (1968)

Because the pH is higher (5.5 to 6.0) than the other fruits (pH 3.0 to 4.5), the dates sustained more bacterial growth. However, apples and other cut fruits (apricots, nectarines, peaches, and pears) had very low counts averaging less than 800 bacteria per gram. Likewise, sulfured dried fruits do not support microbial growth at levels of sulfur high enough to prevent color deterioration (Van Arsdel et al., 1973b).
Although dried fruits retain exceptional storage stability for extended periods, most have a definite storage life. Their storage life depends on the storage temperature. Barger *et al.* (1948) showed that dried fruits stored at 0° C and 55% relative humidity prevented mold growth. However, dried fruits distributed commercially are typically stored at room temperatures, thus decreasing the potential for longer storage life.

Zerophilic Growth

Storage life for dried fruits reduces even more in the presence of zerophilic fungi (fungi that lives best in low water concentrations). The spoilage mold *Xeromyces bisporus* Fraser grows at a lower water activity (a_w) than any other known microorganism. The organism is fairly uncommon, but known to be fairly widespread (Pitt and Christian, 1968). The presence of this microorganism appears mostly on dried fruits and spices, which contain very low water activities and are usually regarded as safe from microbial attack. Pitt and Hocking (1982) noted that this organism contributed to significant spoilage of Chinese dates and fruit cakes averaging $0.72a_w$. Sexual reproduction (in the form of ascospores) took place at a remarkably low water activity of $0.67a_w$, while germination took place at $0.61a_w$ in a study conducted by Pitt and Christian (1968).

Color Retention

Color changes represent the most obvious signs of deterioration in dried cut fruits. Fruits showing the most color deterioration are apples, pears, peaches, figs, and other fruits with lightly colored flesh. Raisins and prunes do not show obvious changes because their natural colors are dark brown or black after dehydration.

Enzymatic Browning

Browning in fruits is associated with increased enzymatic activity of peroxidase (POD), polyphenyloxidase, and other phenolic compounds (Lee *et al.*,1990; Joslyn and Ponting, 1951). Sulfur dioxide prevents the browning reaction by acting as an antioxidant. The SO_2 binds to the enzyme, thus inhibiting the oxidative reaction that causes browning. Chan and Cavaletto (1978) reported that high levels of SO_2 decreased the drying rate of papaya leather, made by dehydrating papaya puree. The report concluded that, according to Raoult's Law, high levels of SO_2 lowered the vapor pressure, thus increasing the boiling point. Therefore, the drying rate would decrease because of reduced evaporation, caused by the elevated boiling point. Sayavedra-Soto and Montgomery analyzed dried apples for the effects of storage temperature and sulfur dioxide on color retention. Their research found that both storage life and color stability would significantly increase when stored at temperatures near 1° C.

Although most widely used to prevent enzymatic browning of dried fruit, SO_2 (1) has a corrosion effect on equipment, (2) causes destruction of vitamin B1 and other nutrients, (3) induces off-flavors, and (4) causes severe allergic reactions on certain individuals who consume sulfite-treated foods. Also, increased demands exist within the United States for SO_2-free dried fruits. Therefore, alternative treatments have been investigated (Roberts and McWeeny, 1972). Some of these treatments include lowering pH with organic acids, rapid dehydration to reduce the water activity below levels that allow for browning reactions, and thermal inactivation (quick blanching with steam).

Nonenzymatic Browning

Nonenzymatic browning reactions create other problems that occur during the dehydration of fruits. These reactions not only result in the loss of acceptable color, but also the development of off-flavor and loss of nutritive value (Resnik and Chirife, 1979). Air dehydration accelerates the rate of nonenzymatic browning in fruits. Labuza (1972) stated two reasons for the accelerated browning reactions: (1) as water is removed, the dissolved reactants become concentrated and their closer proximity increases the likelihood of a reaction, and (2) the temperature rises within the product to increase the mobility of reactants.

Resnik and Chirife (1979) reported that a possible mechanism for nonenzymatic browning is the degradation of reducing sugars (D-fructose and D-glucose) in the presence of organic acids (e.g. malic acid in apples) and heat. Acids act as a catalyst in the initial degradation of the fruit sugars. Some of this product then polymerizes to form brown resinous materials. The series of reactions involving sugars and amino acids that initiate nonenzymatic browning are referred to as Maillard reactions.

Shaw (1988) stated that maximum reaction rates for the first stages of nonenzymatic browning occur at moisture contents of 25 to 30 percent. The products formed during the first stages of the reaction are known as Amadori compounds, which adversely affect the nutritional quality of the processed food. The amino acids involved in the reaction become nutritionally unavailable once reacted with the carbonyl groups located on the reducing sugars. Also, losses in the glucose and fructose content occur because of these initial reactions. These losses in the reducing sugars are known to be accelerated by elevated temperatures (Brons and Olieman, 1983). In the typical dehydration process, the fruits usually pass through the moisture content range of 25 to 30 percent at elevated temperatures. This combination of effects makes dried fruits more susceptible to losses in nutritive value and to nonenzymatic browning.

Gee *et al.* (1977) showed that a variety of fruits (e.g. dried peaches, apples, pears, mangos, etc.) dried to 0.5 a_w retained a natural bright color and remained shelf-stable for many months stored at room temperature. The process did not include any pre-treatments such as sulfuring or blanching to preserve color. The fruits were cut to 6 to 9.5 mm thick pieces and placed one layer deep into a forced draft home dehydrator with cross-flow air. The temperature was maintained at 50°C. Low temperature processing (e.g. 50°C) to dehydrate the fruits (1) stabilizes microbial growth by reducing the water activity (Haas *et al.*, 1975), (2) minimizes enzymatic browning by reducing the water activity, and (3) minimizes nonenzymatic browning reactions by not initiating the reaction with high temperatures (King, 1971).

Effects of Freezing

Szczesniak and Smith (1969) noted that freezing and thawing of fruits resulted in extensive disruption of the cells. A subsequent release and mixing of juices and enzymes would enhance the reaction rates of (1) enzymatic degradation of color pigments, and (2) the breakdown of sugars. Therefore, a rapid degradation in the quality of the frozen fruit may occur upon thawing (Luh *et al.*, 1986). The enzymes, *invertase* (EC 3.2.1.26) and *sucrose synthase* (EC 2.4.1.13), break down sucrose to form fructose and glucose, and fructose and UDP-glucose[1], respectively (Skrede, 1983). Enzymatic browning may also occur rapidly during the thawing of fruit unless a preventative agent such as ascorbic acid is added to the exposed surface before freezing. However, fruits that are dehydrated to very low water activities (0.45-0.5 a_w) minimize enzymatic activity (Acker, 1969). The quality deterioration of dried fruit may not occur to the extent of that in fresh fruits while thawing occurs.

Textural Properties

Textural changes often occur in the cell wall and intercellular tissue of processed fruits when heat is applied in the process. Pectins, hemicellulose, and cellulose make

1 uridine-5'-diphospho-glucose

up much of the plant tissue that has water-binding capability. Of the three main components, pectins are the most sensitive to both enzymatic and heat-induced degradation (Parrott and Thrall, 1978). Levi *et al.* (1988) reported that significant correlation exists between the firmness and total pectin content in dehydrated peaches. This confirms that the pectin content significantly contributes to the textural properties of dehydrated fruit. The report also concluded that optimizing blanching conditions helped stablize the pectins against enzymatic attack, while reducing the degree of heat degradation.

Bourne (1986) recognized that complex changes took place in the textural properties of dried apples as the water activity decreased during dehydration. After obtaining an instrumental texture profile for nine water activities (ranging from 0.99 to 0.01a_w), the study concluded that textural changes occurred most rapidly at the water activities near the BET monolayer level (calculated to be 0.14 a_w) in apples. The BET monolayer level indicates the transition from multiple layers of adsorbed water to a monolayer. At this level the fruit becomes hard and also remains well below the water activity suitable for any microbial growth.

Physically induced changes, such as bruising, result in structural changes in the fruit tissue. After dehydration, the bruised area often becomes very "leathery" and poses a serious problem for the product quality. O'Brien *et al.* (1984) noted that the form of bruising referred to as "brown spot" is caused by direct impact forces that occur from dropping the fruit onto hard surfaces. The maximum drop heights were obtained for several different surfaces. These drop heights could be used in the design of fruit handling systems used in dehydration processing.

CHAPTER III

MATERIALS AND METHODS

I. OVERVIEW

This research took place in two phases: (1) determination of energy use during dehydration of the fruits, and (2) determination of overall quality. The first phase included harvesting, preparing, weighing, and drying the fruits. Dried fruit products were then stored in a freezer for approximately six months until the second phase. The second phase involved qualitative determinations that consisted of measurements of color, shelf-life, and carbohydrate composition. Figure III-1 and figure III-2 show the procedures involved for completing the first and second phases of the experiment, respectively.

II. EXPERIMENTAL DESIGN AND APPARATUS

Experimental Dryers

Four batch dryers purchased from Nutriflow Co. (Portland, Oregon) were used in this study. All dryers had similar designs (length: 57.2 cm x width: 41.3 cm x height: 36.8 cm). Each dryer had a capacity of ten perforated, plastic trays (length: 41.3 cm x width: 36.5 cm) except one dryer that had a capacity of twelve trays. A fan (diameter: 16.5 cm), located toward the rear of the dryer, propelled the heated air at a constant flow rate (approximately 73.0 L/s) across the fruit. The 800 Watt heating element, located a few inches in front of the fan, was unable to maintain a temperature

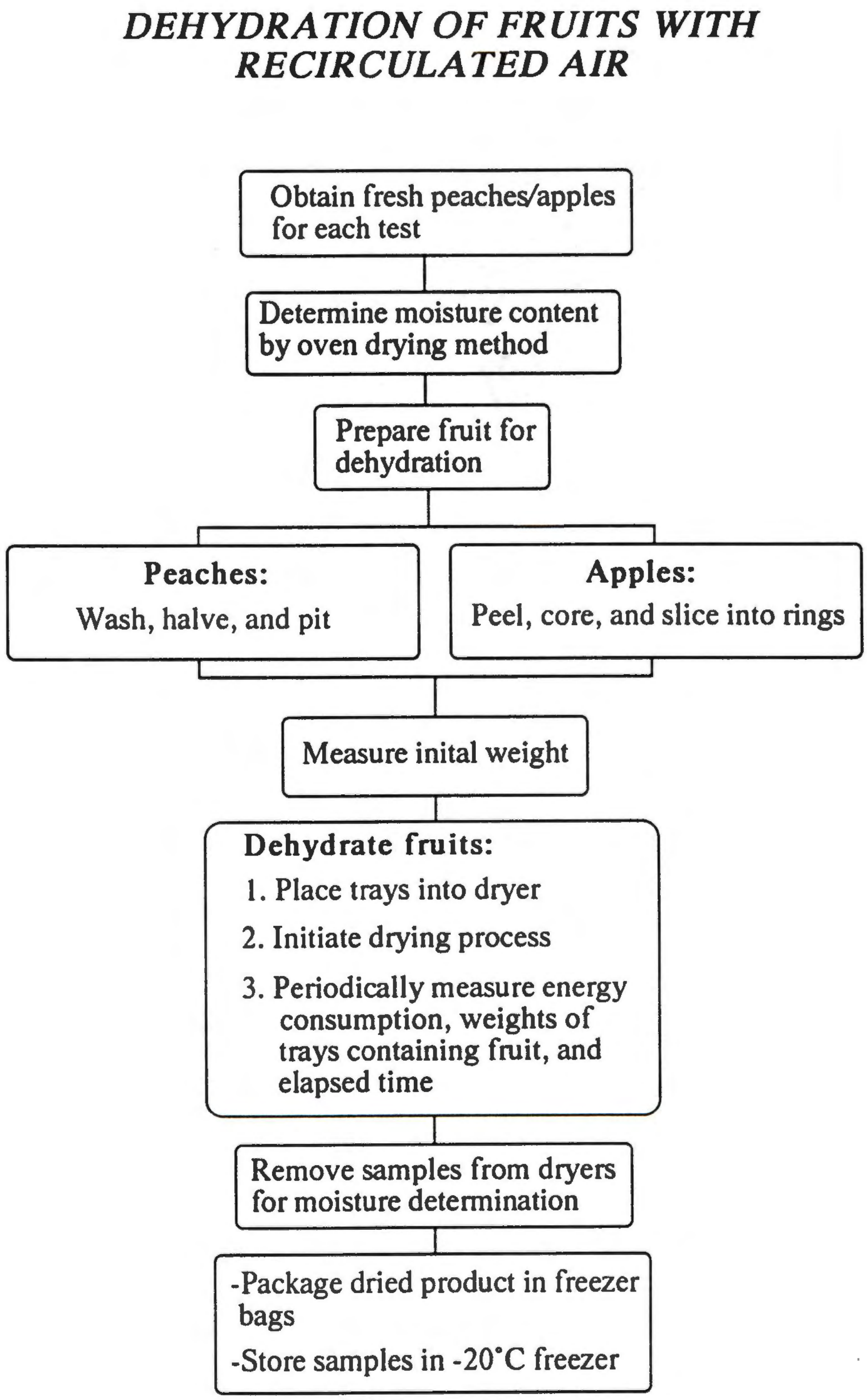

Figure III-1. Flowchart of the procedure for dehydrating the cut fruit.

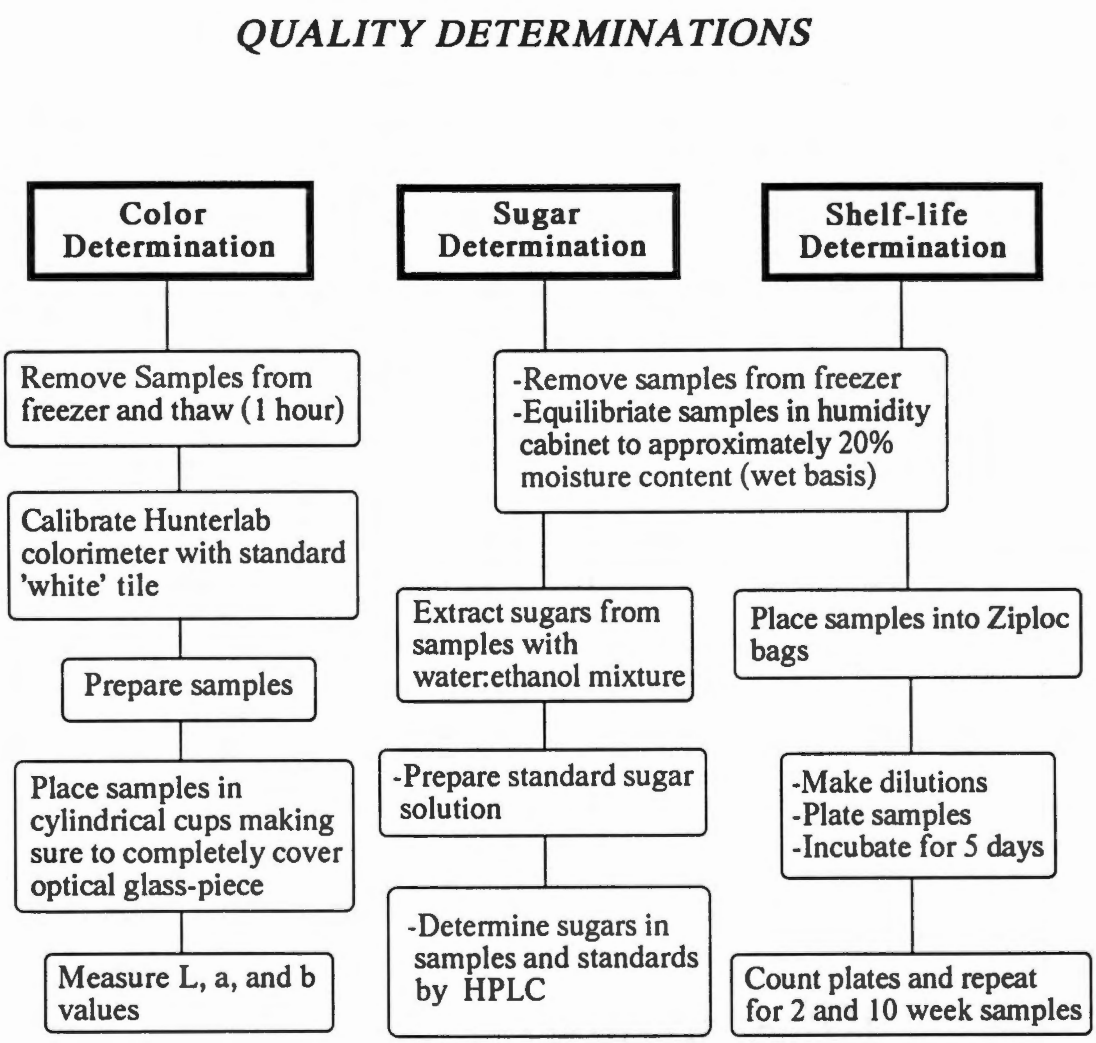

Figure III-2. Flowchart of the procedure for determining the quality parameters.

of 65.6°C inside the drying chamber. It was replaced with a 1500 Watt heating element. A high temperature fuse (121°C cutoff) was installed in each dryer to protect the element. The thermostat controlling this element was removed and replaced with a PID controller. The PID controller required a type T thermocouple input.

The thermocouples were attached to a wire screen mounted just in front of the heating element. Five thermocouples were connected in parallel to the controller input so that the average of these five thermocouple inputs was used as the input control parameter. The average temperature at the five locations was nearly equal to the average temperature of the air exiting the dryer under no-load conditions. This indicates a constant temperature across the air flow pattern through the dryer.

Recirculation Mechanism

The exhaust of the original dryer consisted of a Plexiglas window placed at the outlet of the dryer. A small crack was left near the bottom of the window to exhaust the drying air. This window was removed and replaced with a recirculation mechanism. Air exiting the dryer was first guided through a flow diverter that exhausted part of the air while recirculating the remaining part back through the dryer. The air that was recirculated mixed with fresh outside air in the recirculation duct before being passed over the drying fruit.

Components

Each dryer unit contained a recirculation system, built as an addition to the original dryer. Six basic components were used to construct each recirculation mechanism: (1) a standard 15.25 cm diameter PVC pipe (ASTM D-2927 "Sewer pipe"), (2) two 90 degree elbows, (3) one PVC "T" connector, (4) a stainless-steel plate

(3.18 mm thick), (5) a cover box (LxWxH: 0.24m x 0.42m x 0.37m), constructed from plywood (thickness: 1.27 cm), and (6) two PVC adapters (flanges) to connect the pipe to the entrance and exit of the dryer. The complete apparatus can be seen in figure III-3.

Cover Box

The cover box was placed over the dryer's outlet. A 15.25 cm hole bored into the side of the cover and fitted with the PVC flange connected directly to the flow diverter. To secure the cover to the dryer's exit, two rubber elastic cords were connected to hooks located on the cover and at the back of the dryer. Foam weather stripping was used to seal the interface between the cover box and dryer.

Flow Diverter

The "T" connector was converted into a flow diverter valve by boring an exhaust air hole at the top of the "T." A diverter plate, which consisted of stainless steel sheeting cut to an oval shape, was inserted into the "T" section. By rotating the plate about a central pivot, the valve could be adjusted from 100% outside air in (0% recirculation) to 0% outside air (100% recirculation). Foam weather-stripping worked well to seal any air leaks at the two extreme shutoff points.

Experimental Test Design

This experiment was a "Latin square" design. The cut fruit represented the experimental units upon which the treatments were applied. As defined by Ott (1988), the Latin square design "compares t treatment means in the presence of two extraneous sources of variability, which we block off into t rows and t columns. The t treatments

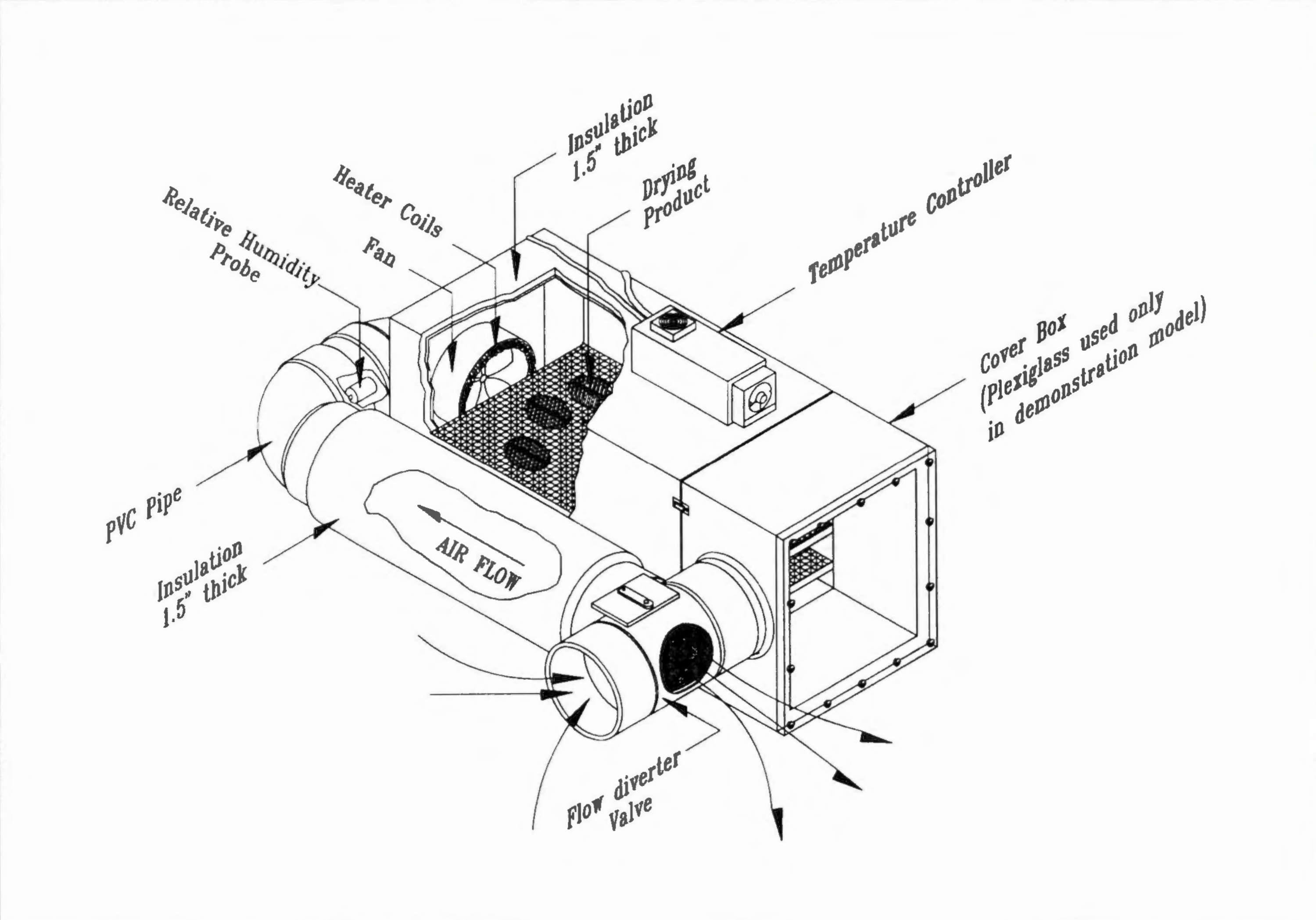

Figure III-3. Experimental batch dehydrator with recirculation mechanism.

are randomly assigned to experimental units within the rows and columns so that each treatment appears in every row and in every column." The two blocking variables were (1) the dehydrators (**DRYER**) and (2) the tests (**TEST**). Four dehydrators dried different batches of fruit during a single test. A total of four tests were required to complete the design. Constant recirculation rates of 0, 25, 50, and 75% represented the treatments applied to the individual batches of fruit. The treatments were completely randomized in the first test. Treatments in the following three tests required a form of restrictive randomization, which allowed for all recirculation rates to be represented only once in each dryer. This randomization scheme was similar to that recommended by Neter and Wasserman (1974). Figure III-4 shows an actual combination of treatments for apples within the four dryers during the last four tests.

The Latin square design primarily helped to eliminate some of the experimental error associated with the day to day variation in weather conditions. This design also helped decrease experimental error caused by the variation among the dryers, which may have occurred due to unidentified differences among dryers.

Evaluation of Test Approaches

Differences in air velocity between dryers created another variation that was due primarily to slight differences in the output velocities of the fans. The air velocity varied anywhere from 0.914 to 1.07 m/s in the recirculation air duct (15.25 cm diameter), as measured by a Model 1640 TSI air velocity meter. These measurements were taken at the front of the first elbow near the cross-sectional center of the PVC tubing, used for recirculating the air. The drying air recirculated at a rate of 100%. The heater was turned off during the measurements and the dryer contained only empty trays.

Test	Dryer I	Dryer II	Dryer III	Dryer IV	Treatment (% recirculation)
1	A	B	D	C	A : 0%
2	C	A	B	D	B : 25%
3	B	D	C	A	C : 50%
4	D	C	A	B	D : 75%

Figure III-4. An example of a "Latin square" design for recirculation treatments on apples.

Another important parameter in the experimental design included the temperature of the drying air. From the literature, several temperature schemes existed for drying cut fruits (Van Arsdel, 1964; Smock and Neubert, 1950; Woodroof and Luh, 1986; Hertzberg *et al.* 1975). A constant temperature of 65.6°C was chosen to dry the fruits throughout the whole process. A PID controller (Partlow Electronics: Type T) kept the temperature of the drying air constant with an accuracy of $\pm 1\,^{\circ}C$.

III. EXPERIMENTAL PROCEDURE

Harvesting Fruits

Locally grown peaches and apples were readily available for the experiment. A nearby peach orchard provided freestone "Sun-High" peaches during the entire month of July, 1991. Only recently harvested peaches were used. Peaches varied in diameter (6.0 to 8.0 cm) within any given batch. Peaches showing any kind of fungal growth and bruises were immediately disposed of to eliminate differences in the physical properties of the fruit's flesh. For each test, the experiment required exactly 128 peaches (approximately two bushels).

The harvesting of "Golden-Delicious" apples took place during the early part of October, 1991 at the University of Tennessee Plateau Experiment Station, Crossville, TN orchard. The newly ripened apples were fairly small and very sweet. The apples varied in diameter (5.7 to 7.6 cm).

Preparing the Batch Dryers

The perforated, plastic drying trays were washed, dried and weighed prior to preparing the fruits. The weight of the fruit on individual trays could then be obtained by subtracting the tray weight from the total weight of the tray containing fruit. The dryers were located near the fruit preparation area for easy access. This helped to decrease the time for transporting the loaded trays to the dryers.

Percent Recirculation Calibration

The flow diverter valves on each of the four dryers were of identical design; however, each valve was individually calibrated to produce the desired recirculation rates (0, 25, 50, 75%). To start the calibration process, the dryers were first configured for drying empty trays in place. The dryers were then brought to thermal equilibrium by operating for approximately 30 minutes before calibrating the valves. Adjustments of the valves by trial and error obtained the desired recirculation rate for each test. The calibration scheme for estimating the amount of recirculated air was derived from the following heat balance.

$$(mc_p\Delta t)_d = (mc_p\Delta t)_r + (mc_p\Delta t)_a \qquad (1)$$

where m is the mass flow rate
c_p is the specific heat of air
Δt is the temperature difference from a reference temperature (e.g. 0°C)

This heat balance consisted of:

1. the air exiting the system that would be recirculated
2. the ambient air drawn into the system
3. the mixture of the ambient and recirculating air in the recirculation duct.

These conditions are portrayed in figure III-5. Assuming that the specific heat of air is similar for all conditions stated above and the reference temperature is zero, the relationship can be reduced to:

$$t_d = \left(\frac{m_r}{m_d}\right) t_r + \left(\frac{m_a}{m_d}\right) t_a \qquad (2)$$

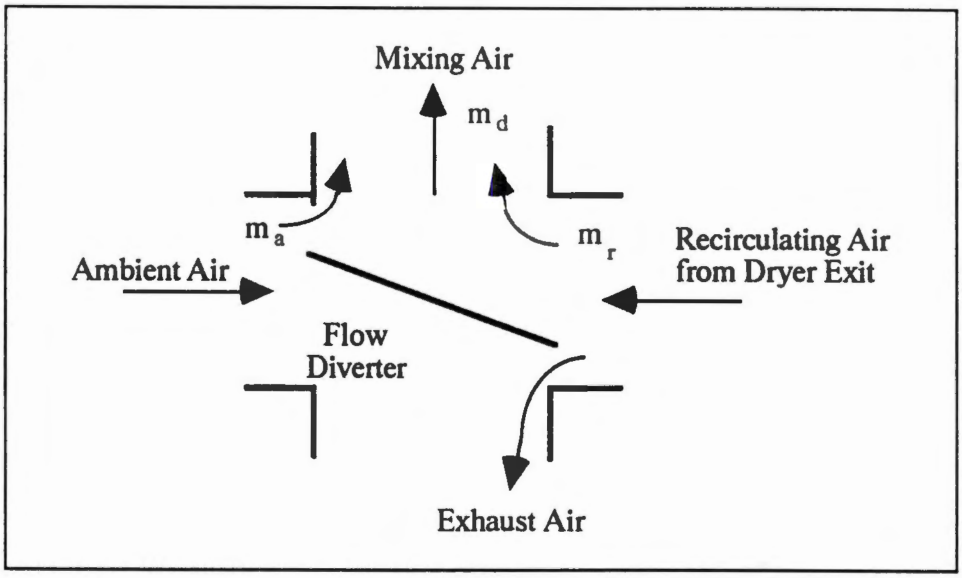

Figure III-5. Air distribution within the flow diverter valve.

where t_d, t_r, and t_a are the temperatures of the mixing air in the recirculation duct, the air exiting the dryer and recirculated, and the ambient air, respectively.

m_d, m_r, and m_a are the mass flow rates of the mixing air in the recirculation duct, the air exiting the dryer that recirculates, and the ambient air, respectively.

By setting the ratio $\frac{m_r}{m_d} = x$, the law of continuity would make the other ratio, $\frac{m_a}{m_d} = 1 - x$, where x is the decimal ratio of air recirculated from the dryer exit.

From equation 2, x can be derived as

$$x = \frac{t_d - t_a}{t_r - t_a} \qquad (3)$$

By measuring the temperatures at the three locations stated above, the recirculation rate was deduced from equation 3 after setting the valve at a constant position. Plugging in the actual values for t_r, t_a and x into equation 3, the duct temperature, t_d, was then approximated. With the duct temperature used for the target value, the valve was adjusted by means of trial and error until the actual duct temperature corresponded to the desired temperature.

Preparing Fruits

Preparation of the peaches for dehydration occurred immediately after transporting them from the orchard. The preparation consisted of first washing the surfaces to remove most of the fuzz layers. The surfaces of the peaches were then allowed to dry for approximately 30 minutes before processing. Next, the peaches were cut along the suture with a paring knife to obtain two halves. Even though the peach variety was of the freestone type, the pits could not be easily removed in most cases. A fruit baller worked best for completely removing the pit without cutting into the flesh around the pit. A total of 16 peach halves were then placed on each drying tray. Only eight peaches were halved and pitted at a time before placing them onto trays. Limiting the number of cut peaches helped reduce the exposure of the peach flesh to the air before further processing. This procedure reduced the degree of unwanted oxidative browning. An electronic balance (Sartorius, Co., Bohemia, NY), with an accuracy of 0.1 g, was used to weigh the trays containing the peaches before they were placed into the dryers.

Apples could not always be freshly harvested for each test. Thus, some apples were stored up to a week in a room (15°C) before preparation for dehydration. Apples were allowed to come to room temperature, if the apples were previously stored at 15°C, before preparation. A machine (Goodell, number 938) was used to peel and core the apples. The apples were then sliced into rings 7.62 mm thick using an adjustable apple slicer. Sixteen apple slices were placed onto each tray. The trays containing apples were then weighed and placed into the dryers.

Experimental Measurements

Measurements of psychrometric properties were made at five selected locations within each dryer and recirculation system. The locations and type of measurement are listed below and also shown in figure III-6.

1. Temperature and relative humidity of the ambient air at the valve entrance.
2. Temperature and relative humidity of the mixed air in the recirculation duct.
3. Temperatures at the heating element (heated air 65.5°C).
4. Temperature at the halfway point of the dryer trays.
5. Wet and dry-bulb temperature at the dryer exit.

Type T thermocouples were used for all temperature measurements. A Campbell Scientific, Inc. (CSI: Salt Lake City, Utah) AM416 multiplexor, with 32 channels interfaced most of the temperature sensors to a CSI 21x micrologger. The 21x micrologger collected data at 5 seconds intervals and averaged over 15 minute periods throughout each test. A Zenith laptop computer collected this processed data for final storage on floppy disk. Relative humidity probes (CSI - Model 207) directly measured the relative humidity and temperature (with a thermistor) through single ended inputs to the CSI AM416 multiplexor card mentioned above. The relative humidity and temperature measured in the recirculation duct were used to determine the humidity ratio and partial pressure of the water vapor in the air.

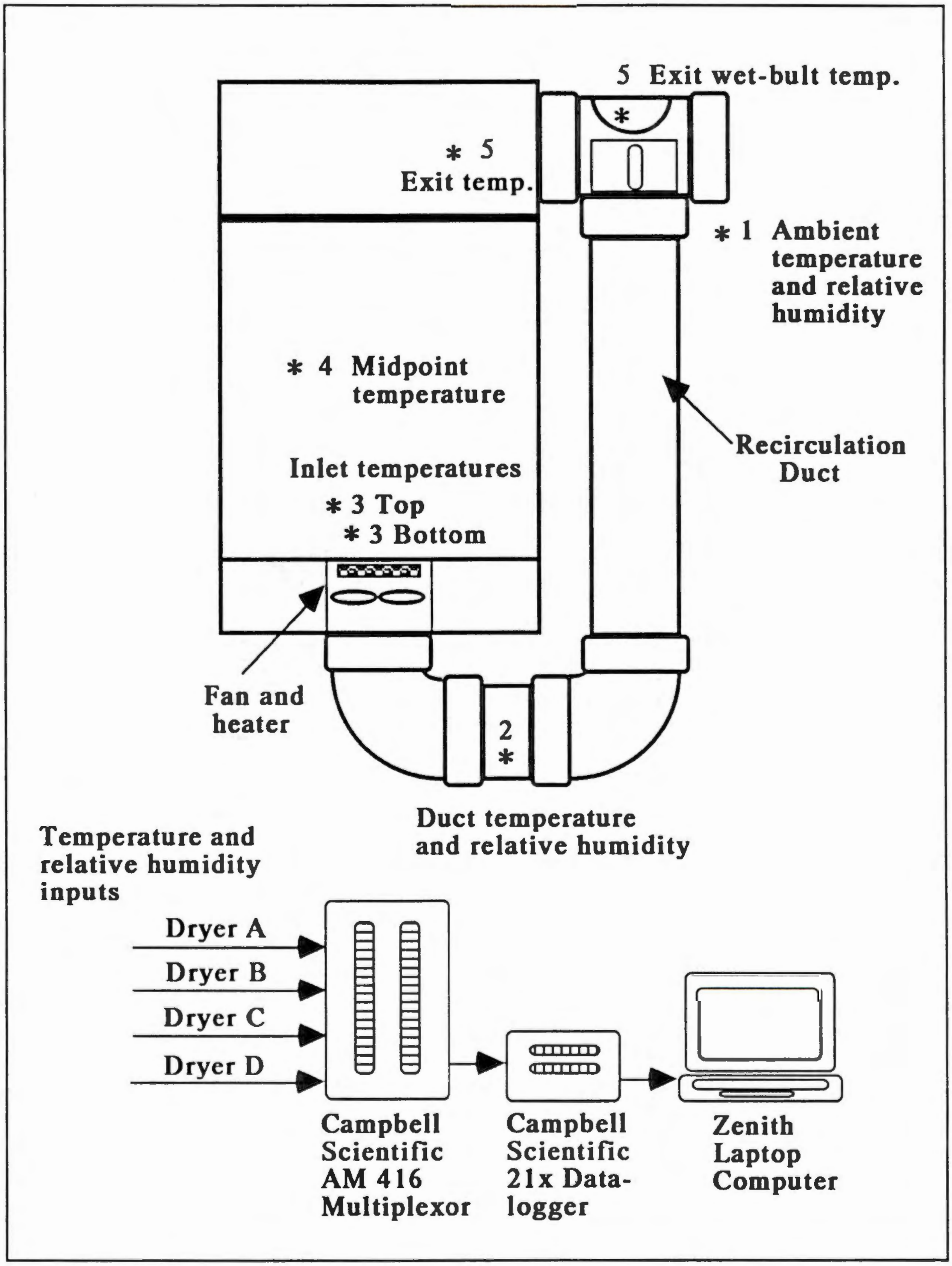

Figure III-6. Experimental apparatus showing temperature and relative humidity measurement locations and the corresponding data flow.

The energy required to dehydrate the apples and peaches to the approximate desired moisture (25% wb) was determined for each test by individual kilowatt-hour meters (Sangamo Electric Co., Springfield, Illinois) connected to each of the four dryer systems. A local electrical utility meter shop calibrated these meters to within 99.9 percent accuracy.

The power outlet from these meters were connected to each of the dryers' temperature controller units and dryer fans with a multiple outlet connector. The kilowatt-hour readings were taken directly from the dials on each meter periodically during the dehydration period. Photoelectric sensors were mounted within each watt-hour meter to measure the number of revolutions of the meters' disk. The output from these sensors was transferred to the 21x micrologger through the four pulse-channel inputs located on the micrologger's connector board. A thin black band was painted on the reflective underside of each meter's disk. A small reflective break left by the band allowed each photoelectric sensor to generate a pulse as the break passed over the sensor.

The photoelectric sensors used to read the actual number of rotations by the meters' disks did not perform as expected. Unfortunately, during the apple tests, one sensor periodically failed to respond. This failure was later explained by loose wire connections. Thus, the photoelectric sensor data were not used. The watt-hour meters' dial readings did produce reliable data. However, these manual readings were taken less often than the photoelectric sensor data, resulting in less detailed measurements of energy use over the entire drying period.

Another problem noted with the photoelectric sensors occurred during periods when power was not supplied to the dryers' heating elements because of the action of the temperature controllers. The disks on two of the meters often moved slowly in the reverse direction until power was applied to the heating elements by the temperature controllers. This triggered extra pulses from the photoelectric sensors resulting in erroneous data.

Test Procedure

The procedure for taking data during each test included removing the dryer trays and weighing them, and then recording the energy consumption and time that corresponded to when each tray was weighed. The micrologger also recorded the time at 15 minute intervals throughout the process. Upon returning the trays to the dryer, each tray was rotated 180 degrees so that the fruits originally facing the front of the dryer faced the back. In addition, the trays in each dryer were rotated vertically by moving the bottom tray to the top and moving all other trays down one position. This shifting of the trays helped the fruits dry more uniformly. All sixteen trays from the four dryers could usually be weighed within ten minutes.

Final Moisture Content Estimation

The final target moisture content for all fruits was 25% (wet basis). A problem occurred when directly measuring this targeted moisture content at the end of the process. The difficulty arose because of the long period required to determine the moisture content by conventional oven drying methods. Yet, the trays of fruit were removed from the dryers once the fruits obtain their final moisture content on an average basis.

The method chosen for this study required determination of the final desired weight of the trays containing the dried product. This final desired weight could be accurately determined by a method based upon the initial moisture content of the fruits and the final desired moisture content. The final desired weight of the trays containing fruit was estimated by the following relationship:

$$W_f = D + R_f + W_t \tag{4}$$

where
W_f is the final desired weight of the tray containing dried fruit (g)
D is the total dry matter weight (g)
R_f is the weight of the remaining moisture left in the fruit (g)
W_t is the weight of the drying tray (g)

Equation 4 could be equivalently expressed as:

$$W_f = W_0(1 - m_0)(1 + M_f) + W_t \tag{5}$$

where
W_0 is the initial total weight of the tray containing fruit (g)
m_0 is the initial average moisture content (wet basis) of the fruit
M_f is the final desired moisture content (dry basis) of the dried fruit.

The initial moisture content, m_0, must first be obtained before calculating the final desired weight. The method chosen for obtaining an approximate initial moisture content utilized a convection drying oven (Lab-line, Model 3485M Imperial IV) set at 70°C. Preparing the fresh fruit followed the same procedures described for the preparation for dehydration. The prepared fruits were placed in pre-weighed aluminum drying dishes and weighed on a scale (Sartorius, Inc. - accurate to 0.001 g). The trays were then placed into the convection oven. After the fruits became mostly dry, samples placed in the convection oven were transferred to the vacuum oven (Fisher, Model 281 Isotemp) under a vacuum of 15 kPa. Weighing the pans of fruit continued until no change of weight occurred (approximately 24 hours). Recording the final dry weight of the pan containing fruit allowed for the determination of moisture content (wet basis) by the following equation:

$$m_0 = \frac{Weight_{initial} - Weight_{final}}{Weight_{initial} - Weight_{pan}} \quad (6)$$

Storage of Dried Fruit

After the product was dried to a moisture content of approximately 25%, the fruit trays were removed from the dryers and allowed to cool to room temperature. The fruits from each tray were then placed into plastic freezer bags labeled with the test number, dryer number, and tray number. Metal ties sealed the freezer bags which were then placed inside one large bag. The large bag was labeled with the type of fruit, test number, and date for later identification. The bags were then stored in a freezer (-20°C) for approximately six months before the qualitative tests were run.

IV. QUALITY DETERMINATIONS

Color Determinations

Color and appearance are the basis for rejection or acceptance of many food products (Francis and Clydesdale, 1975). The consumer often expects all units of the same product to have similar color and appearance. When one unit varies from the rest, it is often rejected immediately. Several instruments have been developed to measure the color by using principles similar to the way that the human eye perceives color. A Model D-25 HunterLab colorimeter (Reston, Va.) measured the color by yielding three values listed below:

(1) L, lightness where L=0 representing black to L=100 representing pure white,

(2) **a**, where +a values represent the degree of redness and -a values represent degrees of greenness, and

(3) **b**, where +b values represent the degree of yellowness and -b values represent degrees of blueness.

Preparing Dried Fruit for Color Measurements

Samples of both dried peaches and apples were taken from two different tests. Four pieces of fruit, taken from each dryer tray, made up one sample. These samples were placed onto trays that contained 16 sections. The sections separated the individual samples according to their respective dryer and tray. One tray proved sufficient for holding all samples taken from one test.

The trays containing the dried fruit were then placed into a humidity cabinet (Tabai Espec Corp., Model LUH-112M-U). This humidity cabinet brought the fruits to equilibrium, which enabled all fruit pieces to reach similar moisture contents. This chamber was set to 70% relative humidity and 20° C. These conditions equilibrated dried apples to 21.2% moisture content (wet basis) and peaches to 17.4% moisture content (wet basis). The equilibration process took anywhere from three to five days. Peaches typically required more time than apples because of their greater thickness. Only one type of fruit was placed into the chamber at any time.

The peach halves had a dark reddish-brown color in the area where the pit had been removed. Apple rings contained holes in the center that were nearly uniform in diameter for all samples. To obtain accurate measurements of the flesh color for both fruit, the central regions of both types of fruit were filled with the flesh surface from another dried piece of the same fruit. The pieces used to fill the holes always came from the same tray and test.

A paring knife was used to remove the peach central region and cut similarly shaped pieces from the flesh surface of another dried peach half. The new center piece replaced the central region of the dried peach being measured. A corer (slightly larger in diameter than the apple ring holes) cut pieces of dried apple to fill the hole of the dried apple ring being measured.

Color Measurements

The HunterLab color difference meter measured the L, a, and b values over a given surface area of fruit. The values of L, a, and b were obtained in reference to the standard 'white' calibration tile[1]. The fruit pieces were placed with the surface to be measured facing downward in a cylindrical cup. A clean, unscratched piece of optical glass was used for the bottom piece of the cylinder. Being careful not to dislodge the optical glass from the cylindrical housing, the surface of the dried fruit was pressed firmly against the optical glass during the measurements. Pressing the pieces firmly, after placing the container onto the instrument, helped to eliminate any dark spots that may develop when a space exists between the fruit's surface and the glass.

The hue angle taken from the vertical +b axis (shown in figure III-7) was used to analysis color differences for apples and peaches. This angle was obtained by

$$\textit{Hue angle} \ (\varnothing) = \tan^{-1}\left(\frac{a}{b}\right) \tag{7}$$

The hue angle represented the color change from yellow to red where the angle $\varnothing = 45^\circ$ represents orange.

[1] Specifications: standard number: C2-21125, L: 91.03, a: -1.3, b: 1.6
Hunter Associates Laboratory, Inc. Reston, VA

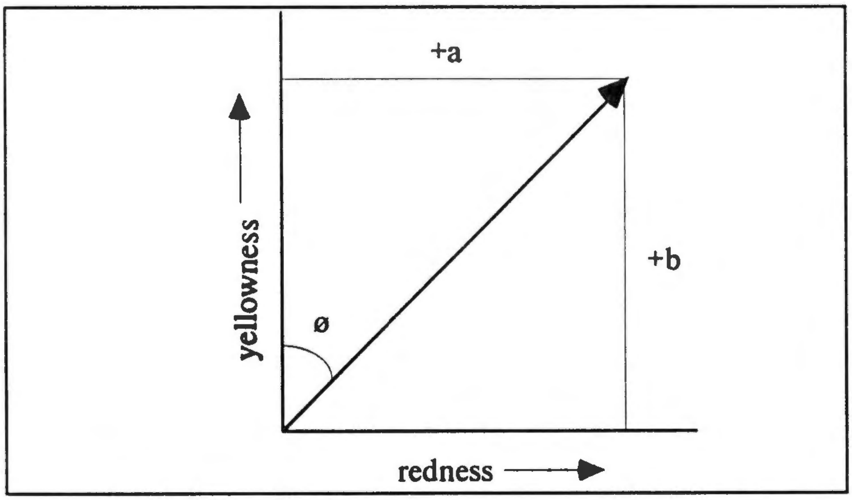

Figure III-7. Plot of **a** versus **b** describing the hue angle (ø) and the magnitude of the color vector in the Hunter system.

Another relationship used in the analysis was the magnitude of color or thequantity of the color defined by the hue angle. The magnitude described how brightnessof the color compared to gray, which has a magnitude of zero. The magnitude was calculated from the a and b values by using the relationship

$$Magnitude = \sqrt{a^2 + b^2} \tag{8}$$

This quantity, along with the hue angle, shows the complete vector quantity for describing the type of color measured by the a and b values. The lightness, L, constituted the final value for the analysis of color.

The color parameters were measured for dried peach halves from each dryer tray in tests 1 and 4. Replicate measurements were done for dried peaches in test 1. At a later date (approximately one year after dehydration), color measurements were taken for dried peaches from two trays of each dryer and test (1, 2, 3, and 4). Apples were taken from each dryer tray in tests 7 and 8. Color measurements were also done in replicate for each sample taken from these tests.

The dried apple and peach pieces (used for color measurements) averaged nearly the same diameter (dried apples: 6.35 cm, dried peaches: 7.12 cm). The fruit diameters nearly matched the diameter of the optical glass. Therefore, proper loading of the fruits into the cylindrical cups required little time. Washing the glass with warm, soapy water worked best for cleaning the optical glass cylinders. These cylinders were washed and dried between measurements.

Shelf-life Study

The shelf-life study determined any signs of microbial growth over a three month period. Quantitative measurements for growth of yeast and molds were obtained by the following five steps:

(1) Preparing sample dilutions.
(2) Plating samples onto Malt Extract Agar media.
(3) Allowing five days for incubation.
(4) Counting the plates
(5) Calculating the number of colony forming units (CFU's).

Preparing Growth Media

Premixed malt extract agar, MEA (Difco Inc.), served as the growth media for yeast and molds, which grow on the surface of fruit. The procedure required the slow addition of the mix to one liter of distilled water (in a one liter erlenmeyer flask) while being heated and stirred on a hot plate-stirrer. The mixture was brought to a boil while being stirred and then sterilized in an autoclave for 15 minutes at 121°C. The agar was poured into petri plates, allowed to solidify, and then stored at 7°C. Since this agar denatures if exposed to high temperatures for a long time, care was taken to not exceed the times and temperatures required for preparing the media. The plates were stored for no more than one week to prevent contamination within the 7°C storage chamber.

Preparing Dried Fruit

The dried fruits were taken from two different tests, as was done for the color measurements. The fruits were placed into the environmental chamber set at 70% relative humidity and 20° C (dried apples: 21.2% MC(wb); dried peaches 17.4% MC(wb)). Once equilibration occurred, two pieces of fruit from each dryer and test were placed into Ziploc® Heavy Duty freezer bags[1]. This process was repeated twice to obtain three samples from each dryer and test. The number of bags totaled to 24 for each fruit. Labeling each bag with the fruit type, test number, and dryer number helped to identify the samples for later dates. All of the bags were placed into an incubator set at 24°C until it was time for plating.

Dilution Scheme

Peptone broth (0.1%) served as the dilution media. The samples were first brought to a one to ten dilution. To obtain a one to ten dilution for eight apple samples, approximately one liter was needed. Nearly two liters were needed to dilute eight peach samples. The dilution was achieved by adding nine times the sample's weight of 0.1% peptone broth to the samples within the Ziploc® freezer bags. The freezer bag containing the sample with dilution broth was then placed into a Stomacher® blender for

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[1] Physical parameters: density: 0.93 g/cm3, softening point: 195°F, thickness: 2.7mm
Permeability: O2: 420 cc/ml/100in2 24hr 1atm @73°F, vapor: 1.0-1.5 g/ml/100in2 24hr 1 atm @100°F 90%rh

two minutes. Dilution blanks containing nine milliliters of peptone broth achieved the necessary dilutions to obtain countable plates . Figure III-8 portrays the actual dilution scheme.

Plating samples

The dried fruit samples were plated onto the MEA plates by using the spread plate method (Busta *et al.*, 1984). A sterile pipette delivered 0.1 mL of diluted sample to the center of a labeled MEA plate. A sterile bent glass rod (hockey stick) was used to quickly, but carefully, spread the 0.1 mL sample over the whole surface of the plate. The petri plates were immediately covered to avoid contamination, then placed into a 24° C incubator, and allowed to incubated for five days.

Counting Plates

A colony counter equipped with artificial illumination, magnification, and a ruled (cm^2) guide plate aided in the determination of CFU's. All colonies, including those of pinpoint size, were counted and recorded. The guidelines listed by Busta *et al.*, 1984 were then followed in determining the actual colony count in CFU/g of dried fruit. In most cases, the plates contained fewer than 25 colonies per plate, therefore, the actual number of colonies present on the lowest dilution plate were reported. Multiplying the number of colonies by the reciprocal of the dilution used computed the colony counts in CFU/g of dried fruit.

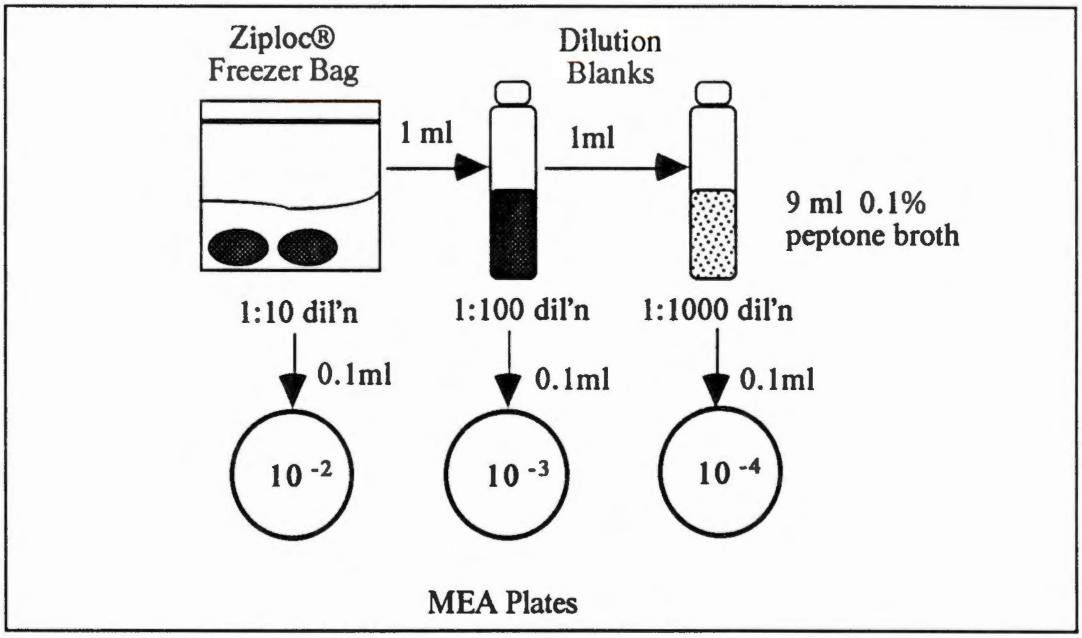


Figure III-8. Dilution scheme for plating dried fruit samples.

Sugar Determinations

To determine the amount of sugars present within the fruit after dehydration, the dried fruit had to first be prepared, then extracted for sugars, and finally analyzed for sugar content by High Performance Liquid Chromatography (HPLC).

Preparing Dried Fruit for Sugar Extraction

Preparation of the dried fruits for extracting the sugars followed the previous preparation schemes listed for both the color determinations and microbial analysis. However, both dried peaches and apples were placed within the environment chamber at the same time. The environmental chamber operated at settings of 70% relative humidity and 25°C temperature. Peach samples were taken from only one test (Test 3), and apple samples were taken from two tests, (Tests 7 and 8).

For the dried peach samples, one slice was taken from each tray of a single dryer, combined, and placed into a plastic storage bag. Each bag was labeled with the test and dryer number. This process was repeated twice for all dryers from Experiment 3. For the dried apple samples of Experiment 7, two slices from each tray within a single dryer were combined and placed into a storage bag. This process was then repeated for the apple samples from test 8.

Extraction of Sugars

Samples weighing approximately 50 g each were then taken from their storage bags and used for the extraction of sugars. Both fruits required dilution before being blended to allow for complete homogenization. The peach solutions were diluted to four times their initial weight with distilled water to make a solution of 2.5 g of dried peaches per 10.0 g of solution. The apple samples were diluted to five times their initial weight with distilled water to make a solution of 2.0 g of dried apples per 10.0 g of solution.

Immediately following the dilutions, the dried fruits were homogenized in an Osterizer blender for five minutes at medium speed. A small blender flask that operated in an inverted position and sealed tightly over the blender's blades provided better homogenization of the diluted fruit. This type of flask helped to obtain a very fine slurry. The fruit samples were blended for 5 minutes. Exactly 10 g of homogenate were then weighed into a 50 ml centrifuge flask (stainless steel) for all samples. Each flask then received 10 mL of 50% ethanol-50% distilled water mixture. The flasks were vortexed for ten seconds before being placed in a boiling water bath for five minutes. The flasks were then vortexed for 15 seconds and loaded into a Model RC2-B Sorval centrifuge. The centrifuge operated at 27,000 x g for ten minutes. The supernatant was decanted and retained in a 50 ml graduated cylinder.

The precipitate was then washed by adding ten milliliters of 50% ethanol-50% distilled water mixture and vortexing the solution for 15 seconds, centrifuging for 10 minutes, and retaining the supernatant. The supernatants were then combined and brought to 50 ml by adding ethanol-water mixture. A Whatman #1 filter paper in a vacuum erlenmeyer flask equipped with a buchner funnel filtered the final extracts. The filtered samples were placed in 50-milliliter, screw-cap vials and held in a 6° C chamber until the analysis. Prior to the HPLC analysis, approximately 1 mL of each sample was filtered through a 0.45 μm LC13 Acrodisc filter (Gelman, Inc.) and retained in a clean, two-milliliter, screw-cap microvial.

Precipitates taken from an extraction of one peach sample and one apple sample were taken to perform an additional ethanol extraction and two extra washes. The additional extraction and washes served as an indicator of any residual sugars left in the precipitate. The extra extraction and washes followed the same procedure as done for the first extraction. The supernatants were combined, filtered, and retained for further analysis. The filtered wash remained undiluted (or were not brought to 50 mL volume). The results from these extra sample washes (used to determine the residual sugars) indicated that the amount of sugars present in the sample washes were less than 10% of the sugars found in the original extract. This implied that most of the sugars present in the fruit were obtained in the first extraction. The basis of the analysis of sugars, however, depended upon the assumption that all extractions followed the same procedure. Therefore, a direct comparison of sugar quantity, based only on the sugars extracted, could be made between individual samples.

High Performance Liquid Chromatographic Analysis

HPLC system

The determination of carbohydrate composition in the dried fruits utilized a High Performance Liquid Chromatography (HPLC) system (Waters Associates, Milford, MA). This HPLC system consisted of a model 6000A solvent delivery system, a U6K injector, and a R-401 differential refractive index (DRI) detector. A Chromatopac C-R2AX data process recorder (Shimadzu, Corp., Kyoto, Japan) recorded all data from the R-401 DRI detector. Figure III-9 portrays the basic components of the HPLC system The operating conditions for the HPLC system included a 2.0 mL/min. flow rate for the mobile phase with column pressures not exceeding 600 psi. The operating temperature was ambient. The Chromatopac recorder's attenuation was set at 4 mV/full scale and an attenuation of 8x was set on the R-401 DRI detector. The other Chromatopac recorder's settings consisted of the chart speed set to 5 mm/min., mode set to 0 (no component name, time window method, and one point calibration), and method set to 2021 (utilizing the area normalization method).

HPLC column

A 25 cm x 4 mm stainless steel Partisphere column (Whatman) packed with polar-amino-cyano (PAC) stationary phase separated the sugars present in the dried fruit samples from the water solvent. An 85% solution of hexane served as a nonpolar storage solution for the column. Approximately 10 column volumes of the intermediate polar compound, tetrahydrofuran (THF), were run through the column prior to running the mobile phase overnight to initially equilibrate the column. The reverse order of solvents were run through the column after completing the HPLC analysis.

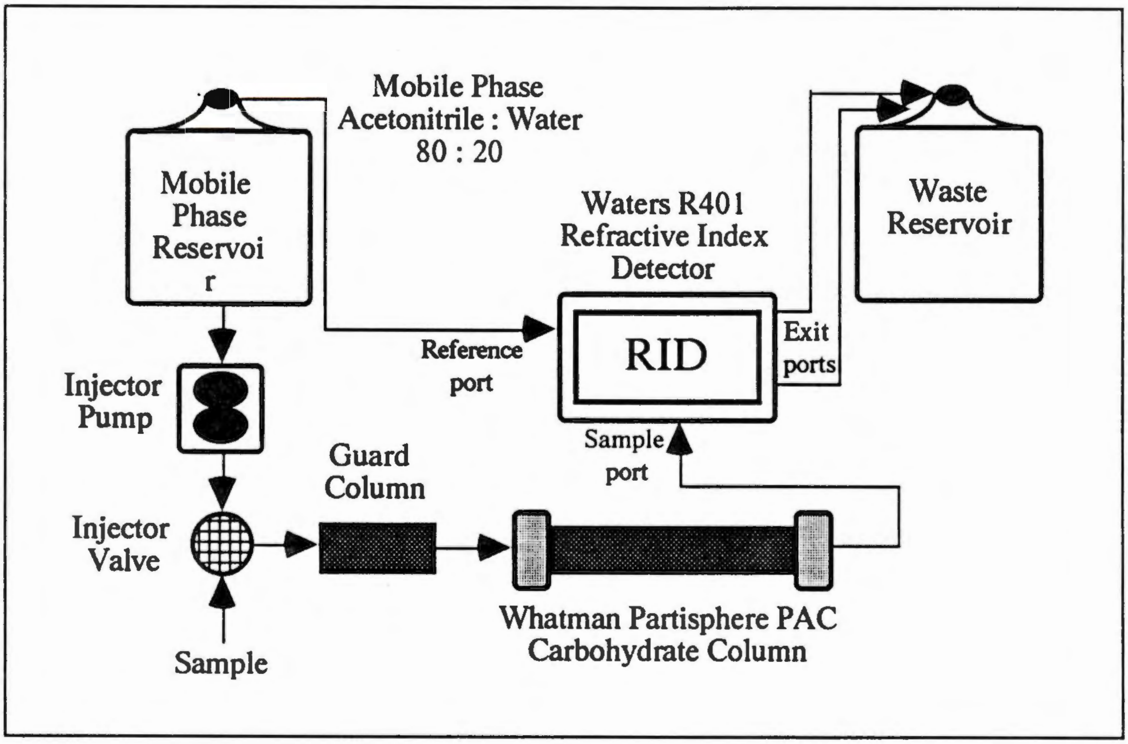


Figure III-9. HPLC apparatus for determining the carbohydrate content of dried peaches and apples.

Reagents

The mobile phase consisted of a mixture of 80% acetonitrile-20% water (both HPLC grade) by volume, which was degassed and filtered through a 0.45 μm filter. The sugars, D (-) fructose, D (+) glucose, and sucrose (Sigma Co., St. Louis, MO) served as the reference standards. The mixed standard solution contained 1.5 g of each reference sugar dissolved in 100 mL of distilled water. These sugars were initially mixed with water in a 250 mL erlenmeyer flask. A 2 mL portion was then filtered through 0.45 μm Acrodisk filter into a 2 mL screw-cap microvial.

Chromatography

A Microliter 802 syringe (Hamilton: 25 µL capacity) was used to inject the standard sugar solution in 5 µL increments from 5 to 25 µL. The Chromatopac recorder determined the peak heights for each sugar in the injected standard solution. Volumes injected in 5 µL increments helped obtain an accurate standard curve for determining the amount of sugars present in the extracted samples. The sample injections consisted of 20 µL portions injected in duplicate. The Chromatopac recorder determined the peak heights that corresponded to each sugar present in the extracted samples. These peak heights were then compared with the standard curve to determine the average amount of each sugar present within the duplicate samples.

Calculation

The following equation (Iverson and Bueno, 1981) determined the amount of sugars in g per 100 g sample.

$$W = \left[\frac{PH}{PH'}\right] \times \left[\frac{V'}{V}\right] \times C \times \left[\frac{100_g}{S}\right] \times \left[\frac{I}{1000\frac{mg}{g}}\right] \qquad (9)$$

where

W	is the weight of sugar (g)
PH	is the peak height of the sugar in the sample extract
PH'	is the peak height of the sugar in the standard mixture
V	is the volume (µL) of sample injected
V'	is the volume (µL) of the standard injected
C	is the concentration of each sugar in the standard mixture(mg/ml)
S	is the weight (g) of the sample taken for assay
I	is the volume (mL) of the sample assay solution

The peak height for the standard sugar mixture (PH') was obtained by linear regression from the five standard injections. The peak height corresponded to the injection volume used for all sample injections (20 µL).

CHAPTER IV

RESULTS AND DISCUSSION

I. ENERGY CONSUMPTION AND TIME REQUIREMENTS FOR RECIRCULATING FRUIT DEHYDRATORS

This study examined the effect of fixed recirculation rates upon drying energy use. However, fixed recirculation rates, while easily controlled, did not provide repeatable drying conditions from test to test. Changes in the ambient air conditions and different loading conditions produced variation in recirculation air properties.

Figures IV-1(*a*) and (*b*) presents data for typical peach and apple drying tests, respectively. These graphs show an elevation in the humidity ratio as the recirculation rate increases. The 75% recirculation rate shows a considerable amount of moisture in the drying air during the early phases of drying. The moisture decreases gradually, approaching the values for other recirculation rates during approximately the last 15% of the drying period. The dips within the curves were more than likely caused by the opening of the dryers to remove the trays for weighing. These dips appear frequently during the initial phases of drying because the samples were weighed more often to monitor the rapid removal of moisture during this period.

The humidity ratio for the 75% recirculation rate generally ranged from 0.03 to 0.05 (kg moisture/ kg dry air) for peaches and 0.02 to 0.04 (kg moisture/ kg dry air) for apples during the initial phases of drying for all tests. The humidity ratio for the 0% recirculation rate typically remained fairly constant during the whole drying period for all tests performed on both peaches and apples. The test to test variation of 0.01 to 0.018 (kg moisture/ kg dry air) was observed for this rate.

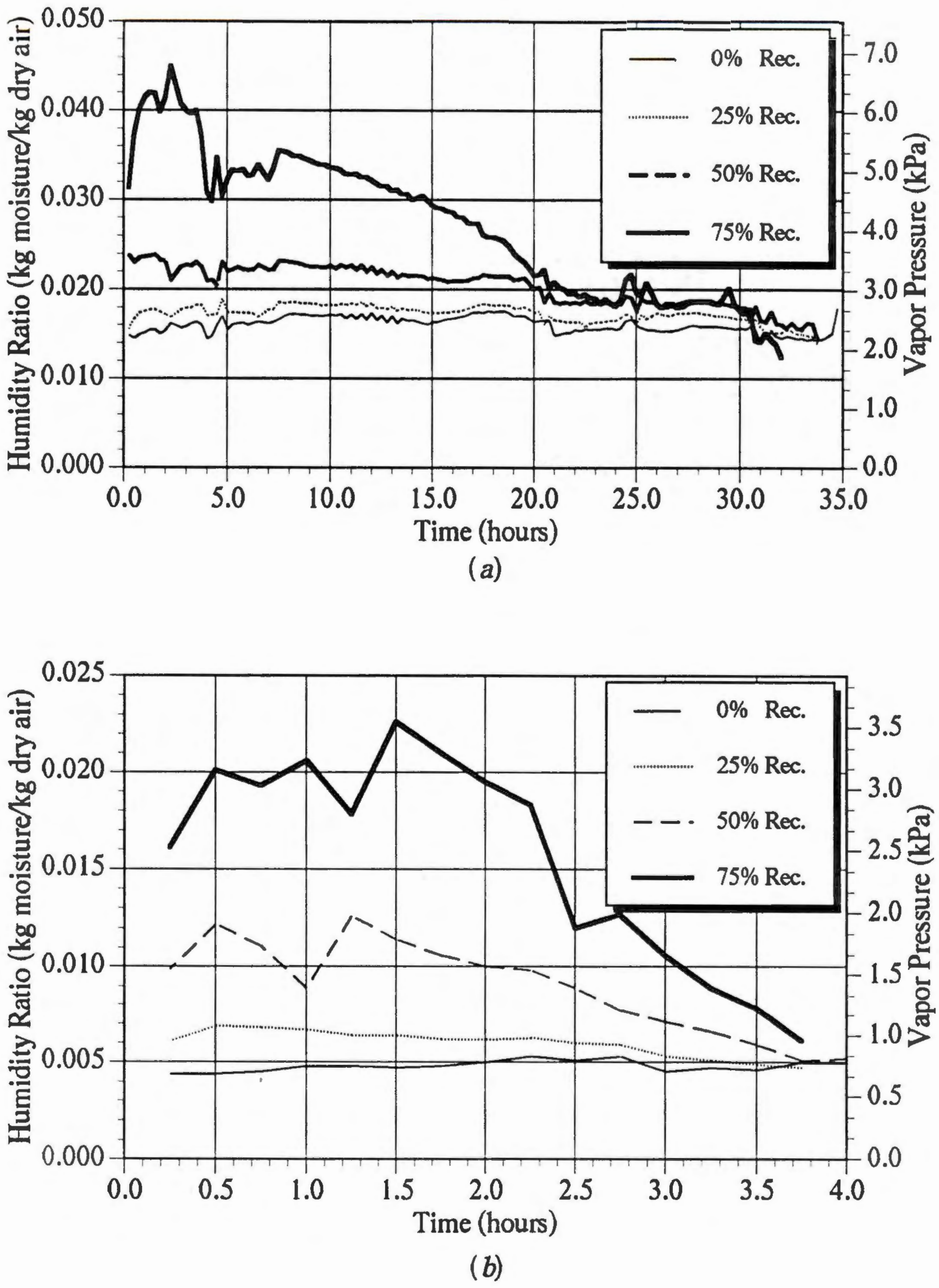


Figure IV-1. The change in humidity ratio and vapor pressure with time for mixing air within the recirculation duct; (*a*) peach Test 3 (*b*) apple Test 4.

Experimental Data

Appendix A shows all data used for the dehydration and dried fruit quality analyses. Tables A-1 and A-2 show the weight loss and energy data for dried peaches and apples, respectively. The total amount of energy consumed and the total process time constituted the basic response variables used for describing the main differences between treatments. Appendix B represents data taken by the Campbell Scientific Datalogger unit for a typical peach drying test. Many of these graphs have large spikes in the temperature curves reflecting removal of the dryer covers during the weighing of dryer trays (see Figures B-2 and B-3). The removal of these covers resulted in a temporary decrease in the exit and duct temperatures. The duct temperatures decreased in all dryers, except the dryer using 0% recirculation, because air was not recirculated while the covers were removed.

The time and energy data corresponded to the readings taken when the last tray was removed from each dryer for all tests. Therefore, 16 observations were used for each set of tests (one Latin square). A total of 32 observations were used for the apple analysis because of the replication of tests (two Latin squares). Occasionally overdrying occurred in the product. The data used in these cases were taken from an earlier time during the process when the trays of fruit were nearest to the target value of 25% (wb). These data were used instead of the data taken for the last tray removed. This problem occurred mainly in the first test for peaches. The actual mean values of the final moisture content for the peach and apple experiments were 26.56 ± 3.65% and 24.38 ± 6.37%, respectively.

Analysis of Total Process Time

The rate of moisture removal with respect to the process time is shown in Figures IV-2(*a*) and (*b*) for dried peaches and apples, respectively. These graphs were obtained using a non-linear regression technique (NLIN procedure) within SAS statistical software (SAS Institute Inc., 1985). This procedure utilized the moisture data from all tests with peaches and apples, respectively. A basic exponential equation of the form

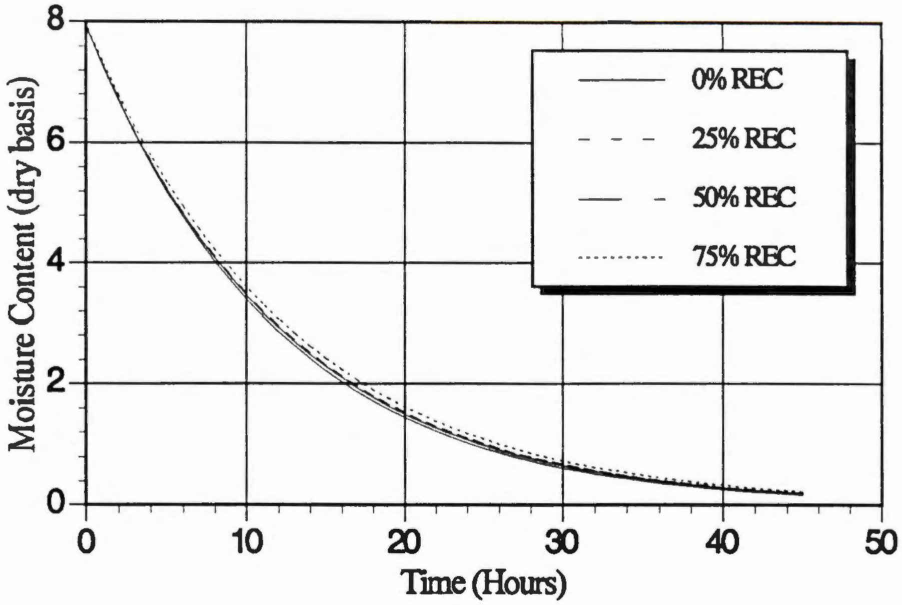
$$MC(db) = c_1 * exp(-c_2 * Time) \tag{10}$$

provided a suitable non-linear equation for fitting the data taken from all tests for each fruit. A pseudo(r^2) value was calculated for all curves. The equation for calculating the pseudo(r^2) for non-linear regression is expressed as:

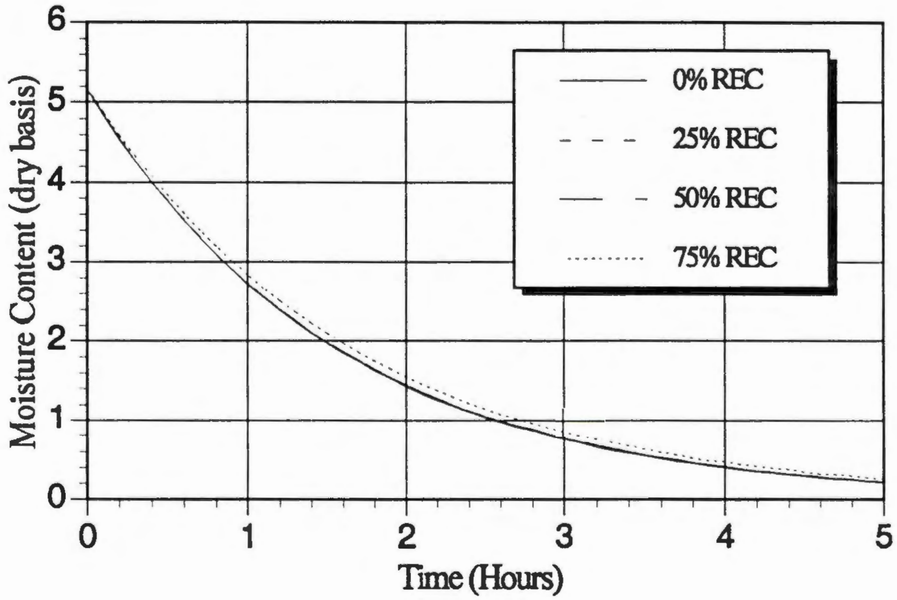
$$pseudo\left(r^2\right) = 1 - \frac{residual\ SS}{corrected\ total\ SS} \tag{11}$$

where ***SS*** represents the sum of squares. These r^2 values ranged from 0.96 to 0.99. The values of c_1, c_2 and pseudo(r^2) that were calculated from the regression analysis are shown in Table IV-1 for the dried peaches and apples for each recirculation rate (**RATE**). The dependent variable, moisture content (dry basis) or ***MC(db)***, was obtained by using the initial moisture content and the weight of the fruit, measured at the corresponding time that each tray of fruit was weighed. The equation used to calculate the moisture content for the fruit slices on each tray was expressed as:

$$MC(db) = \frac{W' - W_0 \times (m_0 - 1)}{W_0 \times (1 - m_0)} \tag{12}$$



(a)



(b)

Figure IV-2. Rate of moisture removal in dried fruit; (*a*) dried peaches (*b*) dried apples.

Table IV-1. Regression constants and pseudo(r^2) values (see eq. 11) for the exponential model $MC(db) = c_1 * exp(-c_2\ Time)$ representing the decrease of moisture content (dry basis) with time for dried peaches and apples.

FRUIT	RATE	a_1	b_1	pseudo(r^2)
PEACH	0	7.9176	0.0829	0.98
PEACH	25	7.9164	0.0820	0.98
PEACH	50	7.9337	0.0850	0.99
PEACH	75	7.9635	0.0794	0.98
APPLE	0	5.1449	0.6326	0.96
APPLE	25	5.1594	0.6348	0.96
APPLE	50	5.1700	0.6422	0.96
APPLE	75	5.1797	0.6026	0.96

where
$MC(db)$ is the moisture content (dry basis)
W' is the weight of the fruit at the corresponding process time
W_0 is the total initial weight of the fruit
m_0 is the initial moisture content (wet basis) of the fruit.

The analysis considered the total process time as a response variable to determine any differences in the treatments or possibly in the blocking variables (DRYER and TEST). Significant correlation coefficients existed for the moisture loss (**TML**) variable (PCC: 0.8670; Pr > R: 0.0001) in the peach experiment and the moisture content (**MCwb**) for the apple experiment (PCC: -0.5884; Pr > R: 0.0004). Therefore, the TML and MCwb variables represented the covariates in the peach and apple statistical models, respectively.

The moisture content (wet basis) of the tray of fruit that corresponded with the total process time was obtained from the moisture content (dry basis), calculated in equation 12. The conversion from moisture content (dry basis) to wet basis was calculated as:

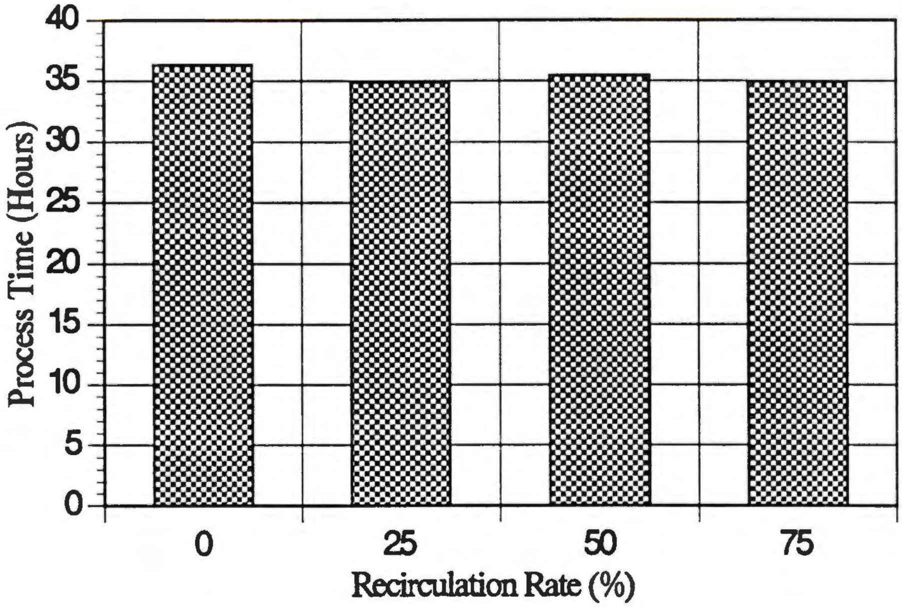
$$m = \frac{M}{M+1} \tag{13}$$

Figures IV-3(*a*) and (*b*) show the least square means for the recirculation treatments. These treatments showed no significant effects (95% confidence level) in predicting the total process time for both peaches and apples. These results are supported by the curves of Figures IV-2(*a*) and (*b*), which indicate very similar drying rates for all recirculation rates in both experiments. The TEST variable indicated highly significant effects (99% confidence level) for both peaches and apples. Figures IV-4(*a*) and (*b*) show the time variable versus recirculation treatment for Tests 1 through 4 for dried peaches and apples, respectively.

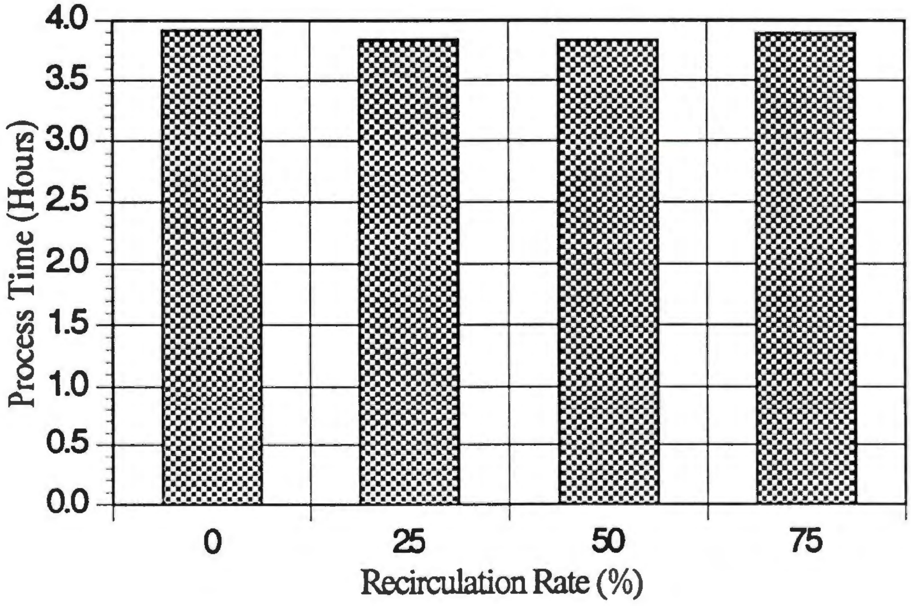
Differences among dryers appeared significant (99% confidence level) for predicting the total time, only in the apple experiment. The least square mean for Dryer A (4.06 Hrs.) showed the only significantly different time among the least square means for all dryers. The mean time for the dryers, other than dryer A, was approximately 3.81 ± 0.04 hours. On the other hand, dryer A in the peach experiment did not require any significantly greater time for processing (95% confidence level).

Analysis of Cumulative Energy Consumption

The effect of recirculation rate on energy consumption for drying peaches and apples is shown in Figures IV-5(*a*) and (*b*). A SAS linear regression technique (REG procedure) was utilized to evaluate all data for peaches and apples. Table IV-2 shows the regression constants (d_1 and d_2) and the corresponding r^2 values for dried peaches and apples. The r^2 values indicated a range from 0.91 to 0.99.

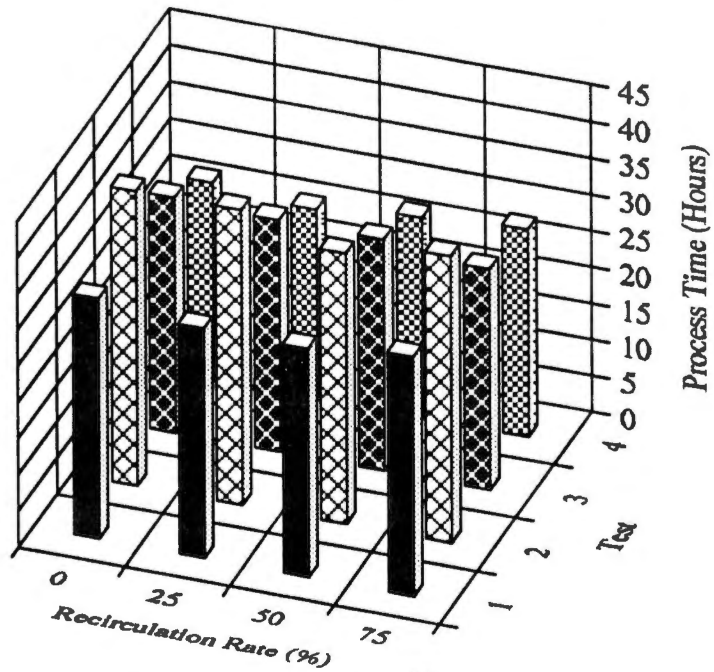


(*a*)

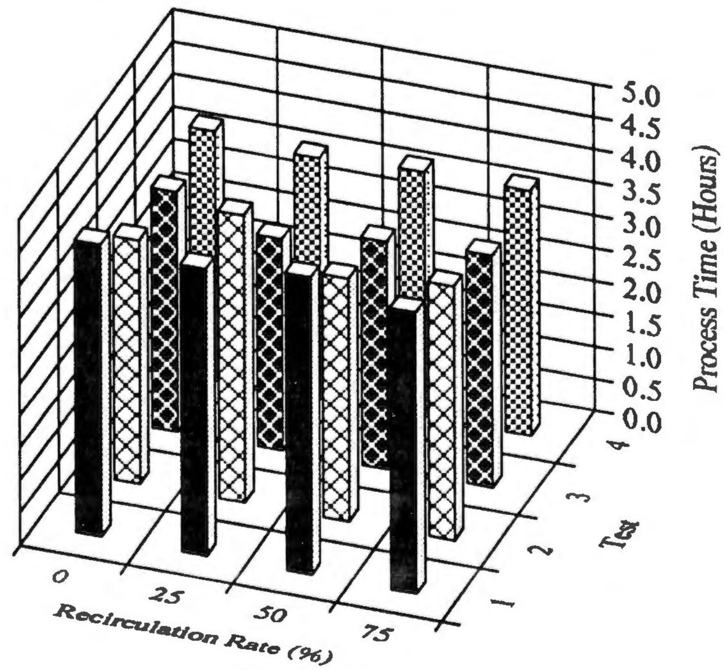


(*b*)

Figure IV-3. Comparison of total process time (least square means) for each recirculation rate; (*a*) dried peaches (*b*) dried apples

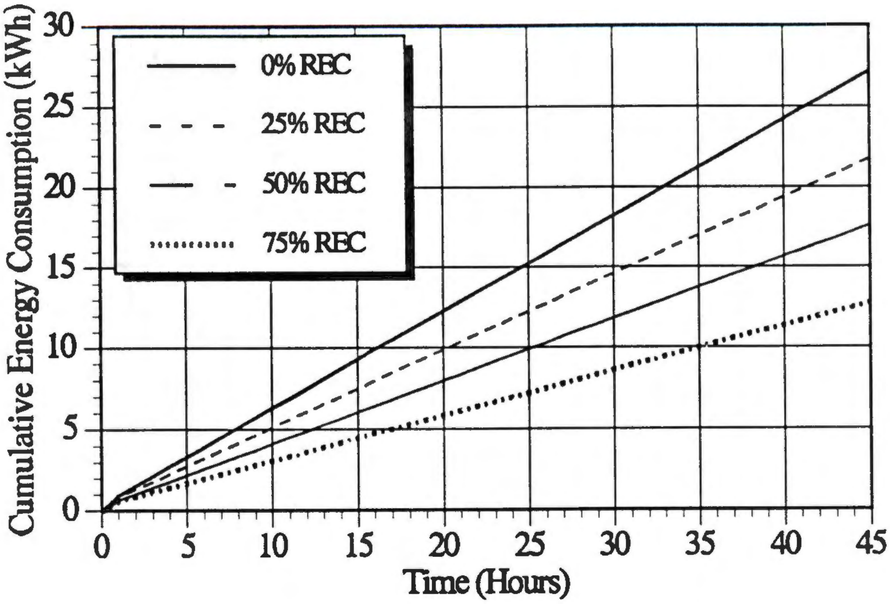


(a)

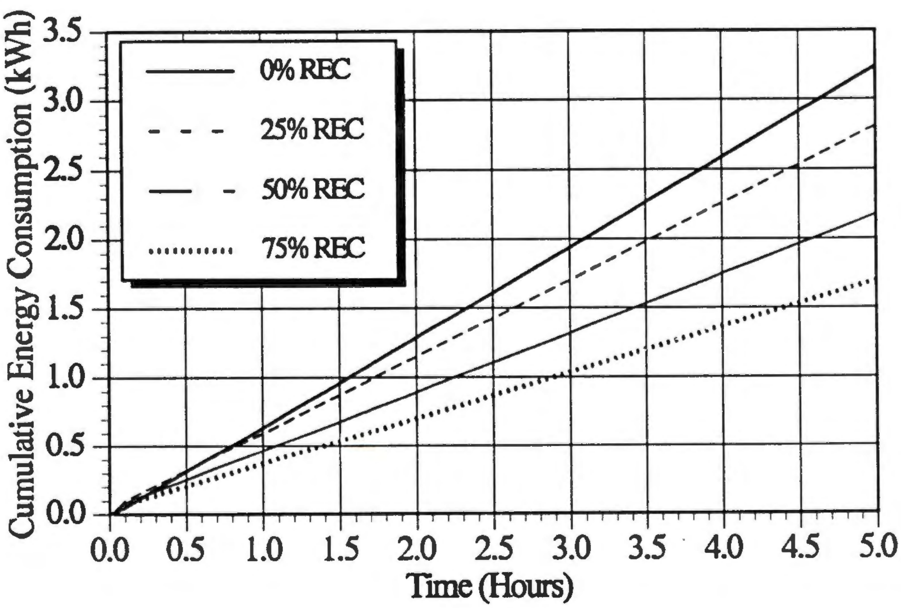


(b)

Figure IV-4. Comparison of total process time versus the recirculation rate for Tests 1-4; (*a*) dried peaches (*b*) dried apples.



(a)



(b)

Figure IV-5. Cumulative energy consumption versus time for dried fruits; (*a*) dried peaches (*b*) dried apples.

Table IV-2. Regression constants and r^2 values for the linear model, ***Energy Consumption** = d_1*Time+d_2* representing the increase in energy consumption with time for dried peaches and apples.

FRUIT	RATE	d_1	d_2	r^2
PEACH	0	0.5967	0.3403	0.99
PEACH	25	0.4752	0.4081	0.98
PEACH	50	0.3856	0.2911	0.98
PEACH	75	0.2761	0.3589	0.93
APPLE	0	0.6510	0.0140	0.96
APPLE	25	0.5535	0.0480	0.96
APPLE	50	0.4270	0.0436	0.96
APPLE	75	0.3318	0.0448	0.91

The statistical analysis for determining the differences between the treatments was performed using SAS statistical software (release 6.03). The general linear models procedure (GLM) was used to perform an analysis of covariance for the energy consumption and time response variables.

The results obtained by this procedure for energy consumption in the peach and apple tests are shown in the Tables IV-3 and IV-4, respectively. The variables considered in these tables included the recirculation rate (**RATE**), the dryer (**DRYER**), the blocking variable (**TEST**), and the time covariate (**TIME**). The Type III sum of squares (**Type III SS** 'partial') for the allowed for adjustments to be made for the covariate in each model. The other statistical measures described in the tables included the degrees of freedom (**DF**), the F value, the probability of making a Type II error (Pr > F, obtained from the F distribution). **PCC** denotes the Pearson correlation coefficients, which were computed for all variables against the response variables.

Table IV-3. Analysis of the effects of recirculation rate, test, dryer, and the covariant (time) on the energy consumption (kWh) for the peach tests.

SOURCE	DF	Type III SS	F Value*	Pr > F	PCC Pr > |R|
RATE	3	243.05	43.45	0.0005	-0.9107
					0.0001
TEST	3	10.37	1.85	0.2250	-0.2466
					0.2087
DRYER	3	10.87	1.94	0.24096	0.0505
					0.4648
TIME	1	6.04	3.24	0.1318	0.1992
					0.1897

*Error Sum of Squares (Model): 9.3234
Error Source DF: 5

Table IV-4. Analysis of the effects of recirculation rate, test, dryer, and the covariant (time) on the energy consumption (kWh) for the apple tests.

SOURCE	DF	Type III SS	*F Value	Pr > F	PCC Pr > |R|
RATE	3	5.9083	69.91	0.0001	-0.9097
					0.0001
TEST	7	0.6527	3.31	0.0207	-0.2466
					0.8934
DRYER	3	0.1635	1.93	0.1624	0.0505
					0.7836
TIME	1	0.2061	7.32	0.0150	0.1992
					0.2743

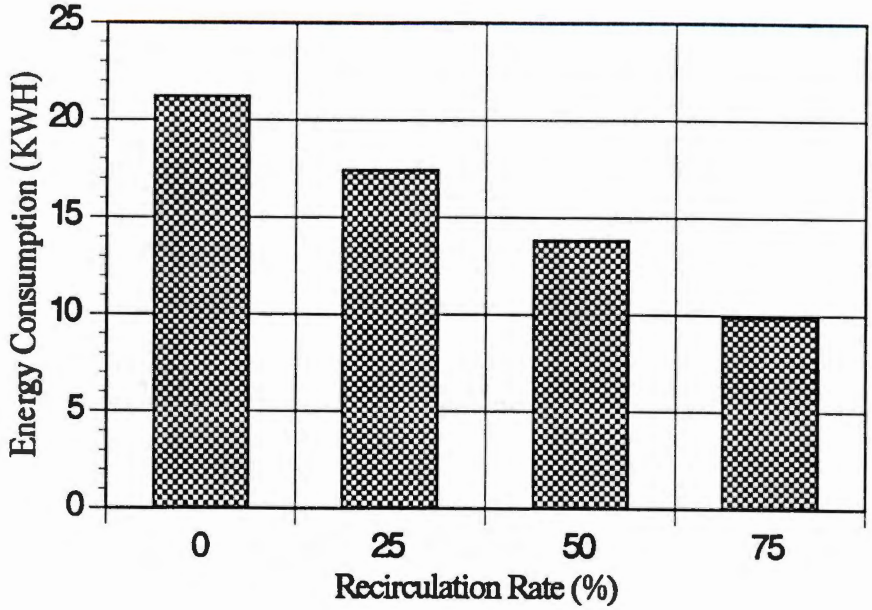
*Error Sum of Squares (Model): 0.4789
Error Source DF: 17

The treatment variable, recirculation rate (RATE), clearly shows strong evidence for predicting the energy consumption for both peaches (Pr > F: 0.0005) and apples (Pr > F: 0.0001). These differences in the least square means for the energy consumption among recirculation rates are shown in Figures IV-6(*a*) and (*b*) for dried peaches and apples, respectively. The Pearson correlation coefficients for the recirculation rate in the peach experiment (PCC = -0.9107) and the apple experiment (PCC = -0.9097) were also highly significant (Pr > |R|: 0.0001).

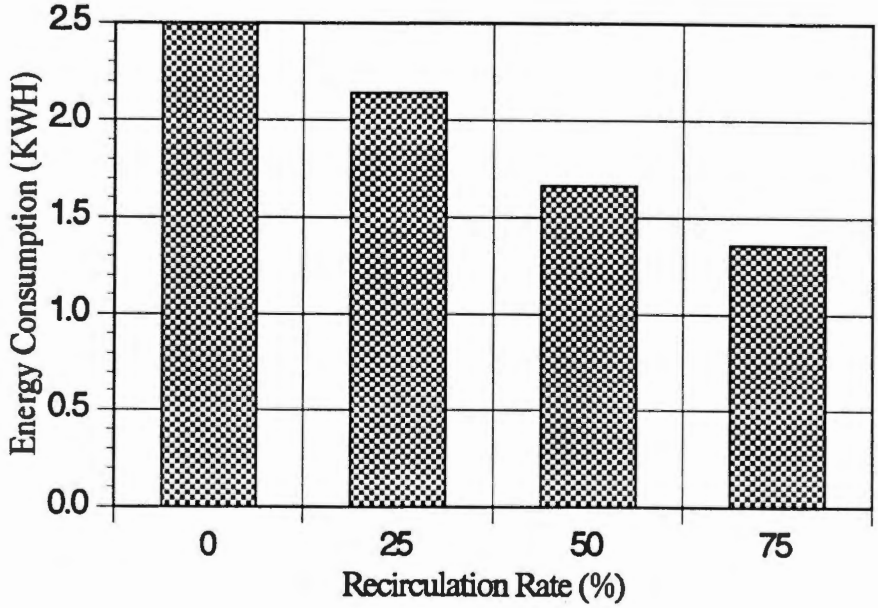
Because the correlation values are close to negative one, a definite trend existed for increasing rates to predict decreasing energy consumption. The other blocking variables, TEST and DRYER, did not show significant effects (95% confidence level) in predicting the energy consumption for peaches.

The apple experiment, however, did show a significant difference (95% confidence level) for the TEST variable. The least square means for the energy consumption in the first apple test (lsmean = 1.47 kWh) showed significant differences (95% confidence level) from all other tests except Tests 2 and 3. The average least square means for all tests, except Test 1, was 1.98 kWh. The other tests did not vary much from this mean (range: 1.83 to 2.19 kWh). This difference in Test 1 could not be readily explained, but changes in both energy consumption and time from test to test were expected because of the variation in the physical size of the fruit and in the ambient air conditions. These expected variations are discussed in further detail later in this chapter.

Figures IV-7(*a*) and (*b*) show the energy consumption versus recirculation treatment for Tests 1 through 4 for dried peaches and apples, respectively. These graphs indicate that differences appeared from test to test, but in all tests the energy consumption decreased with recirculation rate, and the time variable does not show

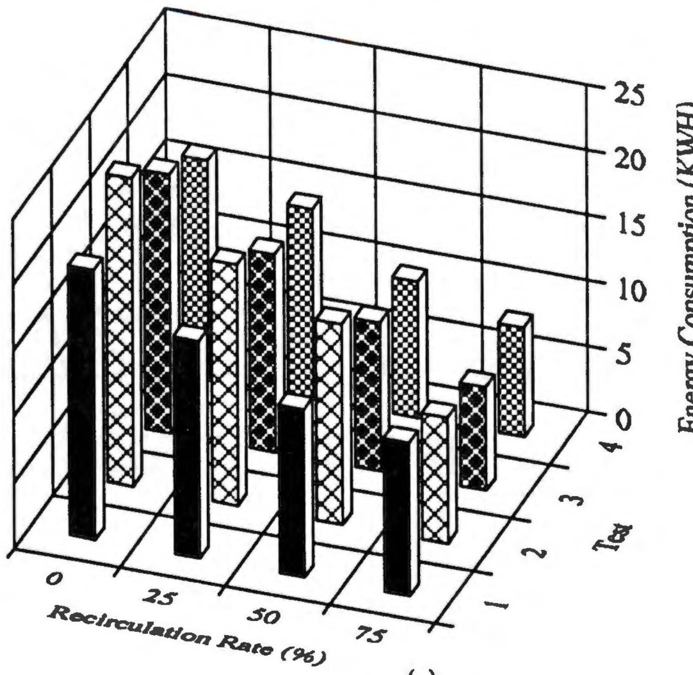


(a)

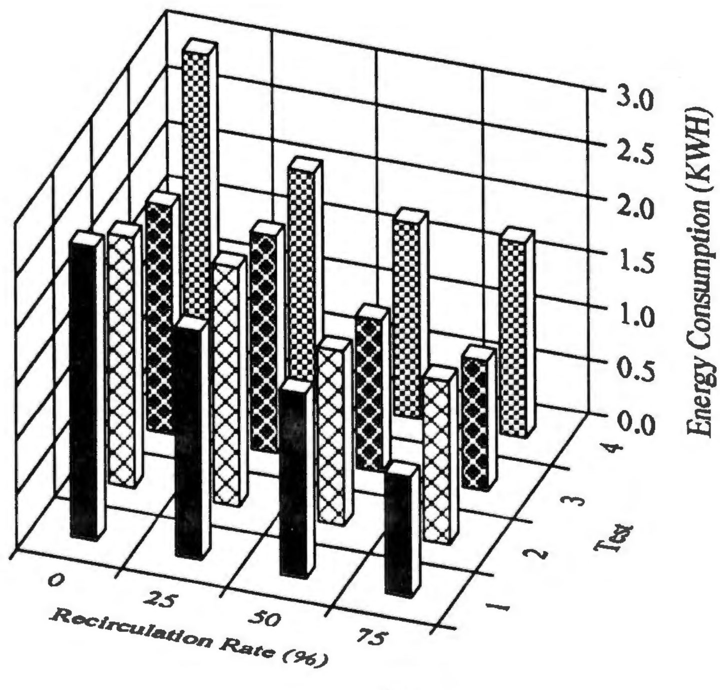


(b)

Figure IV-6. Comparison of Cumulative Energy Consumption (least square means) for each recirculation rate; (*a*) dried peaches (*b*) dried apples .



(a)



(b)

Figure IV-7. Energy consumption versus the recirculation rate for Tests 1-4; (*a*) dried peaches (*b*) dried apples.

much difference for all recirculation rates. Again, these test to test differences were expected because of experimental variations.

The significant effects for all response variables measured in the dehydration and quality experiments are summarized in Tables IV-5 and IV-6 for dried peaches and apples, respectively. Energy consumption (EC) and process time (TIME) represent the response variables in the dehydration tests. L, hue angle (HUE), and the color magnitude (MAG) represented the response variables for the color tests. The fructose (FRC), glucose (GLC), sucrose (SUC) contents, and the percent total soluble solids (%TS) represented the response variables for the sugar tests.

II. ANALYSIS OF THE QUALITY PARAMETERS

The determination of the dried fruit's quality took place during a period of six months to a year after performing the actual dehydration tests. SAS's linear models procedure performed the statistical analysis on all parameters used to measure the product's quality. The analysis for all quality variables (with the exception of the peach sugars) was based on a randomized block design. The test number represented the blocking variable that contained the treatments, which were assigned at random.

Color Analysis

The statistical analysis for the color measurements included the recirculation treatment and test variables for predicting each response variable (L, a, and b). The Type III mean square of the dryer tray variable nested within the TEST*RATE interaction was used as the error term. This analysis indicated that some significant

Table IV-5. Summary table showing the levels of significance of all variables analyzed for the peach tests.

	Dehydration Tests		Quality Tests						
			Color Tests			Sugar Tests			
Source	EC	TIME	L	HUE	MAG	FRC	GLC	SUC	%TS
RATE	***	ns	**	ns	**	ns	ns	ns	ns
TEST	**	***	***	***	***	--	--	--	--
DRYER	*	ns	--	--	--	--	--	--	--
TIME	ns	--	--	--	--	--	--	--	--
TML	--	**	--	--	--	--	--	--	--
MCwb	--	--	--	--	--	--	--	--	--

*** indicates 99% confidence level
** indicates 95% confidence level
* indicates 90% confidence level
ns indicates non-significance
-- represents source variable not used in model

Table IV-6. Summary table showing the levels of significance of all variables analyzed for the apple tests.

	Dehydration Tests		Quality Tests						
			Color Tests			Sugar Tests			
Source	EC	TIME	L	HUE	MAG	FRC	GLC	SUC	%TS
RATE	***	ns	ns	ns	ns	**	ns	ns	ns
TEST	**	***	ns	ns	ns	***	*	*	--
DRYER	ns	***	--	--	--	--	--	--	--
TIME	**	--	--	--	--	--	--	--	--
TML	--	--	--	--	--	--	--	--	--
MCwb	--	**	--	--	--	--	--	--	--

*** indicates 99% confidence level
** indicates 95% confidence level
* indicates 90% confidence level
ns indicates non-significance
-- represents source variable not used in model

effects among treatments on peaches occurred in the lightness and magnitude variables (95% confidence level), but not in the hue variable.

Peaches subjected to 25% recirculated air appeared to have the brightest color and lightness (magnitude lsmean: 27.71; lightness lsmean: 47.40). Peaches subjected to 25% and 75% recirculated air represented the only treatment effects that showed significant differences between the least square means of the magnitude and lightness variables (95% confidence level). The lightness and color magnitude tended to decrease with recirculation rates greater than 25%. The reasons for the differences between the two rates are not known. However, even though not significant, peaches subjected to 75% recirculation did require a slightly longer time to dry. The combination of higher moisture drying air and longer drying periods may have contributed to greater browning in peaches subjected to higher rates of recirculation.

The treatment variable in the apple tests did not show any significant effects (95% confidence level) for any response variable. Therefore, apples exposed to recirculated air did not show significant color differences from apples not subjected to recirculated air. The lack of color difference among apples may have resulted from the short period for dehydration (3-5 hours), which could have decreased the effects from browning reactions. Only slight browning, which mostly occurred in apples just after being sliced, was observed during the apple tests.

The TEST blocking variable showed highly significant effects (99% confidence level) for predicting the L value, the hue angle, and the corresponding magnitude in the peach experiment. The TEST variable in the apple experiment, however, showed no significant effects (95% confidence level) for predicting the response variable. The main differences in the peach tests appeared between Test 1 and Test 4. The least square means for Test 1 showed the lowest L values (43.55), the greatest hue angle (27.49°), and the smallest magnitude (24.79). The least square means for Test 4 were considerably different than Test 1 (L: 49.36, hue: 23.27°, magnitude: 29.36). All least square means for Tests' 2 and 3 fell between the values listed above.

From a visual inspection, the peaches from Test 4 appeared to have a much deeper and brighter color than peaches from the other tests. The other three tests showed more browning, which explains some of the test to test variations in color.

HPLC Sugar determinations

The only sugars found present in the apples and peaches were d-fructose, d-glucose, and sucrose. Shaw (1988) considered these three sugars the principle sugars in apples and peaches. Figures IV-8(*a, b, and c*) give an example of chromatograms of the sugar standards used to obtain a standard curve. Figures IV-8(d) and (e) show examples of typical chromatograms for dried peach and apple samples, respectively.

The standards of these sugars (purchased from Sigma, St. Louis, Mo.) were run individually through the column to obtain the expected retention times. These times were later referenced to locate the peaks of the sugars in the test samples. The average retention times (minutes) for these reference sugars were 4.17 for fructose, 4.74 for glucose, and 6.69 for sucrose.

Brix measurements were also taken to approximate the total solids present before extraction of the samples. The brix measurements for peaches averaged 76.38% total solids and apples averaged 73.75% total solids. The total solids in peaches correspond well with the findings of Hurst *et al.* (1979), who reported that the total solids in dried peaches were 73.6%. The total sugars in dried peaches, however,

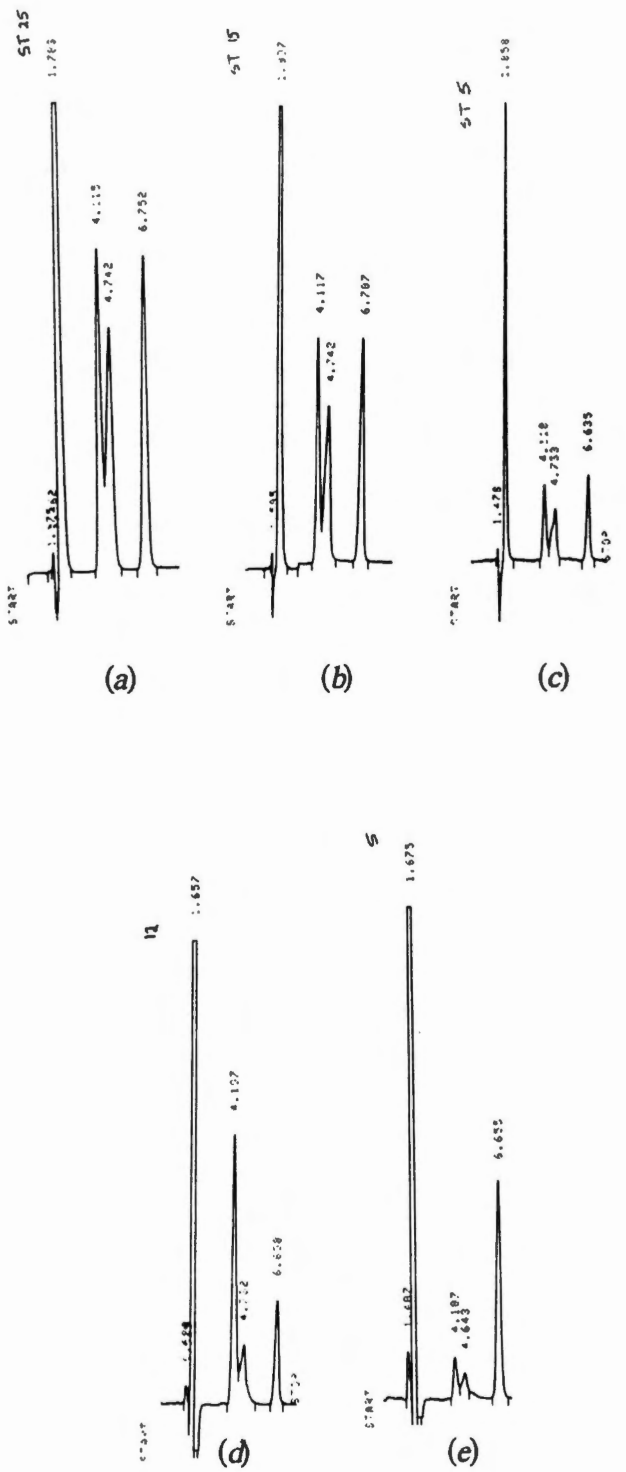


Figure IV-8. Chromatograms taken from the HPLC recorder for the analysis of sugars; standard sugars using (*a*) 25 μL injection, (*b*) 15 μL injection, (*c*) 5 μL injection, and sample sugars from (*d*) dried peaches, and (*e*) dried apples.

were reported by Hurst *et al.* (1979) as 44.6% (fructose: 15.6%; glucose: 15.8%; sucrose: 13.2%).

The peach experiment did not utilize the random block design because peaches from only one test were available at the time of the HPLC determinations. More tests were not used because of time constraints with the available equipment. The statistical analysis considered only the treatment variable, recirculation rate, for predicting the amount of each sugar (g/100 g dried fruit) and the total solids present. Two replicates of peaches subjected to each treatment in Test 3 were used for the sugar measurements. Samples were also analyzed in replicate to obtain an average sugar content. The mean square of the replicate variable nested within the treatment variable (RATE) served as the error term for the peach experiment.

The apple experiment did utilize the randomized block design because samples from two different tests were used (Tests 7 and 8). Therefore, the analysis included the treatment and test variables for predicting the amount of each sugar and the total solids. All samples were analyzed in replicate, as was done for the dried peach samples. The RATE*TEST interaction served as the error term used in the statistical analysis for apples.

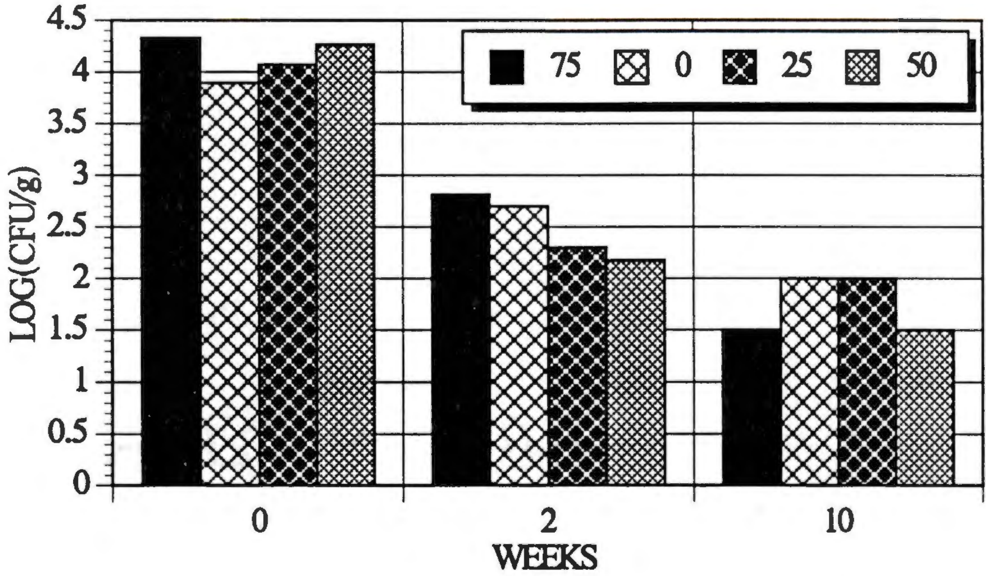
The recirculation treatment showed no significant effects (90% confidence level) for all sugars in dried peaches and for glucose and sucrose in dried apples. The treatment effects were also insignificant (90% confidence level) in the analysis for predicting the total solids for both dried peaches and apples. The only significant treatment effect (95% confidence level) occurred in predicting the fructose content in dried apples. The fructose content in dried apples treated with no recirculation appeared to be the only effect to vary considerably from the other treatment effects. The mean fructose content in apples treated with 0% recirculated air was 24.85g /100g dried fruit. The average mean fructose content for the other treatments was 34.51 ± 1.14g / 100g dried fruit. Fructose is considered to be an unstable sugar when subjected to high temperatures for extended periods of time (Pomeranz and Meloan, 1987).

Shelf-life Results

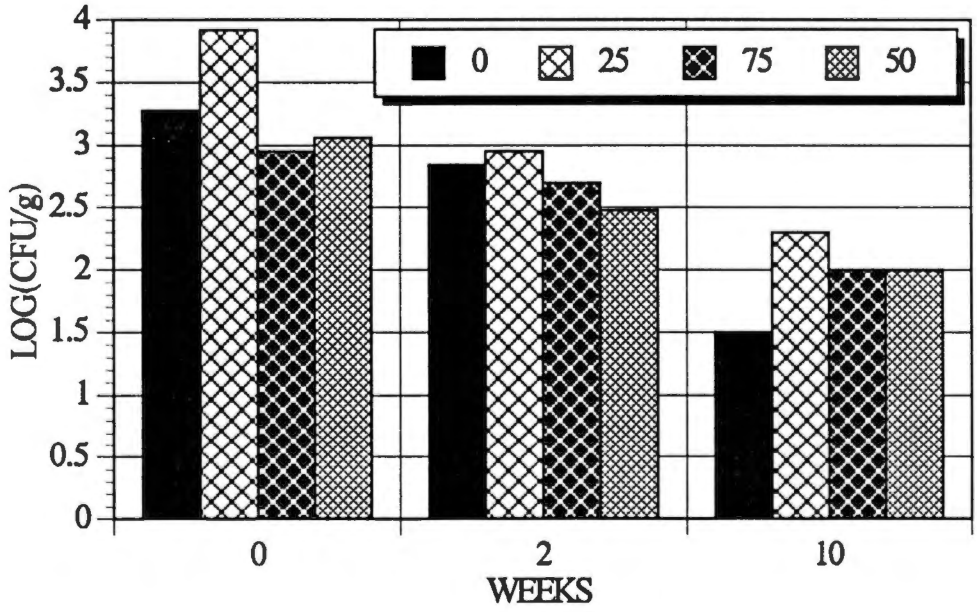
The results from the shelf-life study were approached subjectively for determining any differences among treatments. The study showed a noticeable decrease in the number of microorganisms for all recirculation rates on both dried peaches and apples during the ten week period. The observed reduction in microbial growth probably occurred because of the poor growth environment of the dried fruit (due to concentrated acids and sugars and low water activity). Figures IV-9(*a*) and (*b*) represent the log CFU/g of dried fruit over the ten week period for dried peaches and apples, respectively. No significant differences were observed between recirculation rates for any given time for both dried peaches and apples. This is evident in Figure IV-9 because the counts never vary by more than one log unit between recirculation rates at any given time for the dried peaches and apples. Therefore, the recirculation rates did not appear to affect the shelf-life in terms of microbial growth.

III. EXPERIMENTAL SOURCES OF ERROR AND SYSTEM EVALUATION

Each set of four tests performed on the apples and peaches produced a 'Latin square' experimental design as mentioned earlier. This design compensated for much



(*a*)



(*b*)

Figure IV-9. Microbial growth after 0, 2, and 10 weeks; (*a*) dried peaches (*b*) dried apples.

of the random sources of error assumed to affect the experiment. Some of these sources include differences among dryers and dryer recirculation mechanisms, variations in the ambient air conditions, and physical variations among the fruit. Several differences among dryers were observed and documented. A simple experiment was conducted to observe any differences in heat loss for each dryer. All dryers were operated simultaneously at approximately 65°C drying temperature and no drying load. The flow diverter valves were completely closed to obtain 100 percent recirculation. Temperatures were measured at the inlet, exit, and within the recirculation duct near each dryer's inlet. The temperature differences between each point are listed in Table IV-7. Also, the energy consumption was measured over a four hour period and recorded for each dryer.

Dryer A produced an eight degree (°C) temperature loss from the inlet to duct. Dryers' B, C, and D had lower temperature losses. The locations of the dryers within the laboratory may have accounted for some of the differences. For instance, dryer A was located on one end of the laboratory. Also located on the same end was a large ceiling exhaust fan that operated during most drying tests. Dryer D was located near the other end of the laboratory where the outside air inlet was located. The total temperature losses, shown by Δ(Ti-Te) in Table IV-7, decrease slightly from dryer D to dryer B (4.7 to 3.5°C), but increase considerably for dryer A (8.0°C). Also, the total energy consumed over four hours for dryer A (0.7 kWh) was higher than the other dryers. The differences in heat loss among the dryers would also influence the calibration of the flow diverter valves, because the calibration method required the inlet and exit temperatures.

The next important experimental variation involved the ambient air conditions. The ambient relative humidity and dry-bulb temperature were measured to show this

Table IV-7. Temperature losses and energy consumption for each dehydrator.

Dryer	Temperature (°C)			Temperature Differences* (°C)			EC*
	Inlet	Exit	Duct	$\Delta(T_i-T_e)$	$\Delta(T_e-T_d)$	$\Delta(T_i-T_d)$	(kWh)
A	65.5	63.0	57.6	2.5	5.4	8.0	0.7
B	65.5	63.0	62.1	2.5	0.9	3.5	0.5
C	65.5	64.0	61.5	1.5	2.5	4.0	0.5
D	65.2	63.0	60.6	2.2	2.4	4.7	0.6
Average	65.4	63.3	60.5	2.2	2.9	5.0	0.58

*Ti = inlet temperature,
Te = exit temperature
Td = duct temperature
EC = energy consumption

variation for each test (see Figure B-1 in the appendices). The drying process would be affected by changes in relative humidity. However, air completely saturated (100% relative humidity) at room temperature (25°C) changes to approximately 12 % relative humidity when heated to 65.6°C. Therefore, the driving force for moisture transfer from the fruit to the drying air increases and the effect from the high ambient relative humidity decreases due to the high temperatures involved.

The fan characteristics for each dryer represent another dryer variation that accounted for some of the differences in drying uniformity. For this reason, the trays in each dryer were rotated and moved after each weighing, as described in the previous chapter. Figures IV-10(*a*) and (*b*) show the air velocity at different points within dryers A and B, respectively. All measurements were taken by a TSI air velocity meter (model 1640) at a distance of 7.5 cm from the plane of the fan (this was the

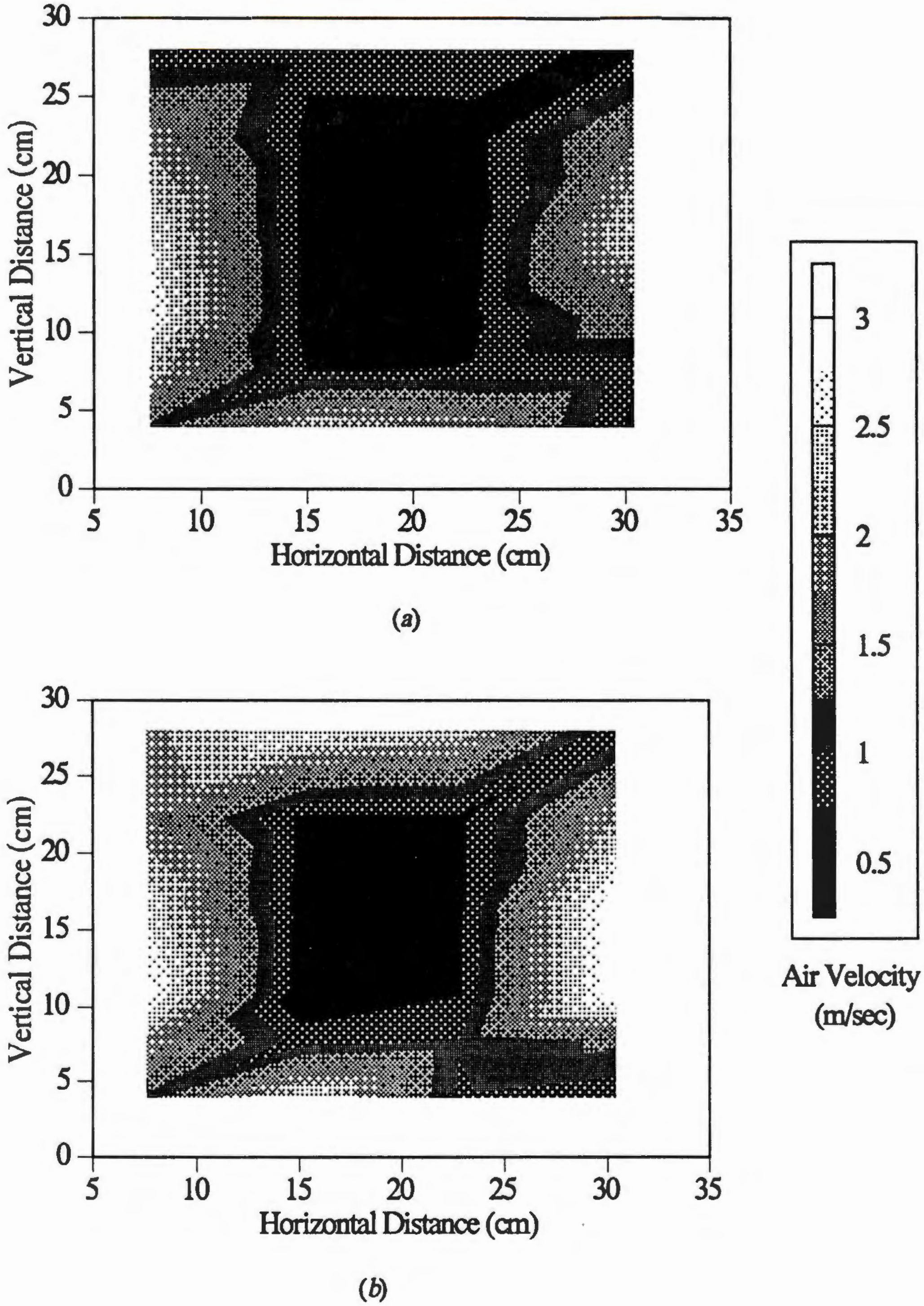
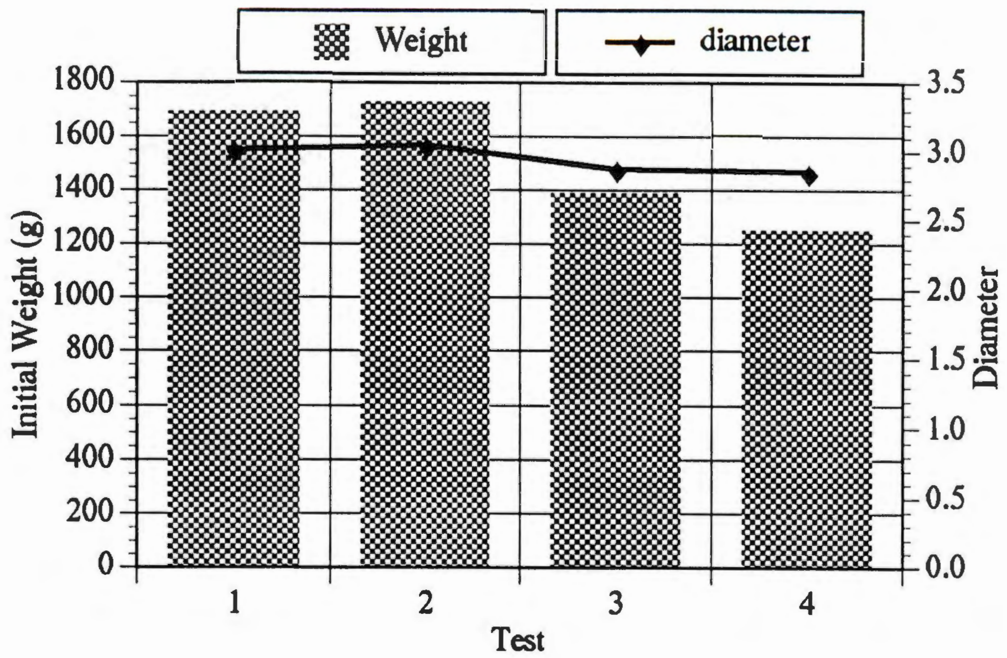


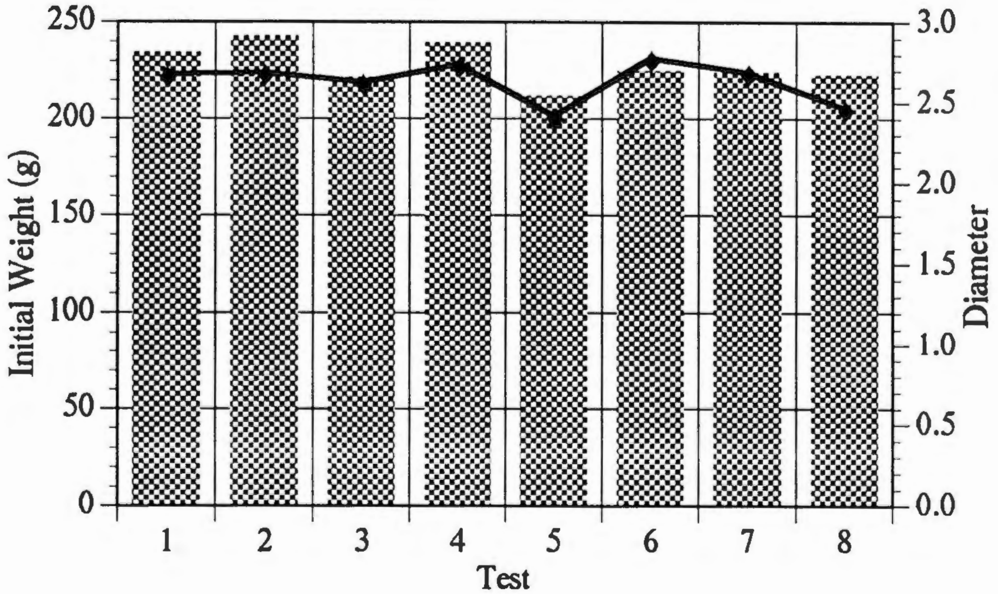
Figure IV-10. Air velocity contour taken 7.62 cm from the back portion of the dryers along the vertical plane; (*a*) dryer *A* (*b*) dryer *B*.

approximate location where the drying air first made contact with the fruit). These graphs show that the higher air velocities occurred toward the outer edges of the drying chamber. Similar results were observed for measurements taken in both dryers. accounted for another important source of error. An explanation for these differences may include many possibilities, such as the time of harvest or ripeness of the fruit, location of the fruit tree in the orchard, and the physical size of the fruit. Figures IV-11(*a*) and (*b*) show the average physical differences, initial weight and diameter, for all tests on peaches and apples, respectively. The diameters were measured before preparing the fruit for drying. The initial weights were determined for each test by taking the average weight of the prepared fruit placed on each of the dryer trays in all dryers. The variation in initial weight can be seen clearly for both fruits.

The variation in the actual size of the fruit affected, in particular, the actual moisture load subjected to each dryer. The dryers containing peach halves usually contained a nearly maximum load on the four trays, however, the apple slices accounted for much smaller drying loads because the apples were thinly sliced. The air flow rate (m^3/sec.) per unit initial fruit load (kg) was calculated for all dryers in each test for the peaches and apples. This provided a means of comparing the dryer's capacity for removing the moisture load. The air flow-rates were calculated directly from the air velocities in the recirculation ducts (previously discussed in Chapter III) taken at the corresponding cross-sectional area. An analysis of variance among the recirculation rates for the peach and apple experiments indicated no significant differences (95% significance level) for the air flow per unit fruit load. The means for the peach experiment ranged from 0.18 to 0.19 m^3/sec/kg fruit (Least significant difference: 0.01). The apple experiment varied from 1.14 to 1.3 m^3/sec/kg fruit (Least significant difference: 0.04).



(a)



(b)

Figure IV-11. Average weights and diameters of whole fruits after harvesting; (a) dried peaches (b) dried apples.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Early studies conducted at California and Oregon experiment stations suggested that recirculating drying air in fruit dehydrators of the continuous tunnel type had many benefits. Some of these benefits included substantial energy savings and the decreased effect of 'casehardening.' The main purpose of this experiment was to not only verify that energy can be substantially saved, but to determine how much energy could be saved at specified fixed recirculation rates (0, 25, 50, and 75%). The idea of recirculating air as a means of saving energy has existed for many years, however, data that describes the actual amount of savings for specified recirculation rates is very limited for batch dehydrators. Recent interest in dehydrating fruit crops on a small scale provided further reason for obtaining results that would help improve the efficiency of the dehydration process.

The quality of the final product was considered to be very important to the results of this experiment. The color differences and the sugar content helped to describe any quality changes that may have occurred because of treatment effects or from test to test variations. A microbial study was also conducted to determine an approximate shelf-life for the product over a ten week period.

Analysis of the results strongly suggested that a substantial energy savings existed for increasing recirculation rates up to 75%. Approximately 53% savings for drying peaches and a 46% savings for drying apples was observed for the 75% recirculation rate. The total processing times for both dried peaches and apples did not indicate any significant differences (95% confidence level) for the 75% recirculation rate when compared to the other rates tested. These results indicate that higher recirculation rates are necessary to obtain the optimum energy savings for the experimental conditions described.

However, in this study, the dryers were not loaded to capacity, especially in the apple experiments. The efficiency of the drying process depends on the rate of moisture transfer, particularly during the first stage of the drying process. Recirculation rates greater than 75% within a dryer loaded to maximum capacity may result in less drying efficiency. Experiments using higher fixed recirculation rates and an increased fruit load in the dryers are highly recommended. These tests would help to establish a fully optimized energy savings for the batch dehydrator with air recirculating at a fixed rate.

In general, the quality analysis showed very small differences in the effects of recirculation treatments on the quality parameters. The test to test variation accounted for most of the differences that appeared to be significant in the statistical analysis. Therefore, the quality, as measured by the experimental parameters, suggests very little variation in fruits subjected to recirculation as opposed to the fruits receiving only ambient air for drying.

Color differences between peaches were observed only between those receiving the 25% recirculation treatment and those receiving 75% recirculation. The differences occurred mainly in the color magnitude and lightness of the peach flesh. These differences indicated that browning took place in the treatments subjected to 75% recirculation. Only apples that received no recirculation showed significantly (95% confidence level) less fructose composition. Because fructose is known to be more heat sensitive than the other sugars present in these fruits, taking temperature measurements of the fruit flesh during drying is recommended to show if any temperature differences in the fruit flesh exist among treatments.

Several sources of experimental error existed within the experiment design. Some of these sources include variations among dryers, ambient air conditions, and the electronic recording of data. It is recommended, as with any known source of error, to minimize the variation as much as possible. The reasons behind any dryer variations must be first be detected and then corrected if feasible to do so.

The problem with non-uniform air flow has been considered by many researchers (Adams and Thompson, 1985; Moyls, 1985) as an important problem to the drying industry. Several alternatives exist for aiding the flow characteristics in dehydrators. A possible recommendation for this experiment includes adding a tunnel section (equipped with wind vanes if necessary) for the air to pass through before reaching the back of the trays.

A problem with recording data occurred because the photoelectric sensors did not perform as expected. Proper electrical maintenance would alleviate the wiring problems encountered. Placing a light bulb that operates continuously on the fan's electrical circuit is recommended to add a constant load on the watt-hour meters. This would stop the disk from moving in the reverse direction when the heating element is physically turned off by the temperature controller.

Another problem occurred with the task of removing the trays from the dryers temporarily for weight loss measurements. Adding a load cell to each dryer to measure the weight loss would solve this problem by eliminating the need to open the dryer. The only drawback would be that the trays could not be easily rotated to obtain better drying uniformity.

Sources of experimental error occurred during the quality study. The main source of error occurred during the extraction of sugar using the suggested method. The extraction procedure did not fully extract all sugars from each sample. Several extra washes with the ethanol-water solution in the heated water bath are recommended to extract more of the sugars. Preliminary tests should first be conducted to find the optimum number of washes for extracting sugars. A comprehensive recovery study is also recommended to optimize the recovery of sugars.

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APPENDICES

APPENDIX A

Table A-1. Time, energy consumption, and total fruit weights for the peach tests.

TEST	DRYER	RATE (%)	TIME (Hrs.)	EC* (KWH)	WT*(g) TRAY 1	WT (g) TRAY 2	WT (g) TRAY 3	WT (g) TRAY 4
1	A	0	0.00	0.0	1538.5	1717.1	1641.4	1431.9
1	A	0	2.83	2.2	1245.2	1385.4	1357.3	1197.1
1	A	0	4.83	3.6	1103.3	1239.8	1237.5	1065.0
1	A	0	7.50	5.4	936.8	1069.3	1057.2	890.9
1	A	0	10.00	6.9	805.5	943.9	896.2	749.6
1	A	0	15.08	10.2	598.2	673.1	640.0	535.3
1	A	0	22.83	14.9	389.8	414.4	404.0	341.3
1	A	0	27.83	17.6	294.3	317.5	323.4	264.8
1	A	0	33.17	20.5	245.1	271.8	265.0	217.5
1	A	0	34.83	-	-	-	-	223.9
1	A	0	39.00	24.0	219.5	240.1	237.3	211.5
1	B	25	0.00	0.0	1626.0	1687.5	1517.0	1835.0
1	B	25	2.67	1.4	1367.7	1399.8	1234.6	1589.1
1	B	25	4.17	2.4	1219.4	1271.2	1104.3	1455.2
1	B	25	7.17	3.7	1060.2	1106.6	964.3	1263.5
1	B	25	9.67	5.3	939.2	964.5	826.5	1082.2
1	B	25	15.00	8.0	672.3	700.3	588.1	790.5
1	B	25	22.67	12.2	402.5	450.8	347.6	481.2
1	B	25	27.67	14.6	291.2	308.3	262.7	344.5
1	B	25	33.00	17.2	248.0	260.2	218.6	274.5
1	B	25	33.67	-	-	-	216.9	267.6
1	B	25	35.33	18.3	239.1	246.1	-	-
1	C	50	0.00	0.0	1843.3	1619.0	1746.2	1625.9
1	C	50	2.50	1.3	1548.8	1372.2	1481.0	1377.3
1	C	50	4.50	2.3	1352.9	1218.0	1298.9	1196.0
1	C	50	7.00	3.4	1176.6	1055.3	1102.1	1025.0
1	C	50	9.50	4.6	993.2	881.2	935.7	851.6
1	C	50	14.92	6.7	697.8	637.4	681.3	616.8
1	C	50	22.50	9.6	431.5	393.7	420.4	382.2

Table A-1 continued

TEST	DRYER	RATE (%)	TIME (Hrs.)	EC (KWH)	WT (g) TRAY 1	WT (g) TRAY 2	WT (g) TRAY 3	WT (g) TRAY 4
1	C	50	27.50	11.4	339.3	306.5	322.5	294.9
1	C	50	32.83	13.3	287.5	253.4	258.2	244.3
1	C	50	33.66	-	-		252.2	239.5
1	C	50	39.17	15.4	260.1	216.2	-	-
1	D	75	0.00	0.0	1830.3	1911.4	1698.0	1747.1
1	D	75	2.33	1.1	1553.0	1608.9	1473.6	1561.0
1	D	75	4.33	2.1	1322.0	1431.1	1316.0	1345.3
1	D	75	6.83	3.0	1143.3	1277.5	1121.2	1136.9
1	D	75	9.33	3.9	999.3	1093.1	931.5	967.8
1	D	75	14.83	5.9	686.4	784.9	687.2	705.8
1	D	75	22.00	7.9	430.6	516.8	448.9	464.2
1	D	75	27.33	9.5	317.7	409.8	352.5	345.6
1	D	75	32.67	11.0	268.4	347.2	287.5	278.4
1	D	75	33.67	12.4	262.0	-	-	-
1	D	75	39.20	-	-	297.6	255.2	249.1
1	D	75	44.25	13.5	-	283.3	245.2	-
2	A	75	0.00	0.0	2028.5	1803.7	1771.0	1658.6
2	A	75	2.50	0.7	1843.7	1633.3	1563.9	1513.2
2	A	75	4.50	1.2	1693.7	1494.4	1448.1	1382.9
2	A	75	6.67	1.8	1521.4	1360.6	1310.0	1235.1
2	A	75	9.33	2.9	1341.4	1197.7	1151.6	1093.0
2	A	75	17.33	4.7	964.3	762.2	747.7	706.8
2	A	75	24.25	6.2	721.4	524.7	516.7	499.0
2	A	75	25.75	6.9	619.6	438.9	435.9	427.0
2	A	75	29.42	7.6	513.4	364.1	369.3	355.6
2	A	75	35.58	9.0	393.9	284.9	289.0	280.2
2	A	75	36.50	9.1	-	277.0	281.5	-
2	A	75	40.58	9.9	-	-	-	248.1
2	A	75	44.83	10.3	313.8	-	-	-

Table A-1 continued

TEST	DRYER	RATE (%)	TIME (Hrs.)	EC (KWH)	WT (g) TRAY 1	WT (g) TRAY 2	WT (g) TRAY 3	WT (g) TRAY 4
2	B	0	0.00	0.0	1810.3	1597.4	1837.2	1490.5
2	B	0	2.50	1.5	1594.8	1370.3	1601.2	1321.3
2	B	0	4.50	2.7	1431.4	1232.3	1464.1	1196.2
2	B	0	6.67	4.0	1263.4	1106.8	1327.9	1048.6
2	B	0	9.33	5.6	1121.3	990.6	1162.6	907.6
2	B	0	17.42	10.4	787.2	644.2	797.4	622.8
2	B	0	24.50	14.0	573.9	477.6	577.3	443.7
2	B	0	27.67	15.7	477.7	337.7	497.0	367.4
2	B	0	31.33	18.1	391.7	318.4	409.6	292.9
2	B	0	37.58	21.6	302.6	249.3	305.4	224.2
2	B	0	38.25	22.1	-	245.2	-	-
2	B	0	43.50	25.1	254.5	-	261.8	-
2	C	25	0.00	0.0	1686.8	1789.7	1961.3	1610.8
2	C	25	2.17	1.1	1483.6	1553.4	1734.9	1417.4
2	C	25	4.17	2.1	1300.4	1407.2	1575.8	1270.6
2	C	25	6.33	3.2	1143.1	1261.8	1392.4	1116.8
2	C	25	9.00	4.6	1005.3	1096.2	1203.3	981.4
2	C	25	17.17	8.3	639.3	730.6	827.5	657.1
2	C	25	24.17	11.3	429.2	524.6	612.6	461.2
2	C	25	27.42	12.9	366.1	468.0	533.6	385.0
2	C	25	31.00	14.1	307.9	390.7	447.3	322.3
2	C	25	37.33	16.7	249.2	308.5	355.0	255.4
2	C	25	38.33	17.2	-	-	-	247.9
2	C	25	42.67	19.2	-	272.5	-	-
2	C	25	44.67	20.1	-	-	300.3	-
2	D	50	0.00	0.0	1865.0	1532.1	1734.0	1436.6
2	D	50	2.00	1.0	1642.5	1314.7	1545.6	1271.2
2	D	50	4.00	2.0	1447.7	1190.7	1415.3	1100.1
2	D	50	6.17	3.0	1289.6	1075.1	1249.9	942.5

Table A-1 continued

TEST	DRYER	RATE (%)	TIME (Hrs.)	EC (KWH)	WT (g) TRAY 1	WT (g) TRAY 2	WT (g) TRAY 3	WT (g) TRAY 4
2	D	50	8.83	4.2	1139.7	913.6	1057.2	806.4
2	D	50	17.00	8.0	768.4	517.0	591.4	491.3
2	D	50	23.50	10.6	567.3	329.8	380.8	319.2
2	D	50	27.33	11.8	468.4	270.5	327.2	273.7
2	D	50	30.83	13.1	390.1	237.6	292.4	229.5
2	D	50	34.83	13.9	313.5	214.8	257.8	206.6
2	D	50	37.17	15.6	279.6	-	-	-
3	A	25	0.00	0.0	1368.4	1409.0	1381.2	1431.2
3	A	25	2.00	1.0	1194.3	1210.2	1176.4	1288.1
3	A	25	4.25	2.1	1023.1	1009.9	1036.9	1135.0
3	A	25	6.25	3.2	900.8	901.5	917.8	998.9
3	A	25	14.17	7.5	577.7	593.2	548.8	609.4
3	A	25	20.25	10.0	397.4	416.3	381.3	406.5
3	A	25	24.75	11.9	310.0	311.3	285.1	318.9
3	A	25	30.25	14.2	228.8	226.6	218.7	246.7
3	A	25	31.00	14.6	-	218.7	211.7	-
3	A	25	32.75	15.3	208.1	-	-	-
3	A	25	33.58	15.8	-	-	-	219.7
3	B	50	0.00	0.0	1376.3	1334.4	1371.7	1452.7
3	B	50	2.17	0.7	1209.4	1143.3	1174.0	1255.2
3	B	50	4.42	1.6	1039.6	994.1	1011.7	1112.3
3	B	50	6.42	2.5	907.6	878.4	900.6	979.2
3	B	50	14.08	5.5	560.1	562.9	556.2	608.2
3	B	50	20.42	7.9	360.6	386.3	376.6	389.7
3	B	50	24.83	9.5	273.3	297.8	288.3	300.4
3	B	50	30.33	10.8	204.4	230.8	227.6	228.5
3	B	50	31.17	11.0	-	-	-	221.2
3	B	50	32.83	11.6	-	-	210.2	-
3	B	50	33.58	11.8	-	208.1	-	-

Table A-1 continued

TEST	DRYER	RATE (%)	TIME (Hrs.)	EC (KWH)	WT (g) TRAY 1	WT (g) TRAY 2	WT (g) TRAY 3	WT (g) TRAY 4
3	C	75	0.00	0.0	1375.6	1468.8	1414.4	1405.9
3	C	75	2.25	0.8	1206.0	1252.5	1234.7	1203.4
3	C	75	4.50	1.5	1022.2	978.0	1062.0	1030.1
3	C	75	6.50	2.0	901.6	935.2	937.2	893.1
3	C	75	14.00	4.1	543.9	571.4	581.4	562.1
3	C	75	20.83	5.7	351.7	364.8	374.8	358.5
3	C	75	24.92	6.7	270.2	270.4	288.3	271.8
3	C	75	29.08	7.5	-	220.3	-	-
3	C	75	32.42	7.9	210.3	-	228.4	212.1
3	C	75	32.00	8.2	-	-	218.4	-
3	D	0	0.00	0.0	1364.1	1215.8	1421.1	1386.4
3	D	0	2.33	1.6	1142.7	980.9	1216.1	1201.1
3	D	0	4.58	2.9	957.9	837.9	1074.5	1033.1
3	D	0	6.58	4.4	845.9	742.0	939.0	896.7
3	D	0	13.92	9.2	597.3	430.9	556.1	588.4
3	D	0	20.58	13.0	405.2	292.2	357.5	375.8
3	D	0	24.92	15.9	309.4	214.2	286.1	306.5
3	D	0	28.83	17.8	-	180.9	-	-
3	D	0	30.50	18.7	234.6	-	236.7	232.6
3	D	0	33.50	20.2	-	-	217.3	211.4
3	D	0	34.50	20.7	210.8	-	-	-
4	A	50	0.00	0.0	1297.3	1310.8	1032.3	1274.0
4	A	50	2.00	1.0	1131.4	1116.7	856.9	1067.8
4	A	50	4.00	1.7	994.4	967.8	742.8	960.9
4	A	50	8.50	3.7	731.5	729.5	555.1	690.2
4	A	50	16.83	6.5	422.6	434.8	287.7	357.6
4	A	50	22.83	8.7	280.1	302.5	191.1	232.9
4	A	50	26.58	10.0	-	-	150.9	189.8
4	A	50	27.50	10.3	210.5	218.5	-	-

Table A-1 continued

TEST	DRYER	RATE (%)	TIME (Hrs.)	EC (KWH)	WT (g) TRAY 1	WT (g) TRAY 2	WT (g) TRAY 3	WT (g) TRAY 4
4	A	50	28.67	10.8	198.1	200.8	-	-
4	B	75	0.00	0.0	1245.6	1406.9	1162.5	1261.4
4	B	75	2.17	1.0	1062.3	1194.1	997.2	1046.2
4	B	75	4.17	1.5	930.5	1044.9	869.8	936.9
4	B	75	8.33	2.9	698.5	816.2	679.6	714.9
4	B	75	16.83	5.2	386.7	488.5	387.5	361.5
4	B	75	22.92	7.0	251.8	334.4	229.7	250.5
4	B	75	27.58	8.1	190.9	253.4	174.2	190.6
4	B	75	31.83	9.0	-	204.2	-	-
4	C	0	0.00	0.0	1395.4	1247.3	1240.9	1033.7
4	C	0	2.33	1.5	1136.8	1027.6	1028.6	851.6
4	C	0	4.33	2.6	982.0	908.6	899.1	734.2
4	C	0	8.17	5.0	781.7	717.5	671.1	544.6
4	C	0	16.67	10.7	457.4	368.9	351.9	298.5
4	C	0	23.00	14.3	313.3	249.8	207.3	187.8
4	C	0	25.33	15.7	-	-	182.8	-
4	C	0	26.50	16.2	-	-	-	157.3
4	C	0	27.67	17.0	234.7	187.6	-	-
4	C	0	29.50	18.1	211.5	-	-	-
4	D	25	0.00	0.0	1374.9	1334.0	1148.6	1185.2
4	D	25	2.50	1.5	1123.5	1091.3	961.5	998.7
4	D	25	4.50	2.7	944.5	951.2	842.8	843.6
4	D	25	8.00	4.7	748.3	787.1	630.8	615.4
4	D	25	16.58	9.7	448.3	387.9	265.0	325.9
4	D	25	23.17	12.9	289.3	267.0	166.3	200.1
4	D	25	25.50	14.0	-	-	-	186.0
4	D	25	27.83	15.2	218.8	203.2	-	-
4	D	25	28.67	15.7	208.8	-	-	-

- represents missing data

*EC and WT represents Energy Consumption and Weight, respectively.

Table A-2. Time, energy consumption, and total fruit weights for the apple tests.

TEST	DRYER	RATE (%)	TIME (Hrs.)	EC* (KWH)	WT* (g) TRAY 1	WT (g) TRAY 2	WT (g) TRAY 3	WT (g) TRAY 4
1	A	75	0.00	0.0	228.0	240.3	215.7	233.4
1	A	75	1.00	0.3	172.9	166.0	138.3	159.0
1	A	75	2.00	0.6	118.0	106.1	85.3	115.0
1	A	75	4.44	1.1	47.8	46.7	39.4	48.4
1	B	25	0.00	0.0	240.2	244.5	222.2	230.2
1	B	25	1.08	0.7	158.4	150.6	128.4	145.7
1	B	25	2.08	1.3	100.4	94.5	82.8	96.7
1	B	25	4.42	2.1	45.2	47.1	41.8	42.8
1	C	0	0.00	0.0	240.5	243.7	235.0	212.4
1	C	0	1.17	0.6	135.8	156.1	140.1	120.5
1	C	0	2.17	1.1	85.8	102.0	93.5	78.2
1	C	0	4.50	2.7	43.8	48.6	44.8	40.2
1	D	50	0.00	0.0	218.4	249.5	229.9	259.5
1	D	50	1.25	0.5	122.1	134.2	139.8	175.3
1	D	50	2.25	0.8	74.8	89.8	96.6	112.0
1	D	50	4.58	1.7	42.2	48.8	45.4	50.9
2	A	25	0.00	0.0	242.9	239.5	239.1	229.7
2	A	25	1.33	0.8	157.5	149.0	135.3	132.1
2	A	25	2.33	1.2	103.5	95.1	88.0	91.1
2	A	25	3.67	2.0	62.2	58.9	55.2	55.2
2	A	25	4.42	2.2	53.0	51.0	47.1	47.2
2	B	50	0.00	0.0	226.4	227.4	242.7	264.0
2	B	50	1.25	0.7	140.5	128.5	131.5	158.0
2	B	50	2.25	1.0	87.8	77.2	86.1	105.6
2	B	50	3.75	1.6	49.2	46.9	51.3	60.0
2	C	75	0.00	0.0	235.8	255.0	253.6	238.3
2	C	75	1.17	0.5	153.9	171.8	170.4	150.8
2	C	75	2.33	0.9	86.6	101.1	96.7	93.2
2	C	75	4.50	1.4	53.2	64.9	60.2	55.7

Table A-2 continued

TEST	DRYER	RATE (%)	TIME (Hrs.)	EC (KWH)	WT (g) TRAY 1	WT (g) TRAY 2	WT (g) TRAY 3	WT (g) TRAY 4
2	C	75	4.88	1.5	47.8	58.2	55.1	50.4
2	D	0	0.00	0.0	260.3	229.9	248.6	241.7
2	D	0	1.08	0.8	149.0	121.7	152.6	164.3
2	D	0	2.50	1.5	78.2	69.1	95.5	88.5
2	D	0	3.75	2.3	52.9	47.3	55.9	50.5
3	A	0	0.00	0.0	221.0	230.0	211.2	223.2
3	A	0	1.33	0.7	137.0	137.6	114.7	130.5
3	A	0	3.17	1.6	61.8	59.6	53.2	64.9
3	A	0	3.67	2.1	49.1	49.8	43.8	52.7
3	B	75	0.00	0.0	225.6	228.4	228.6	249.0
3	B	75	1.42	0.6	127.4	123.6	114.2	141.4
3	B	75	3.08	1.1	54.1	54.2	53.8	69.4
3	B	75	3.58	1.2	43.9	46.0	44.8	55.7
3	C	50	0.00	0.0	215.5	215.2	216.0	200.7
3	C	50	1.50	0.6	119.6	114.8	119.0	106.5
3	C	50	3.00	1.2	51.8	53.7	53.2	48.5
3	C	50	3.50	1.4	43.1	44.8	43.2	39.3
3	D	25	0.00	0.0	220.7	212.4	217.2	219.6
3	D	25	1.58	1.0	104.4	96.2	116.2	134.3
3	D	25	2.92	1.8	47.1	48.9	62.3	63.4
3	D	25	3.58	2.0	-	-	47.3	47.2
4	A	50	0.00	0.0	253.7	248.6	228.1	254.9
4	A	50	0.83	0.5	182.7	172.0	149.9	171.5
4	A	50	2.58	1.3	80.5	72.0	69.6	89.7
4	A	50	3.50	1.5	51.2	50.0	50.5	59.2
4	A	50	4.00	1.8	-	-	43.8	50.4
4	B	0	0.00	0.0	229.9	214.7	247.1	218.4
4	B	0	0.92	0.4	150.7	129.9	149.1	138.7

Table A-2 continued

TEST	DRYER	RATE (%)	TIME (Hrs.)	EC (KWH)	WT (g) TRAY 1	WT (g) TRAY 2	WT (g) TRAY 3	WT (g) TRAY 4
4	B	0	2.50	1.9	65.5	59.9	80.8	74.4
4	B	0	3.58	2.5	-	-	48.5	42.5
4	B	0	4.00	3.0	42.5	42.5	56.0	49.3
4	C	25	0.00	0.0	246.6	250.1	224.7	253.3
4	C	25	1.00	0.5	160.8	156.1	143.8	147.4
4	C	25	2.42	1.4	77.1	78.6	71.9	72.3
4	C	25	3.67	2.1	45.2	48.1	45.0	45.3
4	D	75	0.00	0.0	247.1	226.0	254.7	224.3
4	D	75	1.08	-	153.2	133.0	168.5	147.8
4	D	75	2.33	1.2	64.6	68.8	94.7	65.9
4	D	75	3.75	1.8	39.4	43.8	50.7	35.3
5	A	0	0.00	0.0	259.1	212.8	212.4	189.7
5	A	0	1.75	1.4	131.5	98.8	98.5	82.9
5	A	0	2.92	2.0	81.2	56.6	61.3	52.8
5	A	0	3.50	2.4	62.2	44.2	49.2	40.5
5	A	0	4.00	2.8	-	54.5	-	42.1
5	B	25	0.00	0.0	210.4	207.5	226.6	182.9
5	B	25	1.83	1.1	91.5	89.3	88.4	79.4
5	B	25	2.83	1.7	53.8	57.4	52.7	38.2
5	B	25	3.58	2.0	40.2	41.3	46.4	37.4
5	C	75	0.00	0.0	229.8	229.8	211.0	183.3
5	C	75	1.92	0.7	108.4	104.1	96.6	80.0
5	C	75	2.75	0.9	70.0	65.6	62.5	52.5
5	C	75	3.58	1.2	50.1	44.9	44.3	38.6
5	D	50	0.00	0.0	229.6	218.8	191.1	189.0
5	D	50	2.00	0.9	87.5	77.4	82.4	88.5
5	D	50	2.67	1.2	55.5	53.6	59.7	57.2
5	D	50	3.67	1.6	38.9	39.3	40.8	36.4

Table A-2 continued

TEST	DRYER	RATE (%)	TIME (Hrs.)	EC (KWH)	WT (g) TRAY 1	WT (g) TRAY 2	WT (g) TRAY 3	WT (g) TRAY 4
6	A	50	0.00	0.0	223.3	224.6	216.5	217.3
6	A	50	0.75	0.5	164.9	159.4	155.1	159.7
6	A	50	2.25	1.0	87.1	74.1	80.0	89.5
6	A	50	3.08	1.5	59.6	53.6	58.6	61.8
6	A	50	4.17	1.9	45.7	43.9	45.3	46.3
6	B	0	0.00	0.0	245.6	261.6	210.2	212.2
6	B	0	0.83	0.7	162.6	178.3	140.1	151.5
6	B	0	2.67	1.8	78.1	90.0	79.4	80.2
6	B	0	3.17	2.1	55.9	68.2	59.0	56.3
6	B	0	4.08	2.5	-	56.6	47.3	45.4
6	C	25	0.00	0.0	219.1	219.6	227.2	220.2
6	C	25	0.92	0.7	141.6	139.7	147.7	142.6
6	C	25	2.42	1.6	67.9	74.4	77.8	74.8
6	C	25	3.25	2.1	48.6	55.2	54.4	53.7
6	C	25	3.83	2.5	-	48.0	48.4	48.5
6	D	75	0.00	0.0	238.7	223.2	220.1	212.4
6	D	75	1.00	0.4	141.1	142.9	145.9	146.7
6	D	75	2.50	1.1	61.5	73.7	79.6	72.6
6	D	75	3.33	1.3	47.1	56.9	54.6	49.4
6	D	75	4.00	1.5	-	49.8	46.3	44.4
7	A	25	0.00	0.0	225.5	221.4	237.8	226.0
7	A	25	1.33	0.7	136.9	127.6	137.1	129.4
7	A	25	3.17	1.5	86.5	78.1	86.2	86.9
7	A	25	3.67	2.0	50.8	50.3	53.5	55.4
7	B	75	0.00	0.0	247.2	215.0	203.8	249.0
7	B	75	1.42	0.4	155.3	119.7	107.6	143.3
7	B	75	3.08	0.9	94.5	68.0	65.7	90.0
7	B	75	3.58	1.2	57.1	44.5	43.5	54.2

Table A-2 continued

TEST	DRYER	RATE (%)	TIME (Hrs.)	EC (KWH)	WT (g) TRAY 1	WT (g) TRAY 2	WT (g) TRAY 3	WT (g) TRAY 4
7	C	50	0.00	0.0	236.3	202.3	216.8	229.7
7	C	50	1.50	0.7	128.3	107.0	120.1	124.8
7	C	50	3.00	1.4	73.7	64.7	72.2	75.7
7	C	50	3.50	1.9	47.8	41.4	45.0	48.4
7	D	0	0.00	0.0	235.7	224.9	195.6	211.8
7	D	0	1.58	0.8	100.7	95.1	90.6	115.2
7	D	0	2.92	1.5	65.6	64.7	63.0	73.3
7	D	0	3.58	2.4	49.3	47.6	40.0	47.8
8	A	75	0.00	0.0	223.9	217.1	225.8	238.0
8	A	75	1.50	0.6	125.1	117.9	113.6	131.6
8	A	75	2.50	0.9	81.2	75.2	80.8	92.1
8	A	75	3.75	1.2	49.0	50.1	57.0	57.9
8	B	50	0.00	0.0	228.2	235.4	219.7	222.0
8	B	50	1.58	0.9	108.3	106.0	93.7	114.1
8	B	50	2.58	1.2	70.7	68.3	66.2	76.7
8	B	50	3.67	1.5	49.1	50.3	49.9	50.3
8	C	0	0.00	0.0	230.2	200.0	230.9	191.4
8	C	0	1.67	1.2	116.1	91.0	111.2	90.3
8	C	0	2.67	1.9	73.6	61.8	75.7	58.6
8	C	0	3.58	2.5	53.4	46.2	53.0	42.9
8	D	25	0.00	0.0	236.1	223.4	230.4	205.1
8	D	25	1.75	-	98.4	88.1	107.4	107.2
8	D	25	2.75	1.8	63.0	58.6	75.7	67.6
8	D	25	3.50	2.2	51.3	48.1	54.5	47.3

- represents missing data

*EC and WT represents Energy Consumption and Weight, respectively.

Table A-3. HunterLab color measurements (L, a, b) for peaches and apples.

FRT*	TEST	DRY	TRAY	RATE (%)	L Rep1	a Rep1	b Rep1	L Rep2	a Rep2	b Rep2
PCH*	1	A	1	0	51.0	9.0	26.6	46.4	9.9	23.9
PCH	1	A	2	0	41.3	12.6	18.8	42.2	10.7	20.8
PCH	1	A	3	0	43.9	11.3	21.7	44.1	12.4	21.6
PCH	1	A	4	0	45.2	10.8	22.9	42.0	12.2	22.1
PCH	1	B	1	25	46.9	9.8	23.5	43.1	11.9	21.5
PCH	1	B	2	25	45.3	11.5	23.6	42.9	12.1	22.7
PCH	1	B	3	25	49.5	9.9	26.0	46.5	10.2	22.6
PCH	1	B	4	25	41.7	11.0	20.6	43.8	11.5	21.9
PCH	1	C	1	50	39.9	12.2	20.6	45.2	9.9	24.1
PCH	1	C	2	50	41.9	12.2	21.0	41.1	11.8	20.6
PCH	1	C	3	50	40.1	12.4	20.1	39.7	12.2	20.2
PCH	1	C	4	50	40.5	12.5	20.5	43.3	11.9	19.5
PCH	1	D	1	75	43.6	11.2	22.1	43.5	10.6	21.6
PCH	1	D	2	75	40.2	12.1	20.1	38.9	12.8	19.4
PCH	1	D	3	75	37.0	11.1	18.2	38.7	12.3	19.2
PCH	1	D	4	75	46.6	9.8	22.6	37.3	11.9	18.1
PCH	4	A	1	50	49.2	11.3	26.1	-	-	-
PCH	4	A	2	50	48.1	12.8	25.7	-	-	-
PCH	4	A	3	50	50.6	13.2	27.8	-	-	-
PCH	4	A	4	50	49.9	12.3	27.3	-	-	-
PCH	4	B	1	75	48.5	11.1	25.9	-	-	-
PCH	4	B	2	75	49.0	10.8	25.9	-	-	-
PCH	4	B	3	75	49.4	10.9	26.7	-	-	-
PCH	4	B	4	75	48.5	11.1	26.2	-	-	-
PCH	4	C	1	0	47.0	11.6	24.4	-	-	-
PCH	4	C	2	0	49.9	12.5	26.4	-	-	-
PCH	4	C	3	0	49.6	13.2	27.1	-	-	-
PCH	4	C	4	0	50.0	12.2	26.8	-	-	-
PCH	4	D	1	25	51.1	11.7	28.1	-	-	-

Table A-3 continued

FRT	TEST	DRY	TRAY	RATE (%)	L Rep1	a Rep1	b Rep1	L Rep2	a Rep2	b Rep2
PCH	4	D	2	25	48.6	12.2	26.1	-	-	-
PCH	4	D	3	25	51.4	11.5	27.2	-	-	-
PCH	4	D	4	25	52.6	10.2	28.2	-	-	-
APL	7	A	1	25	67.3	1.6	25.4	63.0	4.1	25.6
APL	7	A	2	25	66.4	2.3	25.3	66.4	2.5	26.7
APL	7	A	3	25	61.2	4.6	23.5	68.8	1.1	24.9
APL	7	A	4	25	66.8	1.5	25.6	68.9	1.0	26.7
APL	7	B	1	75	66.9	2.4	26.3	61.5	4.6	24.9
APL	7	B	2	75	66.8	2.0	25.0	66.8	1.3	25.9
APL	7	B	3	75	62.2	2.3	24.1	63.4	2.8	24.6
APL	7	B	4	75	64.1	2.3	24.2	65.8	1.9	24.2
APL	7	C	1	50	66.4	1.9	25.2	66.2	2.3	24.1
APL	7	C	2	50	61.4	4.3	24.8	66.1	1.6	26.3
APL	7	C	3	50	59.2	3.4	23.8	64.6	2.2	26.3
APL	7	C	4	50	65.8	2.2	24.8	67.3	1.4	24.6
APL	7	D	1	0	64.1	3.3	23.8	64.0	2.8	23.0
APL	7	D	2	0	62.9	3.1	24.0	63.4	2.7	25.1
APL	7	D	3	0	61.3	3.2	23.8	61.5	3.3	23.4
APL	7	D	4	0	68.2	1.2	27.0	67.0	1.2	26.2
APL	8	A	1	75	63.1	2.8	25.4	61.2	3.6	23.0
APL	8	A	2	75	64.6	3.9	27.4	61.1	3.7	24.0
APL	8	A	3	75	62.2	3.6	24.8	64.8	2.9	24.3
APL	8	A	4	75	65.0	2.5	23.5	64.9	2.6	24.2
APL	8	B	1	50	66.2	1.4	24.7	66.5	1.4	25.3
APL	8	B	2	50	62.5	3.7	23.9	67.7	1.0	25.1
APL	8	B	3	50	67.6	0.8	25.2	66.0	3.1	26.3
APL	8	B	4	50	65.8	2.1	22.2	65.9	2.2	24.1
APL	8	C	1	0	67.6	1.8	25.9	64.9	2.3	23.7
APL	8	C	2	0	64.3	3.3	25.4	64.0	2.6	25.3

Table A-3 continued

FRT	TEST	DRY	TRAY	RATE (%)	L Rep1	a Rep1	b Rep1	L Rep2	a Rep2	b Rep2
APL	8	C	3	0	65.4	2.6	24.3	65.3	1.2	23.5
APL	8	C	4	0	68.0	1.0	25.7	67.1	1.0	24.6
APL	8	D	1	25	64.5	3.4	24.8	64.0	3.8	24.6
APL	8	D	2	25	66.3	1.9	24.9	67.3	1.5	25.1
APL	8	D	3	25	65.9	2.6	26.2	64.9	3.7	25.6
APL	8	D	4	25	65.4	2.5	23.8	67.0	1.5	24.3
PCH	1	A	2	0	44.8	9.5	22.9	47.4	10.7	24.6
PCH	1	B	2	25	49.4	11.3	25.6	47.6	12.2	25.6
PCH	1	C	2	50	45.0	11.1	22.4	45.7	12.3	23.2
PCH	1	D	2	75	44.0	11.0	21.5	47.6	12.7	24.9
PCH	2	A	2	75	44.1	11.1	23.0	45.2	10.9	25.3
PCH	2	B	2	0	43.6	11.9	23.8	47.4	10.1	26.8
PCH	2	C	2	25	48.0	10.0	26.2	46.7	10.5	24.9
PCH	2	D	2	50	46.2	10.9	22.9	47.3	10.9	25.8
PCH	3	A	2	50	47.6	11.7	26.2	45.2	12.0	25.6
PCH	3	B	2	75	45.7	11.8	25.2	45.5	10.9	23.6
PCH	3	C	2	0	44.4	11.6	23.4	47.5	11.3	25.2
PCH	3	D	2	25	45.5	11.7	23.6	46.7	11.3	25.7
PCH	4	A	2	25	49.8	10.4	28.7	49.3	11.9	30.6
PCH	4	B	2	50	45.0	12.4	24.8	50.5	10.5	29.5
PCH	4	C	2	75	48.2	9.8	26.4	48.2	11.9	28.8
PCH	4	D	2	0	47.2	11.2	26.0	50.1	10.5	29.0

- represents missing data

*FRT, PCH and APL represent fruit type, peach, and apple, respectively

Table A-4. Brix sugars and sugar quantities (g/100 g dried fruit) determined by HPLC.

FRT*	TEST	DRY	RATE (%)	FRC* (g/100 g)	GLC* (g/100 g)	SUC* (g/100 g)	TOTAL* (g/100 g)	BRIX (%)
PCH	3	A	25	4.32	3.48	20.00	27.80	75.00
PCH	3	A	25	3.72	3.15	17.23	24.10	76.00
PCH	3	B	50	3.90	3.01	19.55	26.46	77.00
PCH	3	B	50	4.75	3.84	23.29	31.87	77.00
PCH	3	C	75	4.15	3.22	23.48	30.85	77.00
PCH	3	C	75	3.63	2.62	17.06	23.31	76.00
PCH	3	D	0	5.24	3.85	23.35	32.44	76.00
PCH	3	D	0	5.01	3.89	24.53	33.44	77.00
APL	7	A	25	40.48	10.80	16.04	67.32	72.50
APL	7	B	75	37.24	10.51	14.83	62.59	73.75
APL	7	C	50	37.86	12.81	11.08	61.75	81.25
APL	7	D	0	28.95	8.32	10.87	48.14	71.25
APL	8	A	75	32.92	9.60	12.90	55.43	78.75
APL	8	B	50	28.55	8.41	9.18	46.14	71.25
APL	8	C	0	20.75	6.24	7.33	34.32	71.25
APL	8	D	25	30.02	9.62	9.22	48.85	70.00

*FRT indicates fruit type and PCH and APL represent peach and apple, respectively
*FRC, GLC, SUC represent fructose, glucose, and sucrose contents, respectively
*TOTAL represent the sum of the three sugars

Table A-5. Microorganism counts for determining shelf-life over a ten-week period.

FRT*	TEST	DRYER	RATE (%)	WEEK	DIL'N* 0.01	DIL'N 0.001	DIL'N 0.0001	COUNTS (CFU/g)
PCH	2	A	75	0	213	0	250	21,300
PCH	2	B	0	0	78	0	0	7,800
PCH	2	C	25	0	117	17	1	11,700
PCH	2	D	50	0	182	21	5	18,200
PCH	2	A	75	2	7	2	2	650
PCH	2	B	0	2	5	2	0	500
PCH	2	C	25	2	2	1	0	200
PCH	2	D	50	2	2	2	1	150
PCH	2	A	75	10	0	0	0	<100 est.
PCH	2	B	0	10	1	1	0	100
PCH	2	C	25	10	1	2	0	100
PCH	2	D	50	10	0	0	0	<100 est.
APL	5	A	0	0	19	4	1	1,900
APL	5	B	25	0	83	10	1	8,250
APL	5	C	75	0	9	1	8	900
APL	5	D	50	0	12	2	1	1,150
APL	5	A	0	2	7	0	0	700
APL	5	B	25	2	9	5	0	900
APL	5	C	75	2	5	1	4	500
APL	5	D	50	2	3	1	119	300
APL	5	A	0	10	0	0	0	<100 est.
APL	5	B	25	10	2	0	0	200
APL	5	C	75	10	1	0	0	100
APL	5	D	50	10	1	1	0	100

*FRT indicates fruit type and PCH and APL represent peach and apple, respectively
* DIL'N represents the plate dilution of microorganisms
* <100 est. represents an estimation based on the absence of visible colonies

APPENDIX B

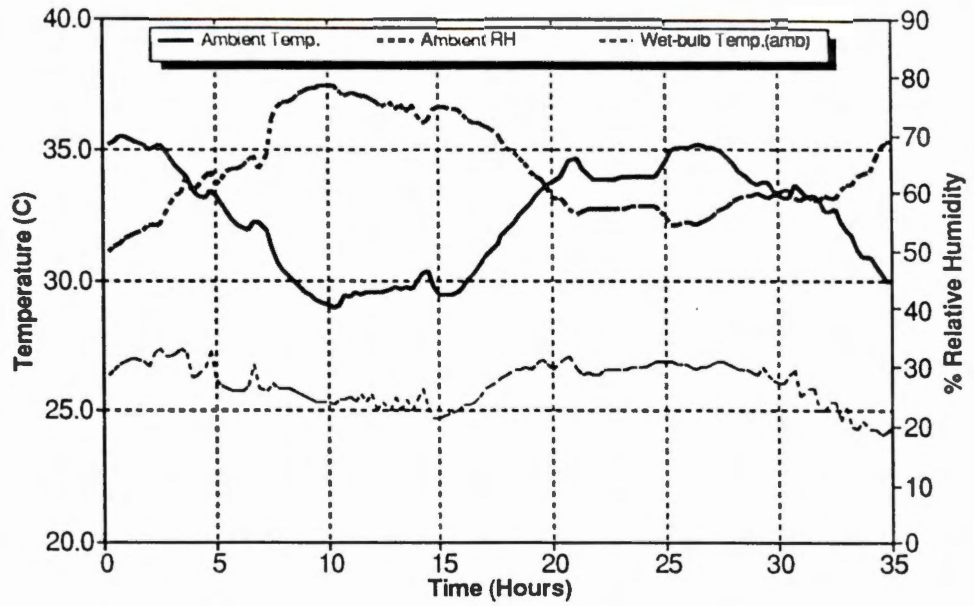

Figure B-1. Ambient conditions during Test 3 for peaches.

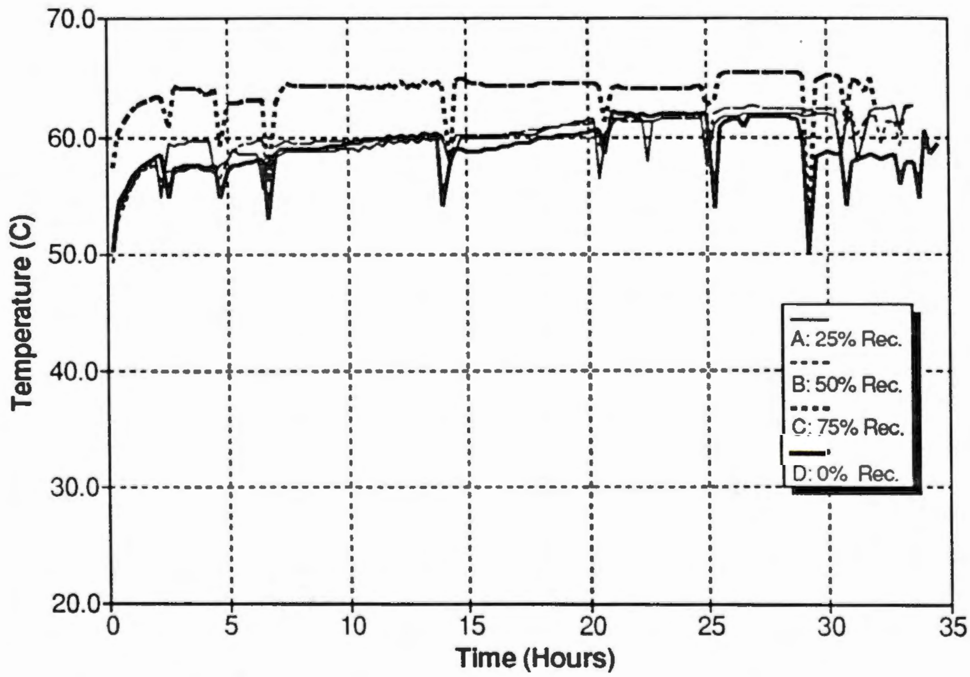

Figure B-2. Temperatures taken at the dryer exits (peach test 3).

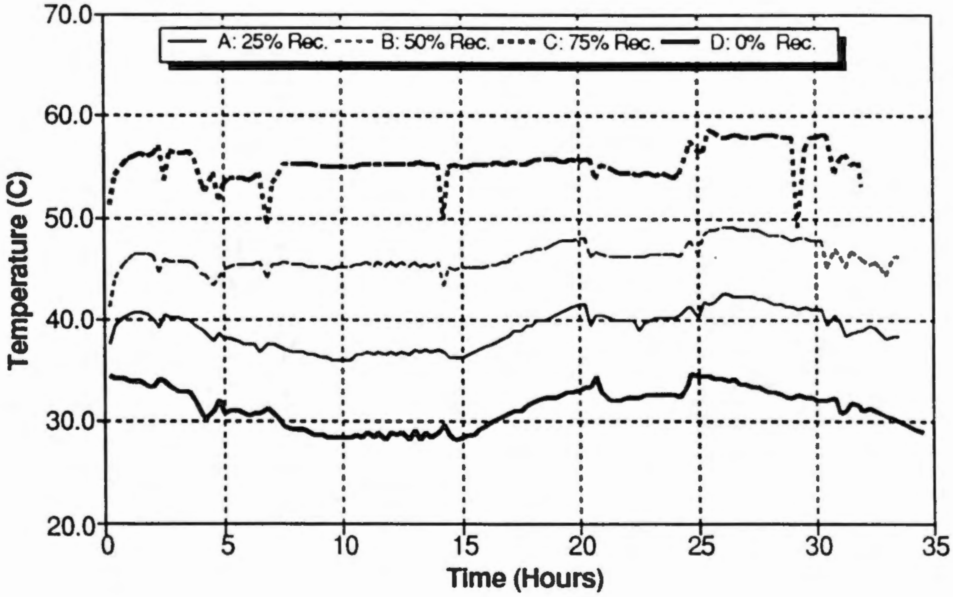

Figure B-3. Temperatures taken within the recirculation ducts (peach test 3).

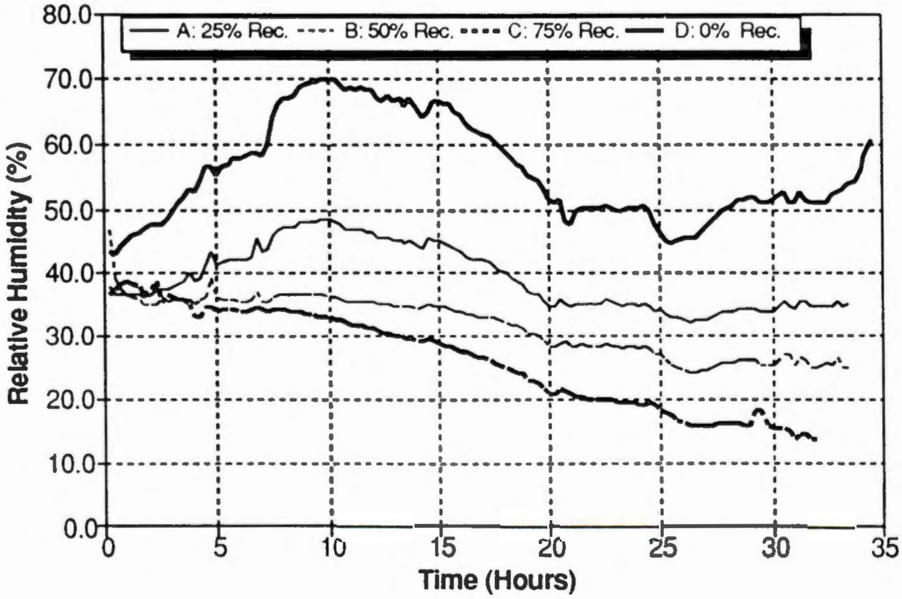

Figure B-4. Relative humidities taken within the recirculation ducts (peach test 3).

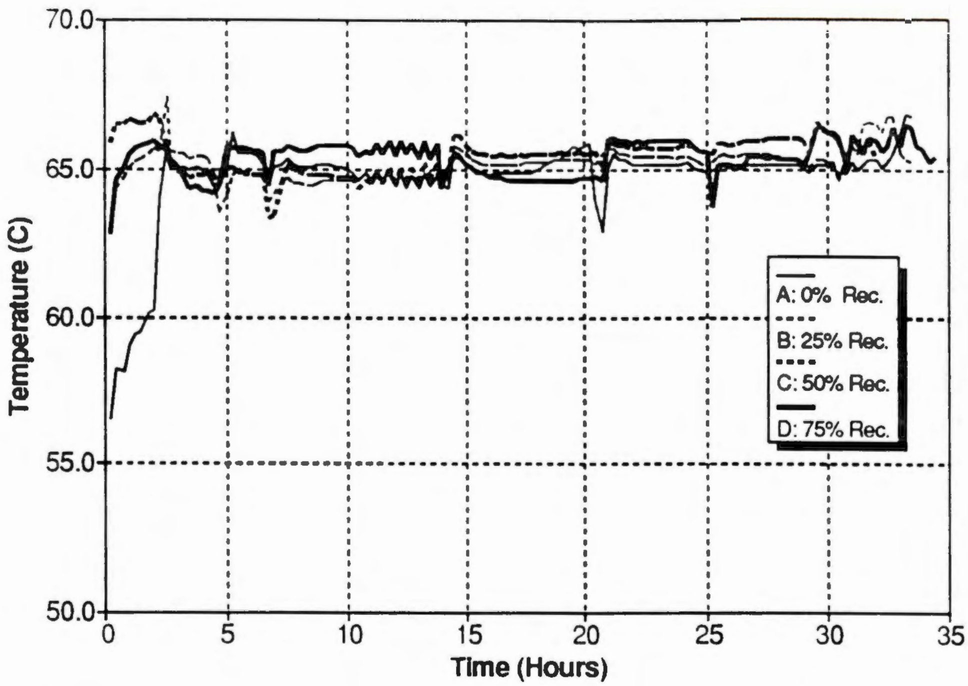

Figure B-5. Temperatures taken at the dryer inlets (peach test 3).

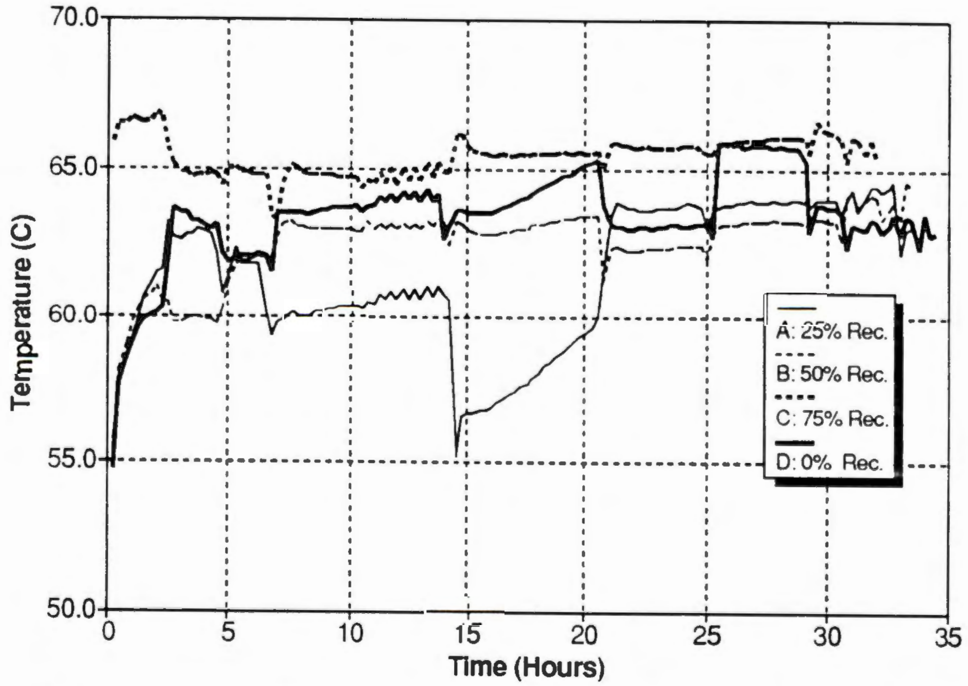

Figure B-6. Temperatures taken near the center of each dryer (peach test 3).

VITA

Terry Hill Walker was born in Marion, Virginia, on March 19, 1966. He graduated from Marion Senior High School in 1984. He attended The University of Tennessee, Knoxville, and received a Bachelor of Science degree in Engineering Science and Mechanics in December, 1989. He accepted a research assistantship with The University of Tennessee Agricultural Engineering Department and completed the requirements for a Master of Science degree in Agricultural Engineering in December, 1992.

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