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APPLICATION OF MICROWAVE VACUUM AND LIQUID MEDIA DEHYDRATION FOR THE PRODUCTION OF DRIED GRAPES

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APPLICATION OF MICROWAVE VACUUM AND LIQUID MEDIA DEHYDRATION FOR THE PRODUCTION OF DRIED GRAPES

By

Carter DeFriest Clary

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ABSTRACT

APPLICATION OF MICROWAVE VACUUM AND LIQUID MEDIA DEHYDRATION FOR THE PRODUCTION OF DRIED GRAPES

By

Carter DeFriest Clary

Use of microwave heating in a vacuum environment exhibits potential for dehydration of grapes and other food products. This process removes water from grapes rapidly, and preserves most of the fresh character of the product including color, shape, and flavors without the use of preservatives. The research described in this dissertation includes evaluation of microwave vacuum dehydration, liquid media dehydration, and defines the relationships of time, energy input, pressure, and other factors on the final moisture content and character of seedless grapes. The results of the research indicate that these dehydration methods offer distinct possibilities for dehydration of grapes, and other food products.

Grapes were successfully dehydrated using microwave energy in a vacuum to produce a puffed, crispy grape. Dried puffed grapes were also produced using the liquid media dehydration system. This product was similar to the grapes processed in the microwave system, except they had a slight oil residue and a caramelized flavor. Golden raisins were produced using the liquid media dehydration system. This product exhibited a wrinkled raisined character, and a yellow-golden color without the use of sulfites. The

combination liquid media and microwave vacuum dehydration system performed successfully in producing puffed grapes in a continuous process.

DEDICATION

This dissertation is dedicated to my wife, Susan Elizabeth Clary. During my course of study at Michigan State University, Susan stayed home in Fresno for more than a year, holding a full-time job, and taking care of three small children. When the course work was completed, I thought that the difficult part was over. Then came the tasks of conducting the experiments, and writing the thesis. During this time, Susan endured in helping to fulfill the long term goal of completing this project, even at times when I was short sighted and focused. I thank you, Susan, for supporting me in accomplishing this goal.

I also dedicate this dissertation to my parents, Mr. and Mrs. Everett B. Clary, who supported the costs of my course work at Michigan State University, and encouraged me to complete this project.

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I express my sincere gratitude to Dr. Vincent E. Petrucci for being my mentor in the profession of research and development.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1. BACKGROUND

1.1.1. History.

Dehydration offers a means for preserving foods in a stable and safe condition, and provides extended shelf life. Historically, dried venison and other meats served as a protein source among early cultures, and dehydration of fruits and vegetables augmented this supply (Salaman, 1940; Brothwell and Brothwell, 1969). Dehydration of fruits including dates, figs, apricots and grapes was practiced long before recorded history. The commercial preservation of fruits and vegetables by sun drying is common today.

Many food commodities mature and dehydrate naturally including grains, seeds of legumes, and nuts (Decareau, 1985). Fruits do not dehydrate naturally and specific practices are required to preserve them after the harvest (Ede and Hales, 1948). One option is sun drying the fruit to produce a stable and natural source of sugars. The low moisture content of the sun dried fruit together with high levels of sugars tend to inhibit attack of pathogens.

1.1.2. Heated Air Dehydration of Fruits.

Heated air dehydration of fruits provides an alternative to losses due to inclement weather during the sun drying season. Dryers consist of heated air tunnels for fruits, including plums and grapes into prunes and raisins. Drum and spray dryers are used to dry a wide array of prepared foods including cereals, dried mixes, and powdered products such as dried milk and eggs. Although dehydration was used extensively during World War II, dehydration technology continues to develop as the array of prepared food products continues to expand (Van Arsdel et al., 1973).

Heated air is used in the dehydration of about 30 percent of dried fruits, especially when color preservation is required and sulfites are used (Nury et al., 1973). This departure from sun drying was most likely brought about by difficulties due to inclement weather (Eissen and Muhlbauer, 1983). Removal of water is accomplished by inducing water in the product to vaporize by creating a vapor pressure gradient between the fruit and the surrounding environment. The primary factors that affect the vapor pressure gradient include the amount of water in the product (moisture content), temperature, pressure, moisture in the drying environment (humidity), and the composition of the product. In the early stage of dehydration, the vapor pressure gradient between fresh fruit and the drying environment is high, and the drying characteristics of fruit is similar to pure water. Since the water is part of a complex matrix of

sugar and other constituents, the rate of transfer to the drying environment slows as the fruit dries (Van Arsdel et al., 1973).

Heated air dehydration uses forced air, heated by a burner fueled by natural gas. The heated air transfers heat to the product, increasing the vapor pressure gradient between the product and the surrounding environment. Heating air lowers its vapor pressure, helping it to carry water vapor away from the product. Whole and cut produce are transported through the heated airstream using trays, conveyers, augers, or drums.

The temperature used in heated air dehydration is limited due to the susceptibility of the product to damage by heat. Although air temperature is elevated above the temperature at which a product will burn, the moisture in the produce vaporizes, keeping it cool. In the early stages of dehydration when product moisture content is high, it releases water vapor readily and at a constant rate. As the moisture content decreases, the vapor pressure gradient lessens and the rate of moisture loss decreases. Dehydration ends when the vapor pressure of the product equalizes with that of the surrounding environment. Attempts to further reduce moisture content, or shorten drying time by elevating temperature, results in overheating the product.

1.1.3. Low Pressure Dehydration.

Van Arsdel et al. (1973) explained that reduction in ambient pressure lowers the vapor pressure of the drying environment and induces water to leave the food product more rapidly. Vacuum dryers consist of evacuated chambers that contain steam heat exchangers to heat and dehydrate slurries and concentrates. Water vapor is removed from the drying environment by the vacuum pumping system.

Freeze drying uses chilled air with vacuum systems to induce very low pressure to reduce the vapor pressure in the drying environment to remove water from a food product by direct sublimation (King, 1973). The absence of heat contributes to obtaining very low levels of final moisture content, and the dried product maintains shape, color, flavor, and nutritional value.

1.1.4. Microwave Vacuum Dehydration.

Microwave processes are classified into six major categories including tempering, blanching, pasteurization, sterilization, cooking, and dehydration. With the exception of dehydration, the purpose of these microwave processes is to raise the temperature of the product to initiate a compositional change, such as enzyme deactivation. Microwaves for dehydration heats the product to cause water to vaporize, without causing undesirable change. Microwave energy penetrates deeply into food products and can reduce process time by 90 percent (Decareau and Peterson, 1986). It offers opportunity to process foods in ways not possible

by conventional means. Microwave heating alone offers distinct benefits in dehydration because of the penetration of energy and uniform heating resulting in water vaporizing from throughout the product. Some applications have combined microwave heating with conventional air heating for dehydration (Shivhare et al., 1991).

Application of microwave energy results in an increase in product temperature. However, if microwave energy is applied in a vacuum, the temperature rise is limited to the boiling point of the water at the lowered pressure. Since water boils at 22 °C at a pressure of 3 kPa, the product temperature would be limited to that temperature during dehydration. The potential benefits of microwave vacuum dehydration include rapid dehydration using reduced temperature to preserve color, flavor, and nutritional value. The uniform heating of microwaves induces an inner pressure that maintains shape of the dried product.

Microwave vacuum dehydration was first used for concentration of citrus juice in France (Decareau, 1985). Microwave vacuum drying of agricultural commodities has included grain (McKinney et al., 1977) and rice (Wear, 1982). This technology was adapted to grapes by McKinney et al. (1983) for production of Grape Puffs$_{tm}$ using zoned microwave vacuum dehydration patented by McKinney and Wear (1987) and described by Petrucci and Clary (1989).

1.2. INDUSTRY SECTOR ANALYSIS OF PRESERVED FRUITS AND VEGETABLES

The United States of America (USA) is a world leader in fruit and vegetable production. These commodities are produced for consumption as fresh and preserved products. The Bureau of Census separates these preserved commodities by end use into five categories including canned specialties, canned fruits and vegetables, frozen specialties, frozen fruits and vegetables, and dehydrated fruits and vegetables (Table 1.1) (Bureau of Census, 1987).

Dehydrated fruits and vegetables represent an important segment of the food industry amounting to almost $2 billion in shipments in 1989 (Bureau of Census, 1987). This segment does not include low moisture products such as breakfast cereals and fried products such as potato chips. Census of Manufactures shows that there were 131 establishments dehydrating fruits and vegetables in 1987, employing over 10,000 workers. While the number of establishments in other segments of the preserved fruit and vegetable industries decreased in the 1988 census (Bureau of Census, 1990-91), dehydrating establishments increased both nationally (131 to 133), and in California (65 to 71). This growth in the dehydration capacity resulted in $49 million in new capital investment. Product value added by the dehydration industry amounted to close to $1 billion nationally in 1987, resulting in a shipped products value of over $1.8 billion. These data show that the fruit and vegetable dehydration

Table 1.1

Preserved Fruits and Vegetables Industry
Number of Establishments and Employees
(Bureau of Census, 1989)

Industry Segment	Establishments		Employees	
	U.S.	California	U.S.	California
Canned Specialties	211	38	24,500	>2,500
Canned Fruit/Vegetable	647	124	65,600	19,100
Dehydrated	*131*	*65*	*10,100*	*6,000*
Frozen Fruit/Vegetable	258	52	49,800	9,700
Frozen Specialties	285	39	37,500	>2,500
TOTAL	1,532	318	187,500	22,610

Value Added Processing and Value of Shipped Products

Industry Segment	Value Added ($M)		Products ($M)	
	U.S.	California	U.S.	California
Canned Specialties	2,652	NA*	5,350	NA
Canned Fruit/Vegetable	5,440	1,823	11,889	3,609
Dehydrated	*932*	*515*	*1,819*	*1,121*
Frozen Fruit/Vegetable	2,986	435	6,606	920
Frozen Specialties	2,803	NA	5,617	NA
TOTAL	14,815		31,282	

*NA = Data Not Available

segment of the food industry is strong, stable, and expanding.

California produces most of the dried fruit in the USA (Greensmith, 1971). These commodities include apples, apricots, figs, peaches, pears, plums, and grapes. Production of prunes and raisins account for over 80 percent of the crop volume (White, 1973). Dehydration of grapes into raisins amounted to 317,515 metric tons in 1992. The following discussion will focus on grape dehydration.

1.3. GRAPES FOR RAISIN PRODUCTION

1.3.1. Classification of Grapes (*Vitis*).

Of the 60 known species of *Vitis*, the species *Vitis vinifera* accounts for more than 90 percent of the world grape production (Winkler et al., 1974). In some cases, this species has been hybridized with American species. Crosses between *Vitis vinifera* and *Vitis labrusca* account for 42 percent of the hybrids. In the U.S., 90 percent of the production is from *vinifera* varieties.

The commercial uses of grapes consist of wine, fresh market table grapes, grapes for raisins, juice, and canning grapes. Grape production is limited primarily to the temperate zones of the world (Winkler et al., 1974). The quality of grapes is based on berry composition including sugar, acid, and pH, although many other quality factors have been described as important. Wine grape production in the USA is based on the climate of the production regions to

select cultivars best suited for the region. Winkler et al. (1974) describe in detail climatic regions for production of wine grapes and the effect of climate and cultural practices on berry and juice composition and wine quality.

Besides sugar and acid content, table grape quality is based on appearance, size, and color of the fruit, and requires intensive viticultural practices including application of growth hormones, girdling, trellising and canopy management, and berry thinning by hand. Seedless character is also viewed as a quality factor in the consumer acceptance of table grapes. Raisin grape quality is based mostly on seedlessness and berry sugar content since most of the water is removed during drying.

Grape production in California accounted for about 90 percent of production in the USA, amounting to 257,275 ha (635,738 acres) in production in 1991 (CCLRS, 1992). By classification, wine grapes accounted for 46.3 percent of the state production area. The land planted to raisin grapes and table grapes was 41.8 and 11.9 percent of the total, respectively. In the Central Valley of California, including Fresno, Kern, Kings, and Madera counties, 143,220 ha (353,902 acres) are producing grapes for all uses. Statewide production of raisin, wine, and table grapes is shown in Table 1.2.

1.3.2. Raisin Grape Production.

Raisins are classified into nine types by the Raisin Administrative Committee (1992) based on method of production and/or grape cultivar. Natural Seedless, Dipped Seedless, Oleate Seedless, and Golden Seedless raisins are produced from the grape cultivar Thompson Seedless and dried in distinctly different ways. The remainder of the raisin types refer specifically by the grape cultivar from which they are made, e.g., Muscat, Monukka.

Raisins are produced within a 160 km (100 mile) radius of the city of Fresno. The compactness of this production area is due to a relatively rain free harvest and drying season which is unique to only a few regions in the world. Since 92 percent of the crop is sun dried in the field, harvest without rain is essential for a quality raisin crop. The fresh fruit is hand harvested, placed on paper drying trays in the vineyard row, and left in the sun to dry. Depending on the weather, drying time ranges from 14 to 21 days. The dried raisins are collected from the field, stored, and processed into the final raisin product. Of all raisins produced, 98 percent of raisins are produced from Thompson Seedless grapes (Table 1.3).

During sun drying, solar radiation heats the grapes causing an increase in the vapor pressure gradient between

Table 1.2

Bearing Hectares and Fresh Grape Production
by Classification - 1991
(CCLRS, 1991)

Type	Hectares	Metric Tons
Wine	132,197	1,991,271
Table	33,709	562,455
Raisin	110,712	1,964,055
Total	257,275	4,517,780

Table 1.3

Combined Tonnage of Raisins for Domestic and Foreign Use
By Type 1987 - 1991
(California RAC Bulletin, 1992)

Raisin Type	1987-88	88-89	89-90	90-91	91-92
			Metric Tons (t)		
Thompson Seedless					
Natural	268,487	283,741	277,869	287,137	280,431
Dipped	7,999	9,398	10,235	9,637	9,346
Oleate	2,522	230	81	0	0
Golden	15,460	14,657	14,970	14,966	15,351
Zante Currants	2,776	3,213	3,376	3,085	3,158
Sultanas	151	117	146	99	129
Muscats	249	279	179	171	163
Monukkas	1,366	799	731	931	937
Other Seedless	0	849	2,259	820	2,150
Total	299,010	313,283	309,845	316,846	311,666

the fruit (78% IMC*) and the drying environment. Relative humidity in the vineyard is below 20 percent during a period of peak daytime air temperature as high as 40° C (105 °F). Due to the direct exposure of the fruit to the sun, the temperature of the grapes rises to as much as 57 °C. The water leaves the fruit tissue near the surface of the berry first, causing this region to dry more quickly and the berry tissue to collapse on itself. The exposure of the grapes to heat also induces compositional changes to the grapes. Oxidation including polyphenol oxidase activity causes a change in color from a light green to a dark purple-black color (Singleton et al., 1985).

1.4. HEATED AIR DEHYDRATION OF FRUITS AND VEGETABLES

1.4.1. Background.

Grapes, plums, and apples make up the bulk of the fruits dried in the USA. The entire plum crop is dried in tunnel dehydrators for the production of prunes. Gas fired, forced air dehydrators were introduced as a substitute for sun drying and first described by Cruess and Christie (1921). Today, 15 percent of the California raisin grape crop is dried in gas fired, forced air dehydrators. Design of tunnel dehydrators and many operational practices are based on research conducted in the 1930's and have not changed except for the use of more automated equipment.

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*IMC = Initial Moisture Content

Tunnel dehydration of grapes is used for production of golden seedless and dipped seedless raisins. The golden seedless raisin product is bright yellow, resembling the color of grapes from which they were made. The dipped raisin is brown with a candy-like flavor.

1.4.2. Factors Affecting Drying Whole Fruits.

Practical considerations in production of high quality dehydrated fruit include choice of fruit, dipping, sorting, traying, sulfuring, and drying (Nichols and Christie, 1930).

Harvesting and Handling. The use of high quality fresh fruit for drying contributes significantly to dried product quality since reduction in moisture content during dehydration concentrates the composition of fruits (Salunkhe et al., undated). Quality factors include fresh fruit sugar content, appearance, color, and flavors. Unlike quality requirements for fruit harvested for the fresh market, early harvest in anticipation of shipping long distances and maximizing shelf life are not factors in raisin production. However, the ripe stage of the fruit dictates that damage be minimized during harvest, handling, and preparation of the fruit for dehydration.

Sugar content is the most important factor in the quality of dried grapes (Nichols and Christie, 1930; Jacob, 1944; Baranek et al., 1970; Christensen, 1985; Kasimatis et al., 1977). Low sugar content at harvest results in a

greater dry ratio* and lower quality dried fruit. Grapes harvested with a soluble solids content of 20 percent will exhibit a dry ratio of about 4.5 kg of fresh fruit to 1 kg dried product.

Fruit sugar content is an important consideration when deciding yield at pruning. Since most of the water in the fruit will be removed during dehydration, production of fruit for dehydration requires the yield of sugar per hectare be optimized instead of total fresh tons per hectare.

Fruit Pretreatments. Whole fruits are inherently difficult to dry due to the fruit epidermis that retards moisture transfer. Cutting fruits such as apricots and apples exposes the inner tissue directly to the drying environment, facilitating transfer of moisture.

Grapes for tunnel dehydration undergo pretreatment to break down the impervious nature of the skin. Pretreating grapes includes dipping in a hot water bath for 5 to 10 seconds. This sudden exposure to heat causes some epidermal cells to rupture and the development of hairline cracks or "checks" in the fruit skin. During the dehydration process, moisture escapes from the fruit tissue through the cracks, thus reducing drying time. Depending on harvest sugar content, dipping the fruit results in drying times of 13.5

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*Dry ratio = kg fresh fruit required to produce 1 kg of dried fruit.

to 19.0 hours. Untreated fruit requires 19.5 to 31.5 hours to dry (Nichols and Christie, 1930).

The water dipping treatment consists of either water heated to 99 °C, or water containing 0.25% sodium hydroxide heated to 82 °C. Actual temperature and concentration of sodium hydroxide varies depending on the source and maturity of the fruit. As a rule, 6 to 12 gm of sodium hydroxide per L of water will usually provide good results. Ideal dipping checks the skin of the grape with many short, fine, and shallow cracks. Dipping that is severe enough to produce long, deep cracks may peel some berries, resulting in loss of juice and yield, sticky fruit, and difficulty in handling. The general flow plan for pretreating fresh fruit for dehydration is shown in Figure 1.1.

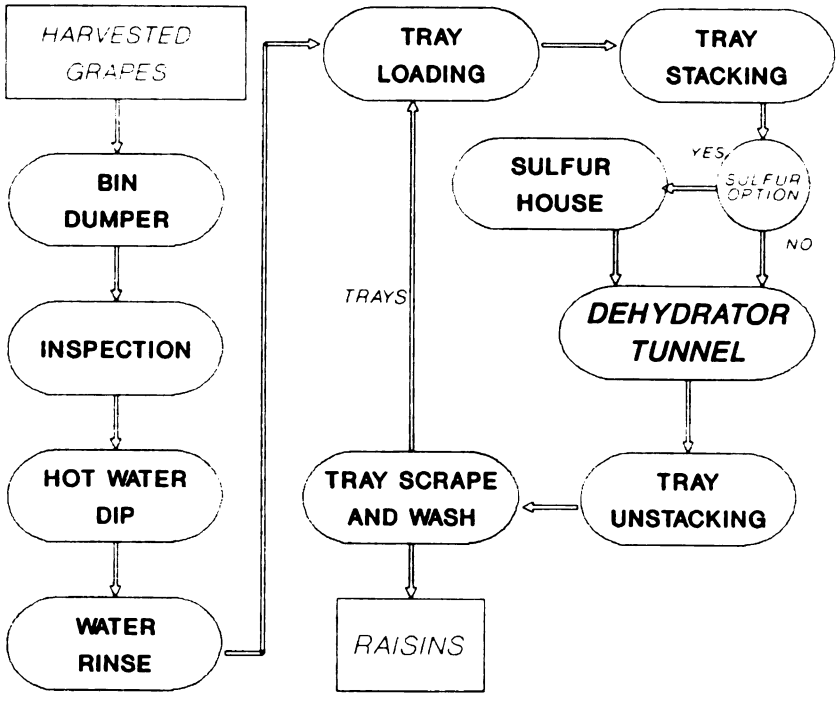

Figure 1.1. Flow Chart of Preprocessing of Grapes for Dehydration. (Ponting and McBean, 1970).

Ethyl- and methyl-esters of fatty acids are used as a pretreatment for grapes in Australia (Grncarevic, 1963; Ponting and McBean, 1970). Use of these compounds originated in traditional Greek and Turkish raisin production, and consisted of dipping grapes in a suspension of potash and olive oil in water, followed by drying on racks. Refined methyl oleate and potassium carbonate mixed in water serves as a detergent to dissolve the hydrophobic platelets on the epidermis of the fruit. This permits more rapid moisture transfer from the fruit tissue to the surrounding atmosphere. This chemical pretreatment is not as effective in reducing drying time compared to dipping in heated water, but has proven effective in reducing drying time of sundried raisins from 14 to 7 days (Petrucci et al., 1983). Use of esters of fatty acids reduced drying time of grapes in a solar dryer (60 °C air at 30 m/min) from 50 to 25 hours (Eissen and Muhlbauer, 1983), and has been used with other waxy fruits including cherries, blueberries, and prunes (Ponting and McBean, 1970).

Dried Grape Character. The exposure of grapes to heat and atmospheric oxygen during the drying process results in changes in flavor, color, shape, and nutritional value. The raisin product maintains little resemblance to the grapes from which it is made (Singleton et al., 1985). Grapes used in production of golden seedless raisins are treated with sulfur dioxide to preserve original colors. Sulfur dioxide is applied in an airtight enclosure at a liquid rate of 2 to

4 kg per metric ton of fresh fruit (4 - 8 lb/fresh ton). A sulfur concentration of about 2000 ppm in the raisin is needed to preserve color for one year. Alternatives to sulfur dioxide to preserve original color are limited. Some researchers have evaluated citric acid, however results have been negative (Salunkhe et al., undated).

Configuration. A number of types of dryer configurations are available for dehydration of food products including crossflow-tunnel, cabinet, continuous belt, through-flow, drum, and spray dryers. Grapes are high in sugar content and therefore difficult to transport on belts or through drum type dryers. The most common method for drying grapes employs a tunnel dehydrator consisting of a long enclosure filled with dehydrator cars loaded with stacks of wood trays covered with fruit (Figure 1.2).

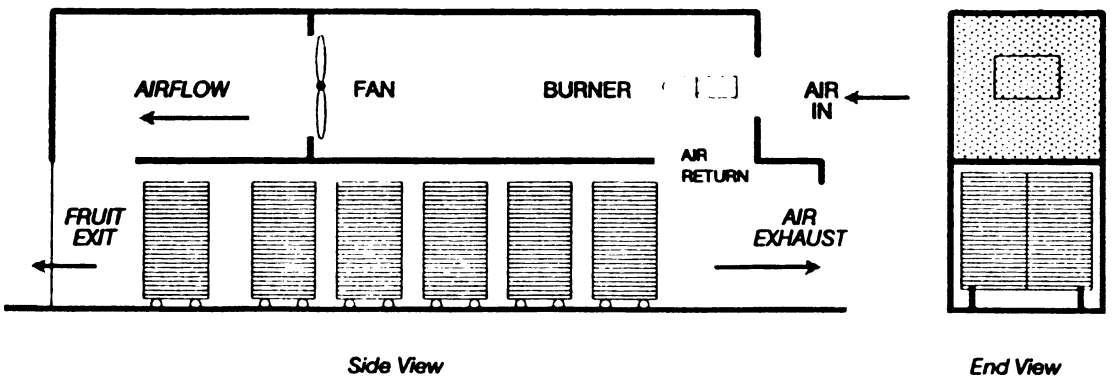

Figure 1.2. Counterflow Raisin Drying Tunnel.

A dehydrator tunnel consists of the drying tunnel and the plenum chamber. Air is drawn past the burner and into the plenum by a fan. The heated air passes from the plenum chamber to the "hot end" of the tunnel, passing through the dehydrator trays and exhausted at the "cool end" of the tunnel. A portion of the exhaust air is recirculated through the return air to save energy. Each tunnel holds 18 to 24 dehydrator cars, each car carrying twenty four 90 x 180 cm (3 x 6 ft) wood trays, each tray loaded with about 27 kg of fresh fruit. The process consists of loading trays with grapes and stacking the trays on dehydrator cars. The cars are moved at intervals into one end of the tunnel. When a car of dried fruit is removed from the other end of the tunnel, the string of cars is advanced one position.

Dehydrator cars carrying fresh fruit loaded into the cool end of the tunnel comprises a counterflow drying regime, and dehydrator cars loaded into the hot end of the tunnel results in concurrent or parallel-flow. Prunes and other larger fruits are usually dried using concurrent flow. However, grapes are dried using the counterflow regime because of the difficulty of attaining an acceptably low final moisture content. The driest fruit is exposed to the highest temperature.

Continuous conveyer dryers are used extensively in drying food products. This type of dryer consists of an endless belt that carries the product through a tunnel and has the advantage of essentially automatic operation that

minimizes labor requirements. Initial equipment cost is higher than tunnels and cannot be justified in seasonal fruit drying operations.

Air Flow. Dehydrators move a high volume of air across the drying fruit to remove water vapor. Grapes and prunes contain 70 to 80 percent water and therefore release a substantial amount of water vapor during the initial stages of dehydration. A dehydrator holding nine metric tons of prunes with a dry ratio of 2.5 to 1 will require removal of over 5,400 kg (12,000 lb) of water in the 24-hour period, or over 3.7 kg per min (Cruess and Christie, 1921).

A heated air flow of about 500 to 600 m^3 per minute results in a drying time of 18 to 24 hours for grapes (Cruess and Christie, 1921). Nichols and Christie (1930) define air velocities of 638 and 804 m^3 per minute (22,532 and 28,392 ft^3/min), respectively for prunes and grapes, and research conducted by Thompson et al. (1981) indicates that prune dehydrators operate at 82 °C using an air velocity of 73 m^3/min (2575 ft^3/min).

Dehydrator Air Temperature and Humidity. Air temperature should not exceed 74 °C (165 °F) for drying prunes and grapes (Nichols and Christie, 1930; Eissen and Muhlbauer, 1983). Research suggests that the level of relative humidity in the exhaust air of a counterflow tunnel should be between 35-40% (Nichols and Christie, 1930; Eissen and Muhlbauer, 1983). Some research has shown that relative humidity of exhaust air could approach 60% although the wet

bulb temperature should not exceed 50 °C (Thompson et al., 1981).

1.4.3. Dehydrator Energy Use and Losses.

Evaluation of an existing prune dehydrator showed the main areas of heat loss are in the exhaust air, burner inefficiency, and air leaks (Thompson et al., 1981). Distribution of heat energy in a dehydrator is shown in Table 1.4. Survey information (Clary and Moso, 1983) indicates an energy usage range of 24.9 to 64.2 GJ/t and 151 to 433 kW·h/t to dehydrate grapes into raisins (241 to 552 therms and 137 to 393 kW·h per dry ton). Based on an electric rate of $0.135 per kW·h, and a gas rate of $0.565 per therm, this amounts to about $0.079 per kg of water removed ($0.036/lb water) from grapes, or about $0.365 per kg of dried product.

Table 1.4

Energy Budget of a Concrete, Concurrent Flow Tunnel Dehydrator for Prunes (Thompson et al., 1981)

Thermal Energy Loss/Utilization	Percent of Total Thermal Energy Input
Moisture Evaporation	58
Exhaust Air	16
Burner and other losses	12
Air Leaks (door, fan belt opening)	8
Walls and Ceiling	3
Fruit and Trays	3

1.5. CONSUMER INTEREST IN GRAPE DEHYDRATION METHODS

Raisins occupy a major segment in the marketing of agricultural products and create a substantial demand for grapes grown in the San Joaquin Valley of California. Any new use of processed grapes offers potential to introduce this commodity as a processed food product and offers stability to the market by broadening the need for grapes. As indicated earlier in this section, the dehydration industry has exhibited significant new capital investment activity. This activity may be targeted toward consumer concern in the ingredients used in food products and emphasis on using natural ingredients.

Traditional methods of fruit and vegetable dehydration often require use of sulfites to preserve color. Until recently, the use of sulfites was expanding into other fresh fruit and vegetable applications. In 1981, restaurant salads were implicated in causing sulfite-induced adverse reactions among consumers (Taylor, 1993; Sapers, 1993). Although sulfites continue to be used in production of golden seedless raisins, the incidents of allergic-type reactions prompted review by regulatory agencies and may have affected public opinion related to the use of sulfites as preservatives in food products. These concerns and new regulations have fostered an interest in the identification of alternatives to eliminate or reduce the use of sulfites in food products.

1.6. GOALS

The goal of this dissertation was to evaluate two methods of dehydration for grapes. The experiments focused on producing a dried grape product that retained fresh fruit character including color, flavor, and shape without the use of preservatives.

In the sections that follow, two methods of dehydration are described: microwave vacuum dehydration and liquid media dehydration. Experimental methods and results are reported. Each method of dehydration was evaluated for performance in effectively reducing the moisture content of grapes and preserving color, flavor, and shape. Analysis of the results of experiments using each dehydration method correlated process variables with the characteristics of the dried grape to optimize dehydration without damage to the dried grape product.

Sections 2 and 3 describe laboratory microwave vacuum dehydration and liquid media experiments, respectively. In Section 4, experiments focused on integrating the two methods of dehydration into a continuous process to produce dried grapes that maintain color, flavor, and shape without the use of preservatives. The process parameters were based on the results of experiments described in Sections 2 and 3.

2. MICROWAVE VACUUM DEHYDRATION OF GRAPES

2.1. INTRODUCTION

2.1.1. History of the Development of Microwaves.

Although its development originated from the basic theories of electricity, magnetism, and radio waves, the refinement of microwave technology has been a recent event (Decareau, 1985). Applications initially focused on using microwave transmissions for communication (Cockburn, 1958). The literature describes applications to communication, radar, diathermy, atomic resonance, and ultimately microwave heating (Cockburn, 1958; Decareau, 1985; Decareau and Peterson, 1986; Thuery, 1991). A brief outline of the events leading to use of microwaves for heating applications is shown in Table 2.1.

In the 1930's, the underlying physics of microwaves was understood, and the pulsed output magnetron and the waveguide provided the tools for radar applications. The term radar (**RA**dio **D**etection **A**nd **R**anging) was originated by two U.S. Navy officers, Furth and Tucker, in 1934 (Page, 1962). World War II fostered immediate demand for pulsed microwave technology and promoted joint research efforts between universities and companies in England and the USA. Because of these research efforts, a British prototype was

Table 2.1

Events Leading to Advancement of Microwave Heating Technology (Knutson et al., 1987)

Year	Event
1921	Magnetron developed by Albert Wallace Hull.
1940	Continuous wave magnetron built.
1945	Dr. Percy Spencer built the first microwave oven from a farmer's milk can and obtained a patent.
1946	Raytheon Co. announced the first Radarange in the trade literature.
1950's	In the U.S. the Raytheon Co. concentrated its research on using 2,450 MHz.
1952	Spencer obtains microwave conveyer dryer patent.
1955	Raytheon Co. introduced the first domestic microwave oven.
1962	Cryodry introduces first industrial conveyer dryers.
1964	Oven prices ranged from $1500 to $2500.
1968	Japanese magnetron development reduced cost of magnetrons.
1970's	"Radiation Control for Health and Safety Act" became effective.
1973-4	Amana (a subsidiary of Raytheon Co.) and Litton spent $5 million to advertise microwave ovens.
1984	Microwave ovens accounted for the largest annual shipment of any home appliance in history, at 9.1 million units.

brought to Bell Laboratories in 1940, and Raytheon Company began production of magnetron tubes.

By the end of the war, the highest pulsed energy output possible was 1 MW on the S band (1,550 - 5,200 MHz) and 250 kW on the X-band (5,200 - 10,900 MHz). One of the two frequencies presently allocated in the United States for microwave heating includes the S-band frequency of 2,450 MHz. Band designations are defined in Appendix 7.1. Although energy output from these early magnetrons was high, the signal was produced in pulses of short duration for use in radar applications.

Following World War II, microwave technology continued to develop into precision applications including radar, communication, nuclear physics, radio astronomy, radio-frequency spectroscopy, frequency standards based on atomic resonance, and any other applications where high resolution was required.

While developing microwave technology for radar, the heating properties of microwaves were apparent. W.C. Brown and P. Derby of Raytheon created the first continuous wave output microwave generator which produced 100 W at 3 GHz in 1943-1944 (U.S. Patent 2,463,524) (Thuery, 1991). The first production model of a microwave oven was marketed by Raytheon as the "Radarange" in 1946, and patented in 1951 by Percy L. Spencer (Cockburn, 1958; Decareau and Peterson, 1986). Although these early microwave heating units showed potential, their applications remained limited to laboratory

and food service use due to a cost of $2,500 per kW of microwave output and technical problems related to control and temperature over-run. It was not until the 1960's that a practical continuous system was devised (Decareau, 1985). By 1970, the potential of microwaves as a heat source was shown by the successful market penetration of the microwave oven. Microwave ovens are now standard household appliances with an estimated 92 percent of U.S. homes having at least one (Baum, 1992).

It was not until 1962 that efforts to develop multi-kilowatt continuous output microwave generators for commercial applications proved successful. Cryodry Corporation of San Ramon, California introduced the first continuous process microwave heating system (Decareau and Peterson, 1986). Applications of the Cryodry units included cooking chicken, pasteurization, thawing, and baking (Jeppson, 1964).

Cryodry Corporation completed 24 industrial microwave drying systems for drying of potato chips. Other potato chip finishing systems were built by a British firm using a folded waveguide design. Seven systems were installed in the USA, all operating at 915 MHz. Raytheon and Litton Industries each installed at least one potato chip processing system during the 1960's. In 1969, microwave food processing in the USA included potato chip finish dryers using a total of 1,060 kW, poultry cooking using 130 kW, and bacon precooking using 60 kW (Decareau, 1985).

Although industrial microwave heating seemed to exhibit clear benefits in food processing, by 1973 only a few installations remained in operation (O'Meara, 1973).

Failure was based on use of microwave technology in uneconomical applications. Other applications, such as blanching vegetables, were technically feasible but influenced by the seasonal nature of the processing and the high capital investment for microwaves. In other cases, development of the microwave technology to address a particular problem came at a time when resources for investment in the technology were not available.

Decareau and Peterson (1986) described commercial applications through 1978 including 122 major installations using a total of 5.1 MW. The majority of these installations were dedicated to tempering frozen foods. By 1986, the applications of industrial microwave technology included tempering, pasta drying, cooking bacon, and other applications amounting to a total of 254 commercial and seven research installations in the USA (Table 2.2). Over 100 U.S. patents have been issued covering 27 food processes ranging from baking and blanching to tempering and vacuum drying (Gerling, 1986). Activities throughout the world in the 1980's seemed to demonstrate that there was a commitment to microwave process development.

The total microwave energy increased to 9.5 MW in 1984 for use in food processing (Smith, 1984). More recent estimates of microwave application show a substantial

Table 2.2

Microwave Food Processing Applications - 1986
(Decareau and Peterson, 1986)

Process	Installation Type	Installation No.	Products
Tempering	I	200	Meat, fish, butter, berries
Cooking	I	16	Bacon, meat patties,potatoes
Drying	I	30	Pasta, onions, rice cakes, seaweed, snack foods, egg
Vacuum Drying	P/I	5	Citrus juices, grains, seeds
Freeze Drying	P	2	Meat, vegetables, fruits
Pasteurization	I	3	Bread, yogurt
Sterilization	P	2	Milk, prepared foods
Baking	P		Bread, doughnuts
Roasting	P	2	Nuts, coffee beans, cocoa, beans
Blanching	P		Corn, potatoes, fruit
Rendering	P	1	Lard, tallow

P = Pilot plant operation
I = Industrial operation

reduction from 9.5 MW in 1984 to 756 kW total microwave energy in 1989 (Sanio and Michelussi, 1989), and 400 kW in 1992 (Geise, 1992). A cost analysis of selected microwave systems was described by Sanio and Schmidt (1989).

As an example of the risks of developing new microwave technology, research indicated that dark spots in potato chips during frying was caused by high sugar content because of potato storage conditions. Microwave heating showed promise in finish drying of potato chips to minimize the caramelization of the sugars and resultant discoloration of the chips. However, by the time commercial scale microwave finish dryers were operational, potato storage practices had been improved, and the existing frying process modified so that the problem had been eliminated (O'Meara, 1973).

Numerous applications that met the test of technical and economical feasibility were never successful because other problems persisted including contractual issues, lack of experience of the engineers involved on both sides, and failure to prepare production personnel for operation of a microwave system (Gerling, 1986). Although microwaves offered significant opportunity in industrial applications, microwave equipment was expensive compared to conventional systems heated by natural gas, and the electric power to operate microwave systems was more expensive than fossil fuels. During the 1970's, these economic factors were often overlooked in a race to gain a foothold in what was viewed as an emerging market. The result was failure, and

microwave technology gained the reputation of being unfeasible in industrial applications. The economics of new applications is now examined in more detail by companies interested in using microwave heating. For success, use of microwave technology must exhibit a commanding economic advantage over existing equipment (Smith, 1984).

2.1.2. Principles of Microwave Heating.

Heating Principle. Microwaves consist of electromagnetic waves between radio and infrared waves on the electromagnetic spectrum (300 MHz to 300 GHz). A description of the electromagnetic spectrum is provided in Appendix 7.1. These waves radiate from a source and can be transmitted, reflected, or absorbed. Microwaves for heating applications are generated using a magnetron tube consisting of a cavity, anode, and antenna that emits a high-frequency radiant energy signal. This signal has centers of positive and negative charge that change direction billions of times per second depending on the frequency used (Mudgett et al., 1980; Decareau, 1985; Thuery, 1990).

When a microwave signal is directed toward a food product, it is absorbed and produces heat. The two mechanisms of microwave heating in dielectric liquids and solids are ionic polarization and dipole rotation. Ionic polarization occurs when ions in solution move in response to an electric field. Accelerated by the electric field, the ions collide with other ions, converting kinetic energy

into heat. More concentrated solutions exhibit greater frequency of collisions, and more heat is released.

Dipole rotation is a more significant factor than polarization in heating food products. Water is a polar molecule in most foods. Under normal conditions, polar molecules are randomly oriented. In an electric field, the polar molecules align with the field. An alternating field causes the changes in polarity at a rate corresponding to changes in the field, and the molecules attempt to match the alternating field. Heat is generated because of the rotation of the molecules. When the field is removed, the molecules return to random orientation. The alternating field introduced by microwaves oscillates at a rate sufficient to cause release of kinetic energy and heat.

The physical state of the material contributes to its heating characteristics. Ice absorbs microwaves poorly because movement of water molecules is restricted. The molecules tend to align more rapidly within a microwave field as the temperature of a product increases.

The behavior of water was predicted by the Debye equations for pure polar solvents as functions of wavelength (or frequency) and temperature, and was described by Decareau (1985) and Decareau and Peterson (1986). The interaction of an electromagnetic field with the chemical constituents of foods leads to instantaneous heat generation due to "molecular friction". The result is disruption of weak hydrogen bonds associated with the dipole rotation of

free water molecules and the electrophoretic migration of free salts in an electrical field of rapidly changing polarity.

Most components of food, other than water and ash contents, are transparent to microwaves. Nevertheless, the extent to which the water molecules are bound by other chemical constituents in the food product will tend to affect the level of response of the water molecules and therefore reduce the dielectric properties of the water.

Decareau (1985) discussed the effects of microwaves on pure water, aqueous ionic solutions, non-interactive and interactive mixtures, liquid and solid foods, and frozen foods. In brief, the dielectric properties of foods are related to their chemical composition, physical structure, and are highly frequency and temperature dependent. Other factors include the impedance of the product relative to the free space. This relationship affects levels of energy transmission and reflection at the product surfaces. An attenuation factor also determines levels of energy absorption within the product as a function of depth from the surface.

Microwave Frequencies. In the USA, the FCC restricts microwave frequencies for heating to 915 and 2,450 MHz because of their proximity to radio wave and radar frequencies. At 915 MHz, microwaves penetrate materials up to 30 cm, and at 2,450 MHz penetration is 10 cm. Use of microwaves for heating outside the USA is allocated to 6

additional frequencies ranging from 433.05 MHz to 246 GHz (Thuery, 1991).

Heat Distribution. Heat distribution is an important factor in uniformity of heating and/or overheating. Three-dimensional finite element models were used to predict temperature and moisture distribution in agar gel and potato "slabs" (Zhou et al. 1992). Larger cylindrical pieces exhibit internal overheating due to the inability of the heat to transfer to the surface and radiate away from the piece.

Microwave Safety Considerations. The safety of microwaves is a persistent consideration (Geise, 1992). Safety concerns have been suggested to have contributed to the slow acceptance of microwave energy in food processing (Schiffmann, 1979 and 1992). Although an athermal effect of microwaves has been suggested, the sole result of microwave interactions in foods is their heating effect. Public Law 90-602 enacted in 1968 established emission standards for home microwave ovens of 1 mW/cm^2 before sale and 5 mW/cm^2 during the lifetime of use. The measurement is made 5 cm from the surface of the device. Although general guidelines and limits of microwave leakage were established in 1973, standards were not set for industrial applications.

Some therapeutic treatment of ailments is based on microwave energy (Decareau, 1985). The conclusion is that to be injured by microwave energy, a person would have to make a dedicated effort to be exposed to such conditions.

The individual will sense the heating effect of the microwave energy in the same way one senses the radiant heat of an open flame or other radiant source. However, it has been shown that microwaves can cause the formation of cataracts on the lens in the eyes of laboratory animals exposed to a level of 80 mW/cm^2 at 5 cm from the source for 1 hour daily for 10 consecutive days.

The limit of whole body exposure to microwaves was established at 10 mW/cm^2 in the early 1950's, since exposure to ten times that intensity caused a slight fever. This has since been adopted by the ANSI (C95.1). As a comparison, the heat applied to the body when sunbathing is about 60 to 100 mW/cm^2 (Decareau, 1985).

Dehydration using microwaves in a vacuum offers the potential of uniform, low temperature heating to increase the dehydration rate. The microwave provides the energy to uniformly vaporize water from grapes rapidly, and the vacuum provides a low vapor pressure environment to maintain a vapor pressure deficit. The dehydration of water helps to maintain low product temperature. These conditions maintain a moisture gradient sufficient to reduce moisture content to less than 5% in a relatively short time compared to heated air dehydration without causing burning of the dried grape product.

2.2. OBJECTIVES

A laboratory batch microwave vacuum unit was used to define levels of microwave power, time of exposure, and resulting product temperature for the dehydration of grapes. The goal was to learn how to produce a dried grape product that exhibited fresh product character including color, shape, and flavor without the use of preservatives. The results of these experiments were used to determine the operating parameters of a larger continuous microwave vacuum dehydration system.

The objectives of the laboratory experiments included:

a. Determine the relationship of microwave energy and time to the final moisture content of dehydrated grapes.

b. Define levels of specific energy that effectively dehydrated grapes yet maintained their integrity, shape, and color.

2.3. DESCRIPTION OF THE LABORATORY BATCH MICROWAVE VACUUM UNIT

The laboratory microwave vacuum unit used for the dehydration experiments consisted of a microwave power supply and magnetron, wave guide, window, microwave control, vacuum vessel equipped with a turn table, vacuum pump and vacuum control, and system controls and instrumentation (Figures 2.1 and 2.2).

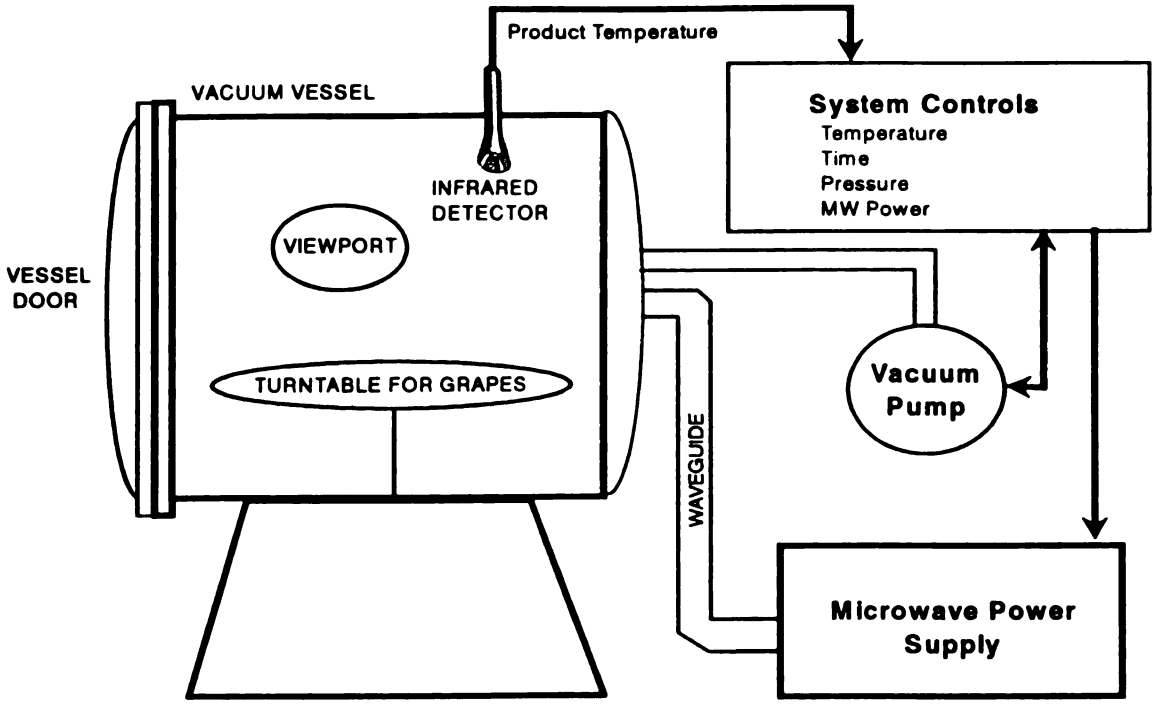

Figure 2.1. Schematic Diagram of the Laboratory Microwave Vacuum Dehydration System.

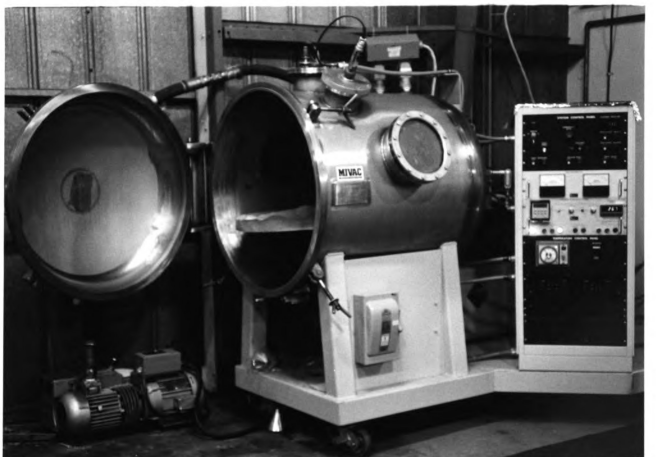

Figure 2.2. Laboratory Microwave Vacuum Dehydration System.

The Gerling Laboratories* power supply system (Model GL103A) used a three-phase 480 V ac service rated at 14.4 MJ (4 kW·h). It supplied medium ripple microwave power at 2,450 MHz and a maximum output of 10.8 MJ (3 kW·h). The power transformers used three-phase wye-connected and delta-connected secondaries to produce a continuous medium ripple waveform. These secondaries were independently rectified and the dc outputs combined in series to give a 12 phase output ripple waveform. This design produced a peak-to-peak ripple of about 5 percent with a minimum of filter components (Gerling, 1991).

The output of the microwave power source was adjusted by modulating the current in the electromagnet surrounding the magnetron and controlling the level of the magnetic field in the magnetron interaction space. If the field was sufficiently high, no electrons would cross the interaction space, resulting in zero output. A reference signal from the magnetron was used to control the magnetic coil. This ensured smooth output without waveform distortion at output levels from zero to full power. The level of microwave power applied to the grapes was displayed by the forward power meter on the system console as power in Watts.

The waveguide assembly included a water cooled circulator (ferrite isolator) to absorb reflected power,

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*Trade names are used in this dissertation solely to provide specific information. Mention of a product name does not constitute an endorsement of the product by the author to the exclusion of other products not mentioned.

forward and reflected power detectors, and a waveguide that routed the microwave power to the vacuum vessel. The waveguide served as a conduit to channel the microwave power into the vacuum vessel. The last section of waveguide included a tuner to scatter the microwave signal within the vacuum vessel. At the vessel vacuum boundary, the microwaves passed through a Teflon window. This prevented the vessel from losing vacuum, pressurizing through the waveguide.

The stainless steel vacuum vessel was about 90 cm in diameter and 120 cm long. One end of the vessel was fitted with a flange and a door. The other end was sealed with a port adapted for the waveguide and vacuum penetrations. Two Plexiglas windows were mounted axially on opposite sides of the vessel to provide light and a view into the vessel. The windows were fitted with screens to prevent microwave emission. Other ports on the vessel provided access for sensors and instrumentation. A turntable (80 cm in diameter) was supported by a vertical shaft that protruded through a seal in the bottom of the vessel. This shaft was attached to an electric gear motor operating at about 5 to 10 rpm. The turntable was used to improve distribution of microwave power to the grapes.

The vacuum pump was attached to the vacuum port of the vessel through two motorized valves plumbed in parallel, connected to a Busch high speed vane vacuum pump (Model R5S 100-132). The vacuum pump maintained the vessel pressure

between 2.7 and 4.0 kPa (20 - 30 Torr) and served to remove water vapor and other gases from the vessel. The absolute pressure was measured using a Schaevitz pressure transducer (Model P3061-15).

The system controls included the Gerling microwave control system and interlocks, an infrared detector for monitoring grape temperature in the vessel, a timer, a pressure sensor, and vacuum control. Vessel pressure was controlled by setting motorized valves to maintain the desired pressure.

Temperature measurement in the microwave environment required a method of measurement that was transparent to microwave power. Thermocouples and thermistors overheated, and glass bulb thermometers ruptured when exposed to microwaves. In these experiments, grape surface temperature was determined by a Mikron infrared temperature detector (Model H-L10000-0300FAU000) with an operating range of -18 to 150 °C (0 to 300 °F). The lens of the detector was shrouded with a 2.5 cm diameter tube extending about 15 cm into the drying cavity to protect the lens and instrumentation from microwave exposure.

2.4. MATERIALS AND METHODS

2.4.1. Microwave Power and Time.

The treatment variables were microwave power level, time of exposure, and the temperature of the grape sample. The total amount of energy applied to the grapes in an

experiment was defined as specific energy expressed as W-h/g fresh grapes. During each test, the power level and the time the power was applied to the grapes was recorded. The intent was to apply a specified amount of power over a desired time that amounted to the treatment level of specific energy.

The total specific energy necessary to dehydrate grape samples to a final moisture content (FMC) of less than 5 percent was estimated by calculations shown in Appendix 7.2. The calculation of total specific energy provided a starting point for establishing power treatment levels.

The total specific energy required to dry the grapes to 5 percent final moisture content was calculated to be 1.39 W-h/g of fresh grapes. This was based on an initial moisture content of 78 percent, a specific heat of the dry matter of 0.40, latent heat of vaporization of 2258 kJ/kg (1100 Btu/lb) of water removed, and a microwave coupling efficiency factor of 0.40.

Two sets of fixed microwave application experiments and three sets of staged microwave application experiments were completed using Thompson Seedless grapes. The range of treatments and a list of measurements for the experiments are shown in Table 2.3. The treatments for each set was replicated three times.

2.4.2. Methodology.

In all experiments, fresh Thompson Seedless grapes were removed from the rachis (cluster stem), a sub-sample of

Table 2.3

Summary of Microwave Energy Treatment Ranges and Independent and Dependent Variables for Experiment Sets 1 - 6

Experiment Sets 1 and 2				
Test#	Microwave Power (W)	Process Time (min)	Independent Variables	Dependent Variables
1	500	30	Microwave Power	Final Moisture
2	500	60	Process Time	Description:
3	500	90	Specific Energy	Color
4	750	30	Initial Sugar	Shape
5	750	60	Initial Moisture	Texture
6	750	90	Temperature	
7	1000	30		
8	1000	60		
9	1000	90		
10	1250	30		
11	1250	60		
12	1250	90		
13	1500	30		
14	1500	60		
15	1500	90		

Table 2.3 (cont.)

Experiment Set 3 - Staged Microwave Power Applications

Test#	Stage 1 Time at 3000W	Stage 2 Time at 1500W	Stage 3 Time at 500W	Specific Energy W-h/g	Independent Variables	Dependent Variables
1	5	90	10	1.42	-Microwave Power	-Final Moisture
2	10	80	10	1.42	-Process Time	-Description:
3	20	60	10	1.42	-Specific Energy	Color
4	30	40	10	1.42	-Initial Sugar	Shape
5	40	20	10	1.42	-Initial Moisture	Texture
					-Temperature	% Puffed

Experiment Set 4 - Staged Microwave Power Applications

Test#	Stage 1 Time at 3000W	Stage 2 Time at 1500W	Stage 3 Time at 500W	Specific Energy W-h/g	Independent Variables	Dependent Variables
1	5	20	110	1.06	-Microwave Power	-Final Moisture
2	10	30	80	1.06	-Process Time	-Description:
3	10	40	50	1.06	-Specific Energy	Color
4	20	10	80	1.06	-Initial Sugar	Shape
5	20	20	50	1.06	-Initial Moisture	Texture
6	10	30	20	1.06	-Temperature	% Puffed

Table 2.3 (cont.)

Experiment Set 5 - Staged Microwave Power Applications

Test#	Stage 1 Time at 3000W	Stage 2 Time at 1500W	Stage 3 Time at 500W	Specific Energy W-h/g	Independent Variables	Dependent Variables
1	5	20	80	0.78	-Microwave Power	-Final Moisture
2	5	30	80	0.93	-Process Time	-Description:
3	5	40	60	0.96	-Specific Energy	Color
4	10	20	80	0.92	-Initial Sugar	Shape
5	10	30	30	0.83	-Initial Moisture	Texture
6	15	25	25	0.90	-Temperature	% Puffed
7	15	30	30	0.94		
8	20	10	5	0.71		

Experiment Set 6 - Microwave Power Applications Based on Temperature

Test#	Microwave Power (W)	Temperature (°C)	Independent Variables	Dependent Variables
1	3000 W until	54	-Microwave Power	-Final Moisture
2	Treatment	60	-Specific Energy	-Process Time
3	Temperature is	66	-Initial Sugar	-Description:
4	reached, then 1500	71	-Initial Moisture	Color
5	and 500 W.	77	-Temperature	Shape
				Texture
				% Puffed

berries was collected randomly for determination of sugar content by refractometer and initial moisture content determined by vacuum oven (AOAC, 1980). The sample of single grapes was weighed and placed on the turntable of the batch unit. The samples consisted of 150 to 200 grapes weighing 907 g in experiment sets 1 and 2, and 300 to 400 grapes weighing 1814 g in experiment sets 3 through 6. The vessel door was closed and evacuated, and the microwave was power applied based on the treatment plan.

A vessel pressure of 2.7 kPa (20 Torr) was used in all the experiments, based on minimizing product temperature and maintaining the stability of the microwave field in the vessel. Using lower levels of vessel pressure increased the potential for the occurrence of ionization of the water vapor in the microwave energy field. The grape sample exhibited higher temperature if a pressure higher than 2.7 kPa was used. Free water boils at about 20 °C at this pressure (Appendix 7.4).

The grape sample was monitored visually for condition. Time, temperature, pressure, and forward and reflected power levels were recorded at regular intervals. The test was stopped when visual evidence of burning occurred. The specific energy was calculated using the actual time of microwave power application. At the conclusion of each experiment, the grape sample was weighed, condition noted, and a sample collected for final moisture content by vacuum oven.

In experiment sets 1 through 4, final moisture content was determined using the whole dried sample. In experiment 5, the dried grape sample was separated into categories of puffed, chewy, and burned to further refine the prediction model. Each category was weighed and the final moisture content determined. A weighted average final moisture content for the treatment was determined based on the weight and final moisture content of the categories. Puffed grapes were defined as those exhibiting the spherical shape of the fresh grapes and a crunchy dry texture. Chewy grapes were usually collapsed and soft in texture. Burned grapes exhibited browning, caramelization, and a hard texture.

Specific energy, time, initial sugar, initial moisture content, and grape temperature were evaluated using multiple linear regression analysis to develop a model for predicting final moisture content. In experiment 5, dried grape texture was coded and included in the analysis. Regression analysis also provided a decomposition of the regression sum of squares value for each independent variable. Regression surface plots were used to describe the interaction of two independent variables on final moisture content. Minitab (version. 5.1.1) and PlotIt (version. 3.0) software programs were used for these analyses.

2.4.3. Fixed Microwave Energy Application Experiment Sets 1 and 2.

The treatments in experiment sets 1 and 2 consisted of single levels of power application for a designated

treatment time (Table 2.4). Treatment levels of fixed microwave energy ranged from 0.28 to 2.48 W-h/g of fresh grapes, with 1.39 W-h/g of fresh grapes as the approximate theoretical midpoint. The treatment combinations amounted to 15 power tests each replicated 3 times. The quantity of grapes used was based on the capability of the microwave power supply to deliver the required levels of specific energy. A sample of 907 g was used in each treatment within each experiment set.

Based on the results of experiment set 1, the experiment was repeated in experiment set 2 to refine theexperimental design and analysis. Although the treatments in experiment sets 1 and 2 were the same, the experiment sets were completed at separate times using different samples of table grapes. Even though the sugar content and initial moisture content were similar, the results of the experiment sets were analyzed separately and are discussed in Section 2.5.2.

2.4.4. Staged Microwave Energy Application Experiment Sets 3, 4, and 5.

Staged microwave energy treatments were intended to expose the grapes to higher levels of power during initial stages of dehydration. Lower levels of power were applied as the fruit moisture content decreased.

In experiment set 3, the cumulative specific energy of the staged microwave treatments ranged from 1.42 to 1.56 W-h/g of fresh grapes (Table 2.5). The microwave power

Table 2.4

Treatments for Correlation of Specific Energy and Final Moisture Content in the Microwave Vacuum Laboratory System

Fixed Power Application Tests
Sample Weight: 900 g
Vessel Pressure: 2.7 kPa

Experiments 1 and 2
Thompson Seedless Table Grapes

Fixed Forward Power (W)		Exposure Time (min) 30	60	90
		Calculated Specific Energy (W-h/g fresh grapes)		
Low	500	0.28	0.55	0.83
Med/Low	750	0.41	0.83	1.24
Medium	1000	0.55	1.10	1.65
Med/High	1250	0.69	1.38	2.07
High	1500	0.83	1.65	2.48

Table 2.5

Treatments for Determination of Power-Time Regime in the Laboratory Microwave Vacuum System - Summary of Staged Energy Application Treatments

Sample Weight: 1.8 kg
Vessel Pressure: 2.7 kPa

Experiment Set 3
Thompson Seedless Table Grapes

Forward Power (W)				Specific Energy Treatments			
3000	1500	500		Stage I	II	III	Total
Time (min)			Total	W-h/g fresh grapes			
5	90	10	105	0.14	1.24	0.05	1.42
10	80	10	100	0.28	1.10	0.05	1.42
20	60	10	90	0.41	0.69	0.32	1.42
30	40	10	80	0.69	0.83	0.05	1.56
40	20	10	70	0.96	0.41	0.05	1.42

treatments were applied in three stages. The exposure times for each power treatment in the initial tests were estimated (± 5 min), but were selected in a fairly broad range to define the limits of these factors with respect to final product characteristics (Table 2.5). Therefore, they served as a basis for developing the prediction model and determining optimum power and exposure times to produce an acceptable dried grape sample.

A 1.8 kg sample was used in this experiment set. Each treatment was stopped after a specific time, or if there was visual evidence of burning. The actual time was noted and the grapes were removed from the vessel. As in earlier tests, if the treatment time was not reached in any stage, the actual time was used for calculation of the specific energy. These treatments were not replicated.

The results of experiment set 3 served as a basis for refining the time and microwave energy combinations for experiment sets 4 and 5. In experiment set 4, total specific energy was 1.06 W-h/g (Table 2.6). Experiment set 4 was not replicated.

Experiment set 5 consisted of eight specific energy treatments ranging from 0.71 to 0.96 W-h/g (Table 2.6). Each treatment was replicated three times.

2.4.5. Temperature Based Staged Microwave Experiment Set 6.

Experiments were conducted to determine the optimum temperature the grape sample would withstand if the

Table 2.6

Treatments for Determination of Energy-Time Regime in the Laboratory Microwave Vacuum System - Summary of Staged Power Application Treatments

Sample Weight: 1.8 kg
Vessel Pressure: 4 kPa

Experiment Set 4
Thompson Seedless Table Grapes

Forward Power (W)			Specific Energy Treatments			
3000	1500	500	Stage I	II	III	Total
Time (min)		Total	W-h/g fresh grapes			
5	20	110	140	0.28	0.28	0.51	1.06
10	30	80	120	0.28	0.41	0.37	1.06
10	40	50	100	0.28	0.55	0.23	1.06
20	10	80	110	0.55	0.14	0.37	1.06
20	20	50	90	0.55	0.28	0.23	1.06
10	30	20	70	0.55	0.41	0.09	1.06

Experiment Set 5
Natural Thompson Seedless Grapes

Forward Power (W)			Specific Energy Treatments			
3000	1500	500	Stage I	II	III	Total
Time (min)		Total	W-h/g fresh grapes			
5	20	80	105	0.14	0.28	0.37	0.78
5	30	80	115	0.14	0.41	0.37	0.93
5	40	60	105	0.14	0.55	0.28	0.96
10	20	80	110	0.28	0.28	0.37	0.92
10	30	30	70	0.28	0.41	0.14	0.83
15	25	25	70	0.41	0.34	0.14	0.90
15	30	30	70	0.41	0.41	0.12	0.94
20	10	5	35	0.55	0.14	0.02	0.71

microwave power was adjusted to limit the grape sample temperature to a specified level. Five temperature levels from 54 to 77 °C (130 - 170 °F) were selected.

The same methodology was used as in earlier experiments, except that adjustments in microwave power were based on grape temperature instead of time. A sample weighing 1.8 kg was used. In each temperature treatment, the microwave system was operated continuously at 3000 W until the grape sample temperature approached the treatment temperature. The power level was subsequently decreased to 1500 W continuous power until grape sample temperature started to approach the treatment temperature. Microwave power was reduced again to 200 to 500 W of continuous power until the grape sample temperature increased beyond the specified treatment level. If the temperature started to decrease, microwave power was increased. Each temperature treatment was replicated three times.

The dried grape samples were removed from the vessel, weighed, and separated into categories of puffed and crispy, soft and chewy, and burned. The final moisture content was determined for each category, and a composite final moisture content was calculated.

2.5. RESULTS AND DISCUSSION

2.5.1. General Observations.

Application of microwave power to grapes under vacuum resulted in dehydration. However, the specific energy of

the microwave and the application time was critical in successfully preserving the fresh grape characteristics. The microwave power caused heating and vaporization of water at a rate dependent on the specific energy. The effect of heating was offset by latent heat of vaporization so that if the time of microwave power application was long enough, the evolution of water vapor from the grapes slowed sufficiently to cause heat damage. The solution to successfully reaching a low final moisture content was to maintain a balance of the specific energy of the microwave and the cooling effect of water vaporizing from the grape sample.

Although infrared temperature detection was effective, its temperature indication was suspected to be higher than the fruit pulp temperature. The infrared temperature sensor may have seen the region exterior to the surface of the fruit and provided a temperature reading that was shifted upward. Based on these observations, infrared detectors mounted outside of the microwave field in future applications may indicate actual grape temperature.

2.5.2. Fixed Microwave Energy Application Experiments Sets 1 and 2.

Fixed levels of microwave power treatments resulted in a constant rate of moisture removal (Figure 2.3). At these constant power levels, the grapes did not reach an acceptable moisture content of less than 5 percent.

Depending on the fixed energy level applied, burning was observed when the grapes were exposed to microwave power

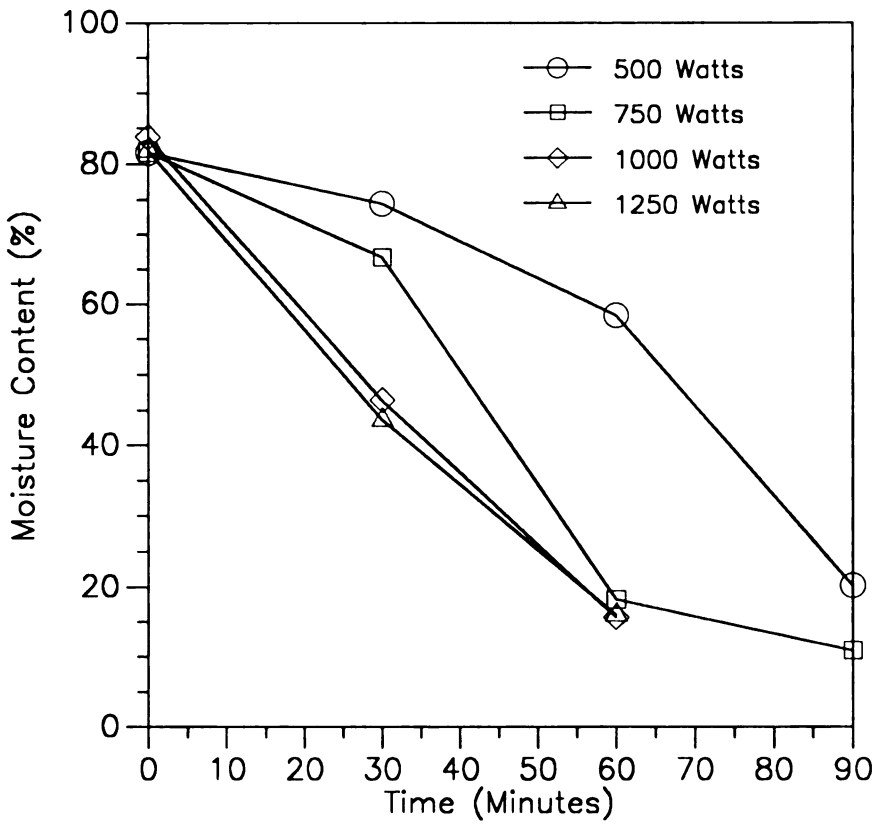


Figure 2.3. **Effect of Microwave Power Used on the Moisture Content of Grapes - Experiment Set 1.**

in a range of 30 to 90 min, at which time the temperature increased abruptly, and the treatment had to be terminated. An example of the relationship of heating by the microwave and the cooling effect of vaporization of water is shown for 60 min tests (Figure 2.4). During the first 5 to 10 min, the grape sample was heated by the microwave to a temperature sufficient to induce vaporization of water. Depending on the level of microwave power used, the cooling effect of vaporization remained in balance with the microwave heating for a period of 20 to 60 min. As the moisture content of the grape sample decreased, the rate of vaporization of water from the sample slowed, and the temperature increased. As shown in Figure 2.4, after 30 min of microwave power applied at 1250 W, the temperature of the grape sample increased suddenly, and the test was terminated. The final moisture content of the sample was 16 percent. Similar results were observed after about 45 min at 1000 W microwave power and about 60 min at 750 W. Application of microwave power at 500 W for 60 min dehydrated the grape sample to a final moisture content of 58 percent. Data for this set are shown in Appendix 7.3.

Multiple regression analysis showed a correlation between final moisture content and several independent variables. Multiple regression analysis of specific energy, initial fruit sugar and moisture content, and maximum grape sample temperature indicated a r^2-value of 0.957 (Table 2.7).

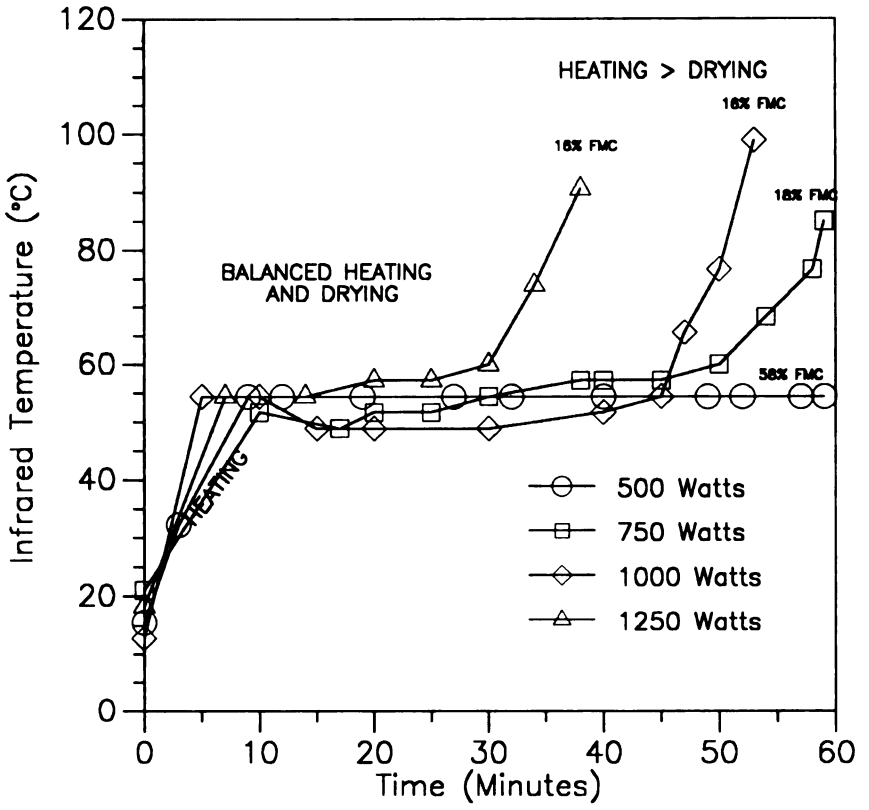


Figure 2.4. **Temperature Increase of Grapes Exposed to 4 Levels of Microwave Power. Numbers at the End of Each Line Indicate Final Moisture Content (FMC) - Experiment Set 2.**

Table 2.7

Multiple Regression Analysis of the Effect of Specific Energy, Fresh Fruit Sugar and Moisture Content, and Final Grape Temperature on Final Moisture Content

Experiment Sets 1 and 2

Regression Equation:

$$FMC = b_0 + b_1(x_1) + b_2(x_2) + b_3(x_3) + b_4(x_4)$$

Variable	Mean Response Coefficient	Decomposition [SSE_{Xi}/SSR]
Constant	$b_0 = 42.41$	
x_1 = Specific Energy (W-h/g)	$b_1 = -98.50$	0.988
x_2 = Fruit Sugar Content (°Brix)	$b_2 = 1.95$	0.010
x_3 = Initial Moisture Content(%)	$b_3 = 0.39$	<0.001
x_4 = Grape Temperature (°C)	$b_4 = -0.03$	0.002
	$r^2 = 0.957$	

Based on the multiple regression, the most significant results of the fixed microwave energy application tests was the correlation of specific energy and final moisture content (FMC). Decomposition of the regression sum of squares indicated that of the factors analyzed, specific energy accounted for 98.8 percent of the variation due to treatment. The linear regression analysis of specific energy and final moisture content resulted in a r^2-value of 0.946 percent (Figure 2.5). Specific energy levels below 0.5 W-h/g fresh grapes resulted in limited dehydration yielding product with a final moisture content of 55 to 78 percent. At levels of specific energy between 0.5 and 0.8 W-h/g fresh grapes, moderate dehydration occurred, resulting in a final moisture content of 30 to 55 percent. At a specific energy above 0.8 W-h/g fresh grapes, burning occurred before the grape sample dried to an acceptable final moisture content of 5 percent or less.

Acceptable levels of final moisture content were not achieved in experiments 1 and 2, and the total specific energy recorded was less than the total specific energy of 1.39 W-h/g fresh grapes calculated to dehydrate grapes.

The conclusion of the fixed power level experiments were that fixed microwave energy treatments caused grapes to overheat and burn before an acceptable final moisture content was reached.

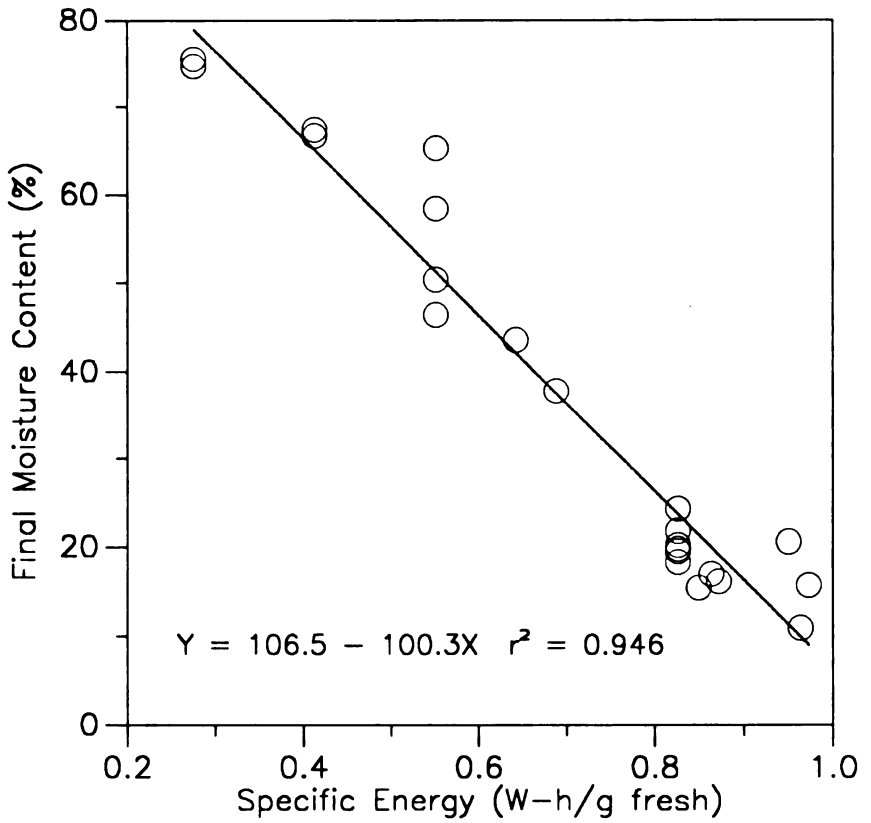


Figure 2.5. **Linear Correlation of Specific Energy and Final Moisture Content at Fixed Levels of Microwave Application.**

2.5.3. Staged Microwave Energy Application Experiment Sets 3 and 4.

A cumulative specific energy of 1.42 W-h/g of fresh grapes was used in all the treatments in experiment set 3, and 1.06 W-h/g was used in experiment set 4. The energy was applied in stages to anticipate the response of the grape sample to the microwave power. During the first stage, 3000 W was applied to heat the water in the grape sample for a time sufficient to induce vaporization. The next two stages of 1500 W and 500 W were applied for periods to maintain a balance between the heating effect of the microwave power and the cooling effect due to latent heat of vaporization (see data for sets 3 and 4 in Appendix 7.3).

Compared to the treatments planned (Tables 2.5 and 2.6 on pages 49 and 51), the actual treatments are shown in Tables 2.8 and 2.9. The lowest final moisture content reached without heat damage was observed in the first test in which the lowest energy was applied in the first power stage. Although the cumulative specific energy levels in all tests were higher than those observed in the fixed microwave power application experiment sets 1 and 3, ranging from 0.72 to 0.83 W-h/g fresh grapes, they were less than the theoretical specific energy of 1.39 W-h/g of fresh grapes. Final moisture content of the grapes dried in experiment 3 ranged from 18.0 to 54.8 percent.

The power levels used in experiment set 3 resulted in heat damage within 20 to 50 minutes (Figure 2.6) depending

Table 2.8

Actual Power - Time Regime in the Laboratory Microwave Vacuum System - Summary of Staged Energy Application Treatments and the Effect on Final Moisture Content (FMC)

One Sample Each at 1.8 kg
Experiment Set 3

Forward Power (W) 3000 Time	1500 (min)	500	Total	Stage I Specific	II Energy	III (W-h/g	Total fresh)	FMC (%)
5	44	0	49	0.14	0.61	0.00	0.74	18.0
10	32	0	42	0.28	0.44	0.00	0.72	24.0
15	24	0	39	0.41	0.33	0.00	0.74	54.8
20	14	0	34	0.55	0.19	0.00	0.74	22.9
25	10	0	35	0.69	0.14	0.00	0.83	20.9
28	0	0	28	0.77	0.00	0.00	0.77	28.7

Table 2.9

Actual Power - Time Regime in the Laboratory Microwave Vacuum System - Summary of Staged Energy Application Treatments and the Effect on Final Moisture Content (FMC)

One Sample Each at 1.8 kg
Experiment Set 4

Forward Power (W) 3000 Time	1500 (min)	500	Total	Stage I Specific	II Energy	III (W-h/g	Total fresh)	FMC (%)
10	20	78	108	0.28	0.28	0.36	0.91	7.7
10	30	32	72	0.28	0.41	0.15	0.84	8.0
10	40	37	87	0.28	0.55	0.17	1.00	11.5
20	10	40	70	0.55	0.14	0.18	0.87	16.7
20	18	0	38	0.55	0.22	0.00	0.80	23.4
20	16	0	36	0.55	0.22	0.00	0.77	21.7

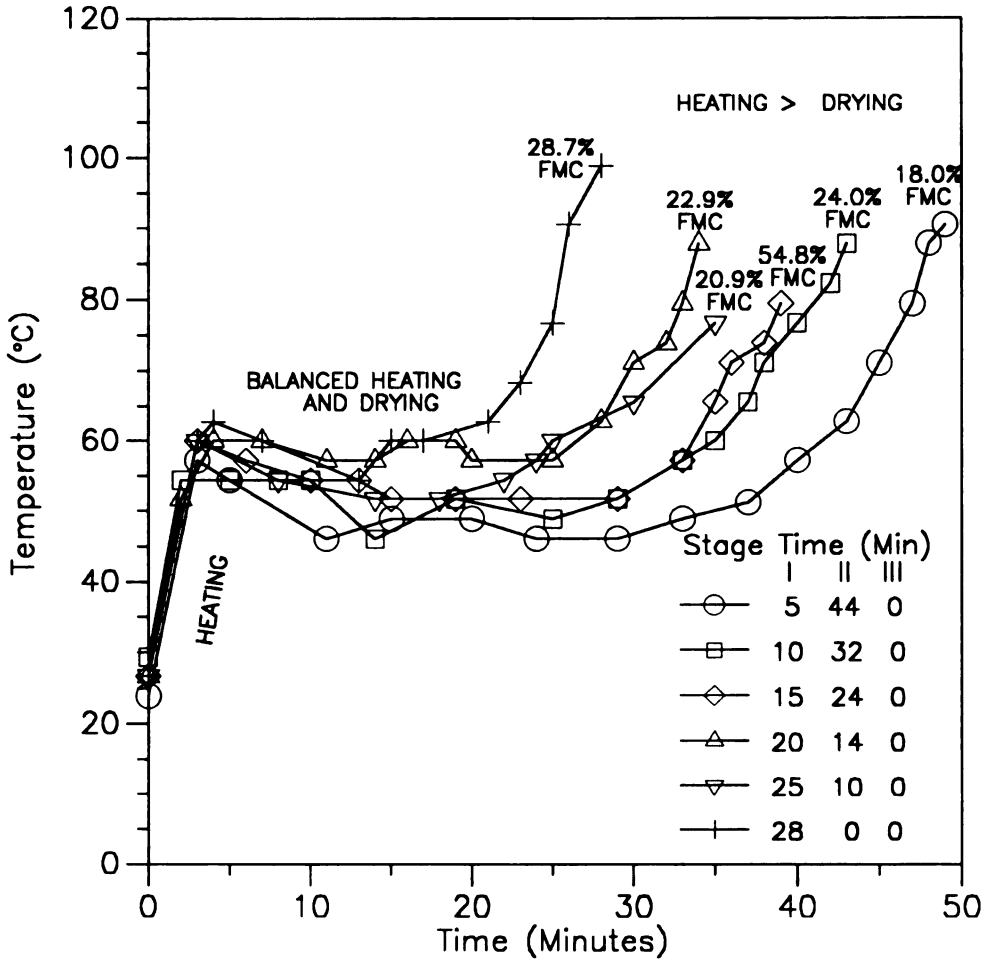


Figure 2.6. Temperature Increase of Grapes Exposed to 6 Combinations of Staged Microwave Power. Numbers at the End of Each Line Indicate Final Moisture Content (FMC) - Experiment Set 3.

on the time the grapes were exposed to a stage I power of 3000 W. The shortest exposure time at 3000 W resulted in the lowest final moisture content. Based on the results of experiment set 3, the distribution of microwave energy was shifted in experiment set 4 to shorter exposure times at higher levels of power, and longer exposure times at lower levels of energy. The total specific energy was reduced from 1.42 to 1.06 W-h/g of fresh grapes.

Actual total specific energy in experiment set 4 ranged from 0.77 to 0.91 W-h/g of fresh grapes (Table 2.9). The highest total energy treatment dried the grape sample to the lowest final moisture content (7.7%). As in experiment sets 1 and 2, specific energy accounted for most of the variation in final moisture content with a r^2-value of 0.945. The results of experiment set 4 showed that the distribution of microwave power should be shifted further to shorter exposure times at higher levels of power, and longer exposure times at lower levels of power.

Treatments applied in experiment set 5 produced dried grape samples with a range of final moisture content from 3.5 to 36.5 percent (Table 2.10). Actual levels of specific energy were 0.71 to 0.91 W-h/g of fresh grapes. Drying times ranged from 35 to 107 minutes. Within treatments employing a 3000 W application for 5 minutes, an increase of 10 minutes in the 1500 W stage increased the portion of finished product that exhibited a dried, puffed texture from 6 to 63 percent. A further increase in the duration of the

Table 2.10

Actual Power - Time Regime in the Laboratory Microwave Vacuum System - Staged Microwave Applications and the Effect on Final Moisture Content (FMC) and Puffed Character of Grapes

Sample Weight: 1.8 kg
Experiment Set 5

Forward Power (W) 3000	1500	500		Stage I	II	III	Total	FMC	Puffed
Time (min)			Total	Specific Energy (W-h/g fresh)				(%)	(%)
5	20	80	105	0.14	0.28	0.37	0.78	17.8	6
5	30	72	107	0.14	0.41	0.33	0.88	7.1	63
5	40	49	94	0.14	0.55	0.22	0.91	3.5	70
10	20	73	103	0.28	0.28	0.34	0.89	6.7	60
10	30	29	69	0.28	0.41	0.14	0.82	7.1	68
15	25	28	68	0.41	0.34	0.13	0.88	7.2	61
15	30	8	52	0.41	0.41	0.04	0.86	10.0	35
20	10	5	35	0.55	0.14	0.02	0.71	36.5	0

1500 W stage to 40 minutes resulted in 70 percent of the dried grapes having a puffed, dried character.

Regression analysis of the application time and power levels used in each stage, fresh fruit sugar, and moisture content indicated that time and power were highly correlated. This was expected since specific energy was calculated using time. Separate analyses of both time and specific energy indicated a r^2-value of 0.875. Decomposition of the regression sum of squares showed that both the specific energy used in each stage (Table 2.11) and the time power was applied in each stage (Table 2.12) accounted for 96.2 percent of the variation in final moisture content due to treatment. This was expected since the same power stages (3000, 1500, and 500 W) were applied in all the tests. Although initial moisture content varied from 76.0 to 84.1 percent, and initial sugar content ranged from 18.2 to 23.0 °Brix within the replications, both factors accounted for 3.7% of the effect on final moisture content.

Analysis of total specific energy as a single factor indicated that this variable accounted for 78.7 percent of the variation in final moisture content (r^2 = 0.787). The best fit of total specific energy and final moisture content is shown in Figure 2.7. A regression surface plot (Figure 2.8) of the effect of specific energy and the time the energy was actually applied indicated optimum results in a specific energy range of 0.85 to 0.90 W-h/g of fresh grapes

Table 2.11

Multiple Regression Analysis of the Effect of Specific Energy, Fresh Fruit Sugar, and Initial Moisture Content on Final Moisture Content

Experiment Set 5

Regression Equation:

$$FMC = b_0 + b_1(x_1) + b_2(x_2) + b_3(x_3) + b_4(x_4) + b_5(x_5)$$

Variable	Mean Response Coefficient	Decomposition $[SSE_{X1}/SSR]$
Constant	$b_0 = 222.85$	
x_1 = Specific Energy Stage I	$b_1 = -107.11$	0.365
x_2 = Specific Energy Stage II	$b_2 = -133.61$	0.369
x_3 = Specific Energy Stage III	$b_3 = -118.81$	0.228
x_4 = Fresh Fruit Sugar Content	$b_4 = -2.12$	0.025
x_5 = Initial Moisture Content	$b_6 = -0.83$	0.012
	$r^2 = 0.875$	

Table 2.12

Multiple Regression Analysis of the Effect of Microwave Exposure Time, Fresh Fruit Sugar, and Initial Moisture Content on Final Moisture Content

Experiment Set 5

Regression Equation:

$$FMC = b_0 + b_1(x_1) + b_2(x_2) + b_3(x_3) + b_4(x_4) + b_5(x_5)$$

Variable	Mean Response Coefficient	Decomposition $[SSE_{Xi}/SSR]$
Constant	$b_0 = -222.85$	
x_1 = Time - Stage I	$b_1 = -2.95$	0.365
x_2 = Time - Stage II	$b_2 = -1.84$	0.369
x_3 = Time - Stage III	$b_3 = -0.55$	0.228
x_4 = Fresh Fruit Sugar Content	$b_4 = -2.12$	0.025
x_5 = Initial Moisture Content	$b_6 = -0.83$	0.012
	$r^2 = 0.875$	

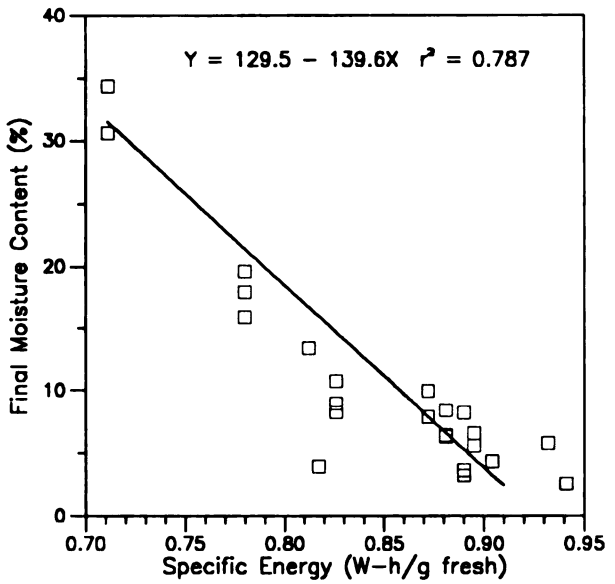


Figure 2.7. Relationship of Total Power and Final Moisture Content.

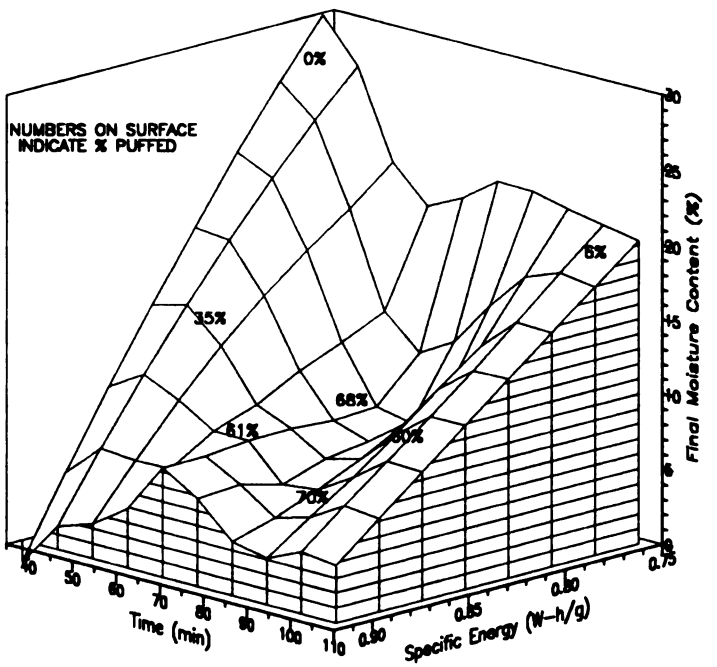


Figure 2.8. Regression Surface Plot of the Effect of Time and Total Specific Energy on Final Moisture Content.

and a total time of 85 to 100 minutes. The dried grape sample had a final moisture content of less than 5 percent and 70 percent of the dried sample exhibiting a puffed, crispy character. Outside this treatment range, a rapid rise in final moisture content was evident.

Although analysis of total specific energy offered some insight in optimizing the characteristics of the grape product, analysis was conducted to define the effects of time at stage I and II of microwave power on final moisture content (Figure 2.9). Application of 3000 W in stage I for 10 to 15 minutes and 1500 W in stage II for 30 to 40 minutes produced dried grapes with a final moisture content of 3.5 to 10 percent. Sixty to 70 percent exhibited a puffed character. Outside these ranges, final moisture content increased, and quantity of puffed grapes decreased.

Similar results were observed in a regression surface plot of specific energy used in stages I and II and final moisture content and product character (Figure 2.10). Analysis of the effect of the first and second stages on final moisture content indicated optimum results in a range of 0.1 to 0.3 W-h/g in stage I combined with 0.4 to 0.575 W-h/g in stage II. The specific energy used within these boundaries resulted in 60 to 70 percent of the dried grape sample exhibiting a puffed character, and final moisture content ranged 3.5 to 10 percent.

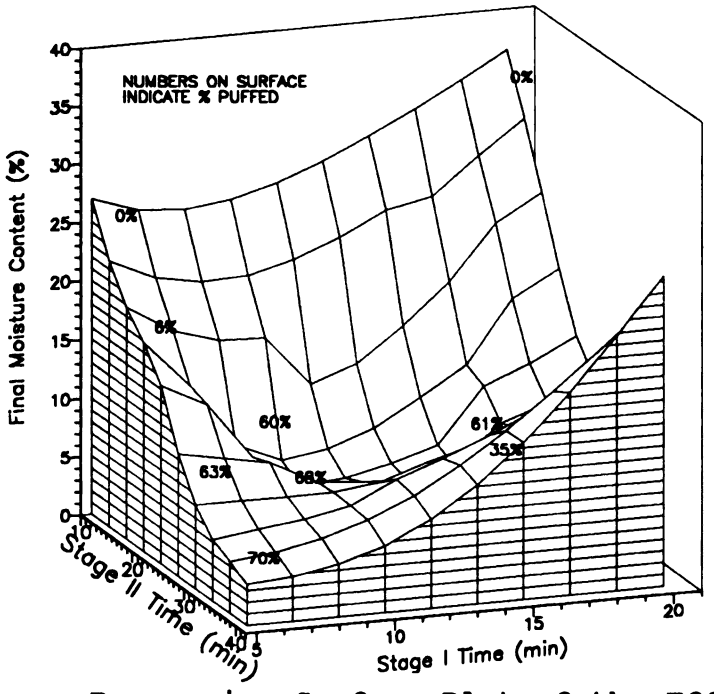


Figure 2.9. Regression Surface Plot of the Effect of Time of Exposure in Stages I and II on Final Moisture Content.

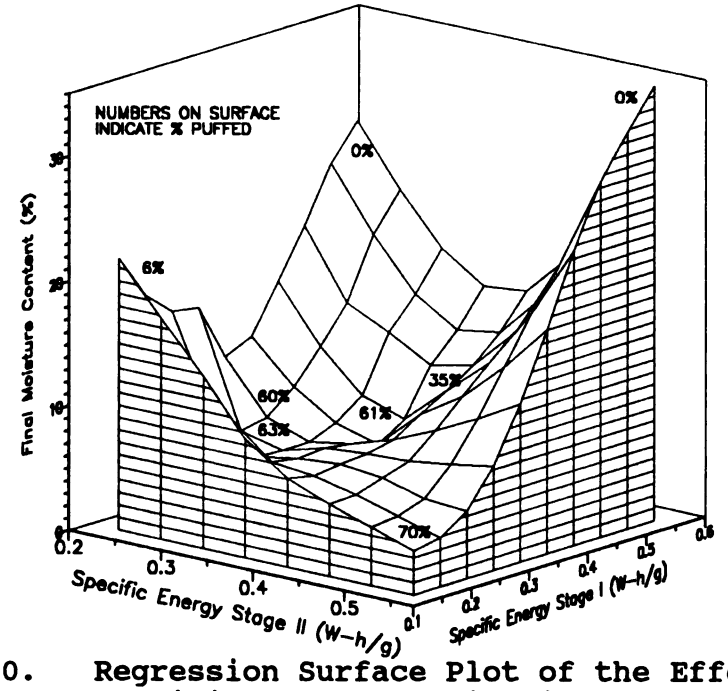


Figure 2.10. Regression Surface Plot of the Effect of Specific Energy Applied in Stage I and II on Final Moisture Content.

The conclusions of the staged microwave experiments were:

a. Application of microwaves in successively reduced stages of power contributed to reduction in overheating and minimized final moisture content.

b. Although 60 to 70 percent of the dried grapes exhibited a puffed, crispy character in some treatments, further refinement of the process was recommended to optimize final moisture content and maximize puffed character.

2.5.4. Temperature Based Staged Microwave Experiments.

Except for observing temperature to determine when to stop tests because of visual evidence of the grapes burning, application of specific energy treatments using previous methods did not consider temperature of the grape sample in optimizing final product character. During the previous experiments, the temperature of the grape sample was the result of the power level and the time the power was applied. It was observed that the temperature of the grapes increased until the power level was reduced as part of the treatment plan (Figure 2.6, page 62).

Experiment set 6 included temperature as a treatment, and the r^2-value of the multiple linear regression analysis of the effect of temperature, process time, specific energy, and fresh fruit sugar and moisture content on the final moisture content of the dried grapes was 0.942 (Table 2.13).

Table 2.13

Multiple Regression Analysis of the Effect of Temperature, Time, Total Specific Energy, Fresh Fruit Sugar and Moisture Content on Final Moisture Content of Dried Grapes

Experiment Set 6 - Temperature Treatments

Regression Equation:

$$FMC = b_0 + b_1(x_1) + b_2(x_2) + b_3(x_3) + b_4(x_4) + b_5(x_5)$$

Variable	Mean Response Coefficient		Decomposition $[SSE_{Xi}/SSR]$
Constant	b_0 =	92.08	
x_1 = Temperature (°C)	b_1 =	-0.40	0.645
x_2 = Time (min)	b_2 =	-0.03	0.057
x_3 = Specific Energy (W-h/g)	b_3 =	4.58	0.070
x_4 = Fresh Fruit Sugar Content	b_4 =	-1.52	0.215
x_5 = Initial Moisture Content (%)	b_5 =	-0.36	0.013
	r^2 =	0.942	

Temperature and fresh fruit sugar content accounted for 64.5 and 21.5 percent of the variation due to treatment. In experiment set 6, temperature replaced specific energy and time as the significant factor in predicting final moisture content. Although temperature was an independent variable, each treatment level was achieved using microwave energy applied for a time sufficient to heat the grape sample to the treatment temperature (see Appendix 7.3).

The final moisture content of the grapes produced in experiment set 6 ranged from 3.5 to 9.8 percent. Within this range, the portion of each sample exhibiting puffed character ranged from 0 to 80.3 percent. A regression surface plot of the effect of time and total specific energy is shown in Figure 2.11. Based on this analysis, the optimum total specific energy was 0.86 W-h/g applied over a period of 70 to 75 min. This treatment regime produced a dried grape sample with a final moisture content of about 4 percent and 80 percent of the sample exhibiting a puffed, crunchy character. A final moisture content of 5 percent was reached in 79 min.

Multiple linear regression analysis of the effect of temperature, time, specific energy, fresh fruit sugar, and moisture content on the amount of dried grapes exhibiting a puffed character indicated an r^2-value of 0.985 (Table 2.14). As in the analysis of the effect of these factors on final moisture content, decomposition of regression analysis indicated that temperature accounted for most of the

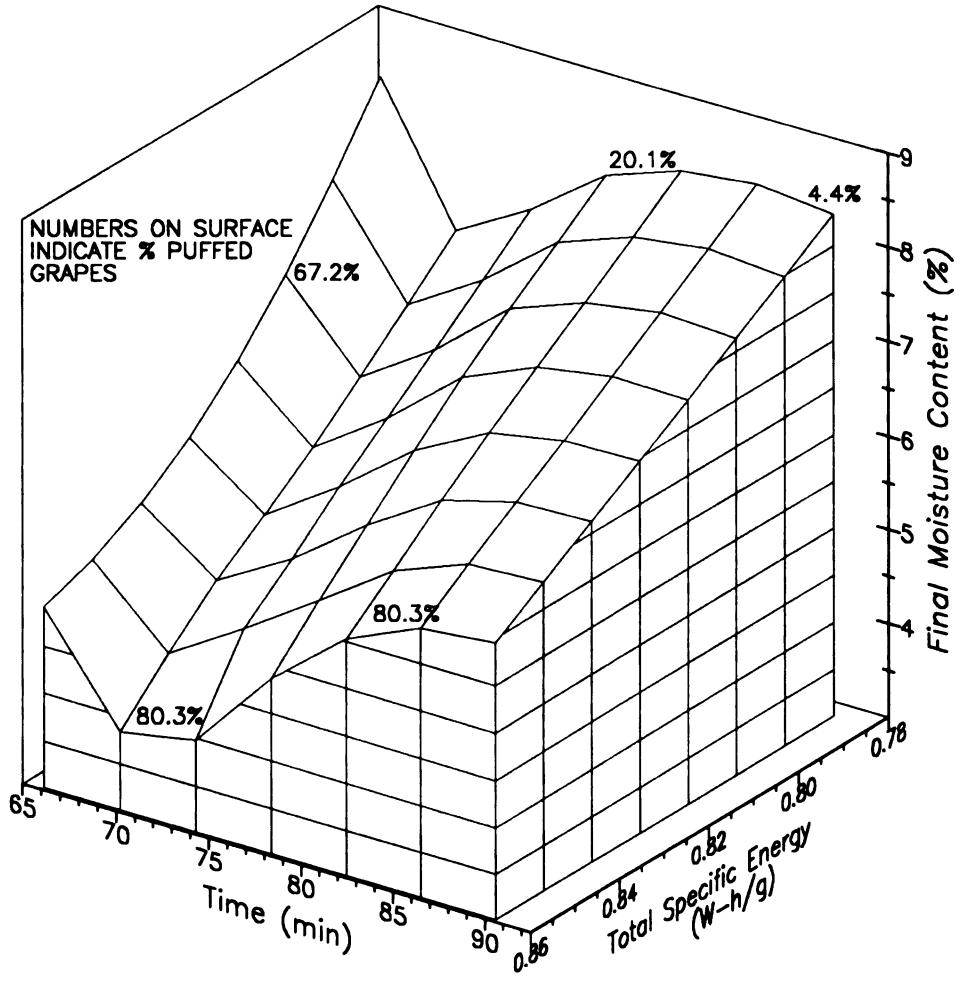


Figure 2.11. **Regression Surface Plot of the Effect of Time and Total Specific Energy on Final Moisture Content.**

Table 2.14

Multiple Regression Analysis of the Effect of Temperature, Time, Total Specific Energy, Fresh Fruit Sugar, and Moisture Content on Portion of Dried Grapes Exhibiting Puffed Character

Experiment Set 6

Regression Equation:

$$\text{Puffed (\%)} = b_0 + b_1(x_1) + b_2(x_2) + b_3(x_3) + b_4(x_4) + b_5(x_5)$$

Variable	Mean Response Coefficient	Decomposition $[SSE_{Xi}/SSR]$
Constant	$b_0 = 3119.20$	
x_1 = Temperature (°C)	$b_1 = -0.02$	0.642
x_2 = Time (min)	$b_2 = -0.10$	0.010
x_3 = Specific Energy (W-h/g)	$b_3 = 24.98$	0.022
x_4 = Fresh Fruit Sugar Content	$b_4 = -39.22$	0.018
x_5 = Initial Moisture Content (%)	$b_5 = -28.23$	0.318
	$r^2 = 0.985$	

definition of the two independent variables that contributed most significantly to the final character of the grapes dried in these experiments, and the optimum levels of these variables are shown in Figure 2.12. A total specific energy of 0.84 to 0.88 W-h/g fresh grapes was found to be the optimum range to dehydrate the samples. Equally important, the power levels used to achieve this total specific energy was applied in stages sufficient to heat the grapes to 70 to 80 °C and maintain this temperature until the grape sample dried to about 5 percent final moisture content. This produced dried grapes that were 82 percent puffed.

As discussed earlier, the temperature indication of the infrared detector was higher than the actual temperature the grapes could withstand. Grape sugar burns at a temperature higher than about 57 °C. The estimated upward shift of the infrared detector was about 10 to 20 °C. Nevertheless, the infrared detector was a useful tool in controlling the process.

The original estimation of the total specific energy required to dehydrate the grape samples in these experiments was 1.39 W-h/g fresh grapes. As shown in Appendix 7.2 (Tables 7.2.1 - 7.2.4), this value was based on the assumption that the final moisture content was 3 percent, the estimated temperature rise from 21 to 49 °C, and the microwave coupling efficiency was 0.40. Based on the actual values defined in these experiments, new estimates for the microwave coupling efficiency are shown in Table 7.2.7 in

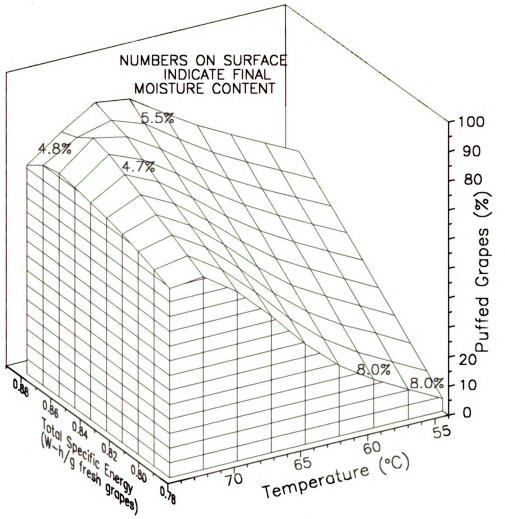


Figure 2.12. Regression Surface Plot of the Effect of Total Specific Energy and Temperature on Puffed Character of Dried Grapes.

Appendix 7.2. The results of this recalculation indicate that the coupling efficiency of the microwave energy with the grape sample was about 65 percent.

The dried grapes produced in these experiments exhibited a color representative of the fresh grapes from which they were made. The appearance was puffed with a resemblance to fresh, whole grapes, and the texture was crisp and crunchy. Flavor was representative of a fresh grape, exhibiting a sweet, tart flavor.

The conclusions of the temperature-based staged microwave experiment set 6 were:

a. Temperature was a significant factor in optimizing reduction of final moisture content of grapes.

b. A specific energy of 0.84 to 0.88 W-h/g and time of application of 70 to 90 minutes was recommended for testing the continuous process system.

2.5.5. Conclusions of the Laboratory Batch Microwave Vacuum Experiments.

Experiment Sets 1 - 5. The conclusion of the fixed power level tests was that grapes overheated and burned before an acceptable final moisture content was reached. As a result of experiment sets 3 and 4, the distribution of microwave power was shifted in experiment set 5 to shorter exposure times at higher levels of power and longer exposure times at lower levels of power. Although a final moisture content of 3.5 to 10 percent was achieved, and 60 to 70

percent of the grapes exhibited puffed character, experiment set 6 was completed to improve these characteristics.

Experiment Set 6. In the temperature based experiments, specific energy was applied in stages to reach a given total specific energy. Instead of basing the changes in power on time, power levels were based on product temperature. Most of the dried grape samples exhibited a color representative of the fresh grapes, a puffed appearance, and a crisp texture.

Conclusions.

a. A relationship existed between microwave energy and time of exposure and their effect on product temperature and final moisture content of grapes. The total specific energy was 0.84 to 0.88 W-h/g for 90 minutes.

b. This range of specific energy based on time dried grapes to less than 5 percent that exhibited the integrity, shape, and color of the fresh grape.

3. EVALUATION OF LIQUID MEDIA IMMERSION ON MOISTURE LOSS IN GRAPES

3.1. INTRODUCTION

3.1.1. Liquid Media for Dehydration.

Successful application of microwave vacuum dehydration technology to grapes may require use of an alternate dehydration method to reduce cost. Microwave heating is effective but may not be economical in removal of bulk water in dehydrating high moisture food products (Buffler, 1993). Although microwave vacuum dehydration alone shows potential to dehydrate food products, other more economical heat sources may serve to remove water during the constant rate phase of the drying. The moisture gradient is high, and the product is not as susceptible to damage during this phase.

Drying fruits and vegetables using an inert liquid medium has been understood for some time (Webb and Webb, 1977; Webb, 1988). Several patents have been issued that describe the use of a liquid medium for heat transfer. Use of a heated medium under vacuum minimized changes in color and shape. Often called vacuum frying, this art has been used in production of products such as apple and banana chips.

Other adaptations of this type of dehydration have included submersing a frozen food material in vegetable oil heated to 160 to 225 °C (325 to 440 °F) under a partial vacuum of 3.2 to 26.8 kPa (23.4 - 201.2 Torr) (Forkner, 1966). The process avoided shrinking with the goal of maintaining the general identity of the form and size of the fresh product. Forkner (1967) described a process applying a similar temperature range to produce dried particles having a form similar to the form of the original particles of source material without excessive shrinkage. Other patents describe processes that used oil under vacuum to produce puffed products having structures and compositions that are unique (Lankford, 1973). Methods have also been outlined for producing puffed, low moisture fruit and vegetable particles (Webb and Webb, 1977) and a process for producing "vacuum fried" banana slices exhibiting a crisp texture and a moisture content of 1.5 to 3.0 percent (Numata and Sugano, 1980).

Variations of vacuum frying systems produced puffed products of low moisture content using heated oil (Sakuma and Sakuma, 1988; Webb, 1989). The desired result of this process was puffing fruits and vegetables. The intent was to produce a puffed structure that was hardened by cooling to create a crisp, low moisture product. Product moisture was cited as being so low (less than 2 percent) that specialized packaging was required to prevent loss of crunchiness.

3.1.2. Liquid Media for Predrying Grapes.

Liquid media dehydration was evaluated on a preliminary basis for dehydration of grapes to an intermediate moisture content for further processing by microwave vacuum (Petrucci and Clary, 1989). This research describes submerging grapes in paraffin wax heated to 60 to 80 °C at a pressure of 3 kPa. Low pressure caused moisture to vaporize from the product at reduced temperature, therefore reducing product alteration due to heat. Absence of oxygen enhanced preservation of compositional characteristics such as colors and flavors.

The laboratory prototype (Figure 3.1) consisted of a vacuum vessel submerged in an insulated water tank. The water was heated by natural gas, and the temperature of the water bath was controlled using a three-way mixing valve. The system was designed to operate in a water temperature range of 50 to 95 °C. Vacuum levels used ranged from 1.3 to 7 kPa (10 to 50 Torr).

The vacuum chamber was equipped with a removable lid that incorporated a wire basket that was raised and lowered using a control rod through the center of the lid. The lid sealed the vacuum vessel, and the wire basket containing grapes was lowered into the liquid paraffin using the lifting handle. The heat in the paraffin was transferred to the grapes causing water in the grapes to vaporize. The water vapor rose to the surface of the liquid paraffin and was removed from the drying chamber by the vacuum pump.

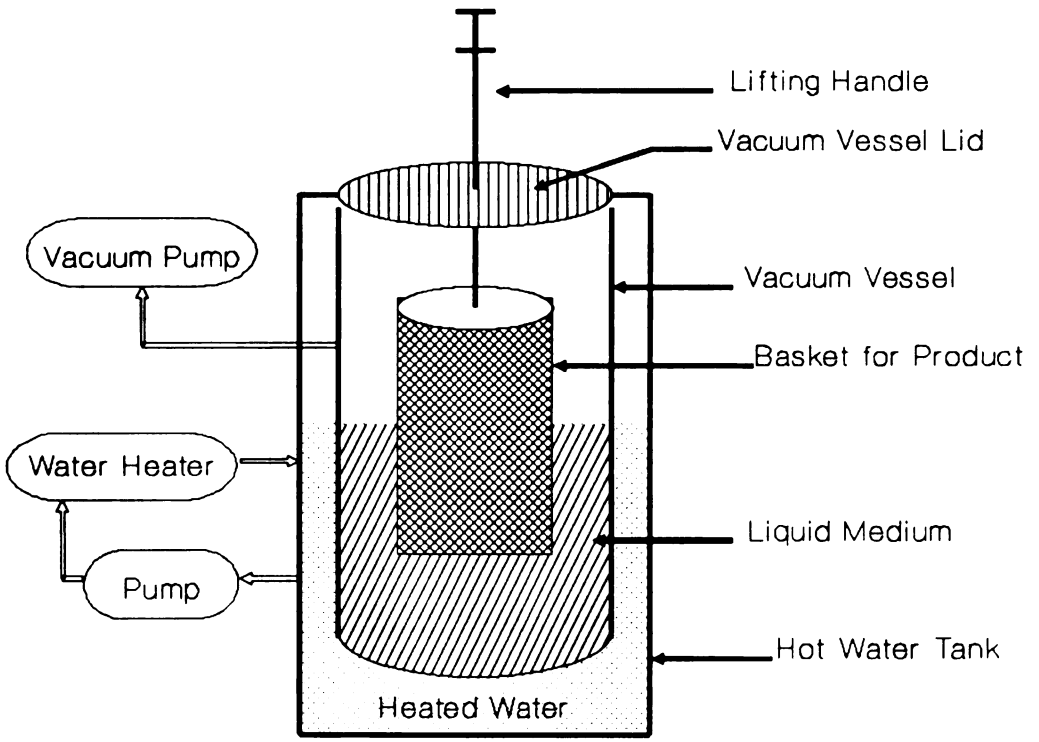


Figure 3.1. Schematic Diagram of First Generation Liquid Media Predryer System.

When the process time elapsed, the wire basket was lifted out of the paraffin wax, agitated to remove paraffin residue on the surface of the grapes, and the chamber repressurized. The lid was removed and grapes were transferred to the laboratory batch microwave vacuum unit for finish drying.

This preliminary research showed potential for predrying of grapes for finish drying in the microwave vacuum process. The ideas of liquid media dehydration were incorporated into the design of a pilot scale continuous system for predrying grapes. Refinement of the process and identification of better media materials was recommended.

3.2. OBJECTIVES

A laboratory test bench apparatus was assembled for screening and evaluation of media materials, and for use in development of a prediction model based on process time, temperature, and pressure. The purpose of the experiments using the laboratory test bench apparatus was to evaluate media materials and define the relationship of pressure, temperature, and time on the characteristics of dried grapes.

The objectives of the experiments using the laboratory test bench apparatus included:

a. Screen liquid media materials for use in the dehydration process,

b. Define the effects of pressure, temperature, and process time on the characteristics of dried grapes including shape, color, texture, and final moisture content, and

c. Evaluate liquid media dehydration as a method for dehydrating grapes before exposure to microwave vacuum dehydration.

3.3. DESCRIPTION OF THE LABORATORY BENCH LIQUID MEDIA DEHYDRATION SYSTEM

The liquid media test bench consisted of a group of Erlenmeyer vacuum flasks connected in series to a vacuum pumping system (Figure 3.2). The flask at the end of the

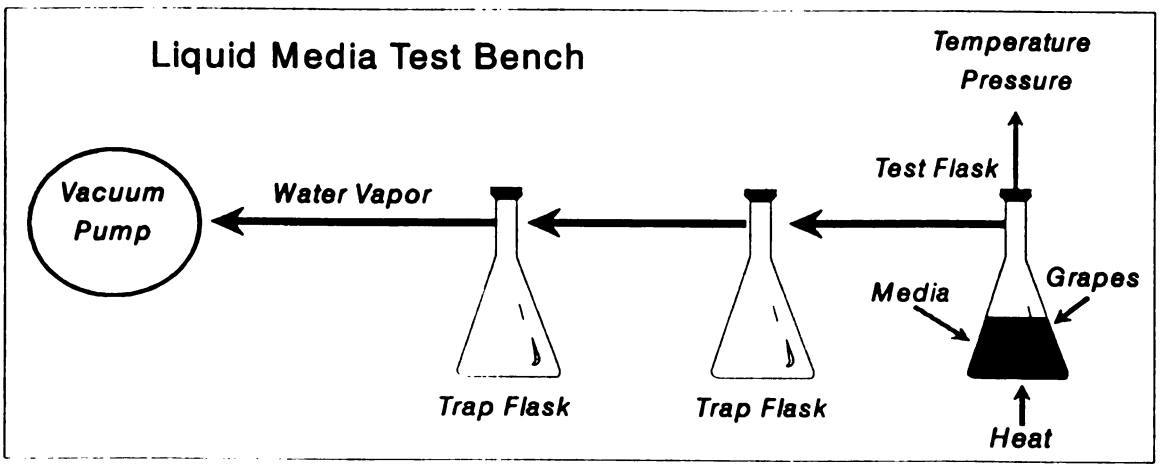


Figure 3.2. Liquid Media Test Bench Configuration.

series contained the liquid medium and grape sample and was heated on a hot plate equipped with a magnetic stirrer. Vapors evolved from the grape sample were carried through tubing to a second and third flask, and ultimately to the vacuum pump.

3.4. MATERIALS AND METHODS

3.4.1. Test Bench Liquid Media Procedures.

The procedure involved selecting a sample of single Thompson Seedless grapes for treatment and determination of their initial moisture and sugar content. The treatment

sample was placed in the first flask filled with test media heated to treatment temperature. The flask was sealed from the atmosphere and opened to the vacuum system.

Pressure was adjusted to the treatment level and monitored by a Leybold vacuum gauge (Model DIN 180 63) reading in mm mercury absolute pressure in a range of 0 - 100 Torr (0 to 13 kPa). Media temperature was measured by a type K thermocouple and digital thermometer and the hot plate adjusted as needed ($\pm$ 5 °C).

When evolution of vapor slowed to a rate of a few bubbles per second, the flask was removed from the hot plate and carefully tilted to drain the media through the tubing into the second flask. In this way, the dried grapes were isolated from most of the media before venting the system to atmospheric pressure. The intent of this procedure was to minimize infusion of media into the grapes when the system was vented. Following removal from the test flask, grape appearance including color, shape, and texture was noted, the sample was weighed, and final moisture content determined by vacuum oven. The following measurements were recorded for each experiment.

Independent Variables.

Initial Moisture Content (IMC).

Initial Grape Sugar Content (°Brix).

Temperature.

Flask Pressure (kPa).

Residence Time (min).

Dependent Variables.

Initial and Final Product Weight Ratio.

Final Moisture Content (FMC).

Product Description (color, shape, texture).

Besides these measurements, the general response of the grapes and each media material was observed for handling characteristics, changes in color and texture, presence of the media on the final product, and flavor. The data were analyzed using multiple regression analysis to develop models to predict the final moisture content of a grape sample based on pressure, temperature, and time.

All the experiments were designed to dehydrate the grape samples to the minimum moisture content possible within the treatment, even if this final moisture content was below the moisture content needed for predrying grapes for the microwave vacuum dehydration process.

3.4.2. Evaluation of Media Materials.

Paraffin used in initial studies presented problems in handling because of its high melting point and the residue wax present in the dried or partially dried product (Petrucci and Clary, 1989). Alternate liquid media materials were evaluated for effects on flavor, composition, and general appearance of the dried product. The basic specifications of the liquid media materials included being classified as food grade, compatible with the dried product,

stable with respect to oxidation, and cost effective. The four media materials evaluated are listed in Table 3.1.

3.4.3. Effect of Pressure, Temperature and Process Time on the Characteristics of Dried Grapes.

The liquid media materials were evaluated to develop a prediction model for dehydration of grapes using liquid media. The levels of pressure, temperature, and time were limited in an attempt to induce dehydration while minimizing damage to the grapes and liquid media material. The treatments for the first four experiments are shown in Table 3.2. Four experiment sets were conducted to define process ranges and refine the methodology for the replicated experiment. The development of the methodology included definition of the variables to be measured, procedures for measuring each variable, sample size, and development of the practice of applying the pressure and temperature treatments consistently. In each successive experiment, the ranges temperature were adjusted to optimize the characteristics of the dried product in reducing moisture content without damaging the grapes.

In experiment set 5, Durkex 500 was the only media material used because of its superior performance. Grape samples were dehydrated using a combination of four levels of pressure and three levels of temperature, each treatment replicated three times. Pressure treatments ranged from 1.3 to 12 kPa and temperature treatments ranged from 54 to 82°C, applied in 36 bench tests.

Table 3.1

Test Bench Liquid Media Materials Evaluation

Media Materials

Durkex 500 (Stabilized Vegetable Oil, Durkee)
Glycerin
White Grape Juice Concentrate
Myvacet (Distilled acetylated monoglycerides, Eastman)

Treatments

Pressure	kPa	Torr
Low	0.6-1.3	5-10
Medium	3	20
High	12	90
Temperature	**±3 °C**	**±5 °F**
Low	43	110
Medium	65	155
High	85	185

Table 3.2

Treatments Using Durkex 500 as a Liquid Media for Development of a Prediction Model Using the Test Bench System

Treatments
Experiment Sets 1 - 4

Pressure Levels (kPa)	(Torr)	Temperature Levels (°C)	(°F)
		Experiment Set 1	
1.3	10	49-54	120-130
2.7	20	60-66	140-150
6.7	50	82-88	180-190
12.0	90		
		Experiment Set 2	
1.3	10	52-54	125-130
2.7	20	63-66	145-150
6.7	50	82-85	180-185
12.0	90		
		Experiment Set 3	
1.3	10	57-60	135-140
2.7	20	60-63	140-145
6.7	50	79-85	175-185
12.0	90		
		Experiment Set 4	
1.3	10	54-60	130-140
2.7	20	66-66	140-150
6.7	50	82-88	180-190
12.0	90		
		Experiment Set 5*	
1.3	10	54-60	135-140
2.7	20	66	150
6.7	50	80-82	175-180
12.0	90		

*Each treatment replicated 3 times.

3.5. RESULTS AND DISCUSSION

3.5.1. Test Bench Liquid Media Experiments.

Based on levels of reduced pressure (Appendix 7.4), moisture was induced to vaporize and rise through the media and out through the media traps to the vacuum pump. In the early stages of dehydration, water vaporized rapidly from the fresh grapes causing a turbulent mixing of water vapor, grapes, and media within the flask. As the grapes dried, the vaporization slowed, a stream of bubbles emerged primarily from the capstem scar of each berry, and the grapes floated to the surface of the media.

The grape samples responded to all media materials similarly. When the grape sample was placed in the Erlenmeyer vacuum flask, the grapes sank to the bottom of the flask, and the water vapor exhausted rapidly, primarily through the capstem scar. This rapid vaporization caused turbulence that mixed the grapes, media material, and water vapor into a "foam". As the grapes dried, they became more buoyant, rising in the media and continuing to exhaust water vapor. When nearly dried, the rate of water loss slowed noticeably.

The treatments combining high temperature and low pressure produced puffed, crunchy dried grapes similar to puffed products described by Webb (1989) and others. Treatments combining low temperature and high pressure resulted in collapse of the fruit tissue into a wrinkled, raisined texture as described by Clary and Petrucci (1991).

3.5.2. Performance of Liquid Media Materials.

Durkex 500, Glycerin, and Myvacet showed potential for dehydrating grapes. White grape juice concentrate demonstrated the most compatibility with grapes. However, the concentrate thickened and was deemed unacceptable as a media material. Glycerin produced a finished product that was off-colored. Residues of Myvacet on the dried grapes samples developed rancidity and off flavors in four weeks.

Although the media materials were not analyzed for breakdown and discoloration, it was concluded that Durkex 500 exhibited the most potential as a media material. This material had the most acceptable flavor and color. Drying time among the treatments ranged from two to three hours. At less than 68 °C (150 °F) and 12 kPa (90 Torr), the dried product exhibited the collapsed, wrinkled characteristics of a golden seedless raisin with a moisture content of about 16 percent (wet basis). Treatments applying high temperature and low pressure produced a puffed crispy grape product. Although the desired final moisture content for predrying was about 50 percent, grape samples in all treatments were dried to lower levels to determine the minimum final moisture content and quality.

Within a pressure range of 0.67 to 12 kPa (5 - 90 Torr) and a temperature range of 40 to 88 °C (104 - 190 °F), multiple regression equations were derived for each media material (Table 3.3). The prediction model for Durkex 500 had a r^2-value of 0.876, while the r^2-values for Glycerin

Table 3.3

Multiple Regression Analysis of the Effect of Pressure, Temperature, and Time on Final Moisture Content Using Durkex, Glycerin, and Myvacet as Media Materials

Regression Equation:

$$FMC = b_0 + b_1(x_1) + b_2(x_2) + b_3(x_3)$$

Variable	Mean Response Coefficient	Liquid Media Material Durkex	Glycerin	Myvacet
Constant	b_0 =	144.84	259.18	63.54
x_1 = Pressure (kPa)	b_1 =	2.91	1.83	1.12
x_2 = Temperature (°C)	b_2 =	-1.98	-2.73	-0.58
x_3 = Time (min)	b_3 =	-0.13	-0.34	-0.19
	r^2 =	0.876	0.855	0.760

and Myvacet were 0.855 and 0.760, respectively. Analysis of the source of variation of pressure, temperature, and time showed that temperature had the most effect on final moisture content.

The conclusion of the evaluation of the liquid media materials was Durkex 500 demonstrated the best performance with respect to transferring heat to the grape samples, effect of residue on flavor, and stability of the dried grape product.

3.5.3. Determination of Preliminary Time-Temperature Experiment Sets.

Experiment Sets 1 - 4. The initial four time-temperature experiments refined the evaluation procedures. This provided information for development of a model to predict final moisture content. Criteria for development of a successful methodology were based on the r^2-value calculated from multiple regression analysis.

During the initial experiment using Durkex 500, it was observed that some grapes split during the drying process. This was coded and included in the multiple regression analysis of data collected in experiment set 1 (Table 3.4). Addition of this factor did not improve the r^2-value compared to the initial test. In subsequent experiment sets, initial sugar content was added as a predictor of final moisture content. Although initial sugar content was expected to improve precision, the r^2-values in experiment sets 1, 2, and 3 were progressively lower, ranging from a

Table 3.4

Multiple Regression Analysis of the Effect of Pressure, Temperature, Time, Splitting, and Sugar Content on Final Moisture Content

Experiment Sets 1 - 4

Regression Equation:

$$FMC = b_0 + b_1(x_1) + b_2(x_2) + b_3(x_3) + b_4(x_4) + b_5(x_5)$$

Variable	Mean Response Coefficient	Experiment Set 1	2	3	4
Constant	b_0 =	2.14	-26.71	6.52	91.63
x_1 = Pressure (kPa)	b_1 =	0.61	1.96	1.33	2.77
x_2 = Temperature (°C)	b_2 =	-0.43	0.17	-0.37	-0.72
x_3 = Time (min)	b_3 =	0.04	0.17	0.09	0.03
x_4 = Split (coded)	b_4 =	--	-20.68	-3.06	-4.48
x_5 = Fresh Sugar (°B)	b_5 =	--	--	--	-4.25
	r^2 =	0.836	0.784	0.737	0.883

r^2-value of 0.876 in the initial and contained lower levels of sugar than natural Thompson Seedless produced for raisin production. The results of experiment set 4 showed the highest r^2-value (0.883) of all previous experiments. The improved precision was attributed to an increased volume of Durkex 500 and a larger sample of more mature grapes.

Experiment Set 5. Multiple regression analysis in experiment set 5 indicated a r^2-value of 0.910 (Table 3.5). Decomposition of the regression sum of squares (SSR) of the five predictors used in this experiment set showed pressure and temperature contributed to 95 percent of the variation. Regression analysis of pressure and temperature as the only predictors of final moisture content indicated an r^2-value of 0.865. Decomposition of the SSR for the remainder of the treatment variables and the coefficient of mean response are also shown in Table 3.5.

A regression surface plot describing the effect of pressure and temperature on final moisture content is shown in Figure 3.3. Decomposition showed that pressure, as a single factor, accounted for 49.3 percent of the variation in final moisture content due to treatment. Independent of the temperature used in the experiments, treatment at high pressure produced dried grapes with a final moisture content of 4 to 13.5 percent. At lower pressures, final moisture

Table 3.5

Multiple Regression Analysis of the Effect of Pressure, Temperature, Time, Sugar Content, Initial Moisture Content, and Puffed Character on Final Moisture Content

Experiment Set 5

Regression Equation:

$$FMC = b_0 + b_1(x_1) + b_2(x_2) + b_3(x_3) + b_4(x_4) + b_5(x_5) + b_6(x_6)$$

Variable	Mean Response Coefficient	Decomposition* [SSE_{Xi}/SSR]
Constant	$b_0 = -28.490$	
x_1 = Pressure (kPa)	$b_1 = 0.965$	0.493
x_2 = Temperature (°C)	$b_2 = -0.218$	0.457
x_3 = Time (min)	$b_3 = 0.031$	0.017
x_4 = Fresh Sugar (°B)	$b_4 = 0.307$	0.008
x_5 = IMC w.b. (%)	$b_5 = 0.407$	0.023
x_6 = Puffed (coded)	$b_6 = -0.287$	<0.001
	$r^2 = 0.910$	

*Decomposition based on order the independent variables were entered in the regression analysis.

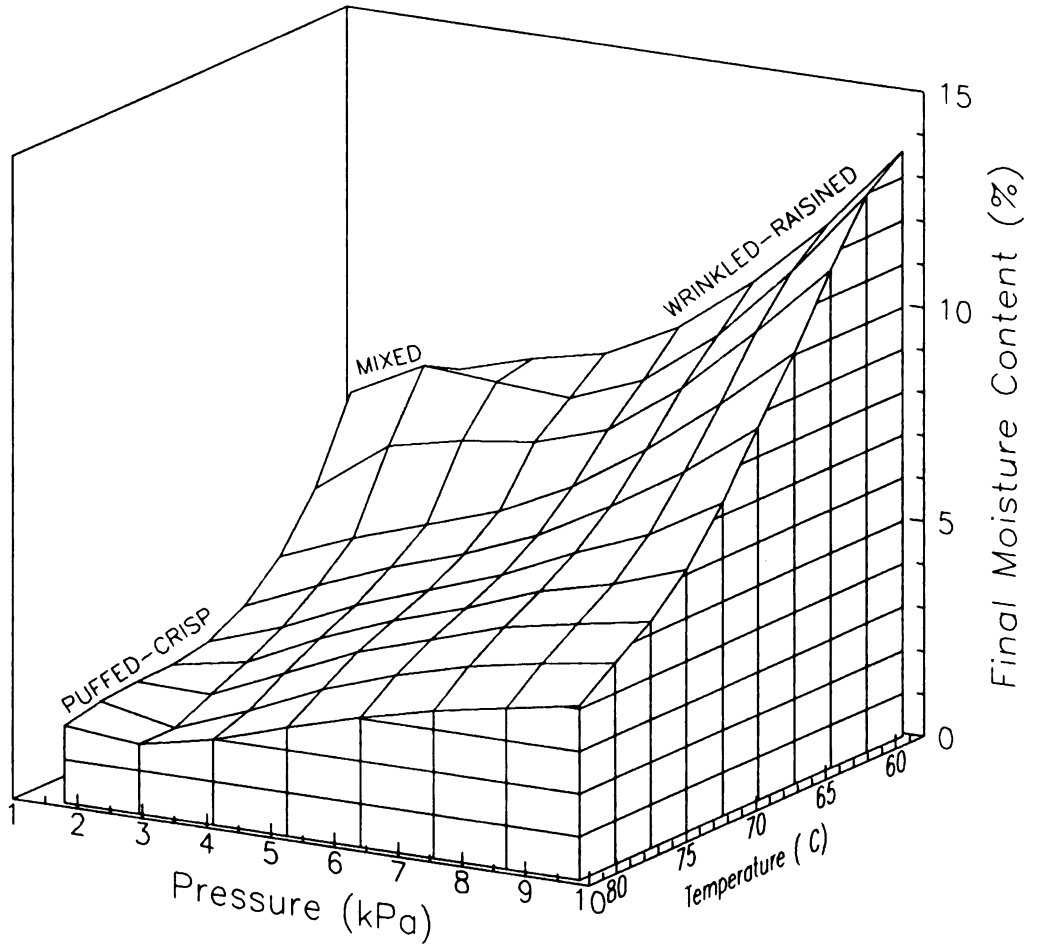


Figure 3.3. **Regression Surface Plot of the Effect of Pressure and Temperature on Texture and Final Moisture Content of Grapes. Lower Pressure and Higher Temperature Produce a Puffed Crispy Dried Grape and Higher Pressure and Lower Temperature Produces a Golden Raisin.**

content was about 2 to 6 percent. Temperature as a single factor contributed to 45.7 percent of the variation in final moisture content due to treatment.

The multi-colinearity of pressure and temperature accounted for 95.0 percent of the variation in final moisture content due to treatment. Treatments at low temperature and high pressure produced a raisined product with a soft pliable texture and a final moisture content of 13.5 percent. Treatments using high temperature and low pressure resulted in a puffed, crispy product with a final moisture content of 1 to 2 percent.

The conclusions of experiment sets 1 - 5 were:

a. Temperature and pressure were the primary factors in determining the texture and final moisture content of the dried grape product,

b. Liquid media dehydration showed potential for dehydration of grapes to a moisture content sufficient for processing in the microwave vacuum system.

4. CONTINUOUS PROCESS LIQUID MEDIA AND MICROWAVE VACUUM DEHYDRATION

4.1. INTRODUCTION

4.1.1. Background.

The results of microwave vacuum dehydration research (Petrucci and Clary, 1989) supported the decision to construct a commercial scale pilot plant using continuous process technology. This provided a research tool to develop models using a continuous system and offered the opportunity for demonstration and technology transfer activities for commercial application.

The pilot plant, completed at California State University, Fresno and described by Petrucci, Clary, and Conrad (1993) was designed to process fresh grapes at a feed rate of 55 kg/h of grapes from 80 percent moisture into a puffed dried finished product of less than 5 percent moisture (Figure 4.1). The cost of the commercialization effort and technology transfer activities was $3 million, including in-kind support. A total cash amount of $1.8 million was awarded by a consortium, consisting of private sector sponsors including Southern California Gas Company, Pacific Gas and Electric Company, Southern California Edison

Figure 4.1. Continuous Microwave and Vacuum Liquid Media Dehydration System - Commissioned March, 1991.

Company, California Agricultural Technology Institute, and food companies for construction of the facility.

4.2. OBJECTIVES

The prediction models described in Sections 2 and 3 exhibited a high degree of reliability as indicated by the r^2-values. Although some factors such as microwave coupling efficiency (Decareau, 1985) may be different, the initial operating parameters used in the continuous microwave vacuum dehydration system were based on these models.

The values for time, specific energy, and temperature determined by the prediction models that produced dried grapes with the desired character were used for operation of the microwave vacuum system. Results of the liquid media experiments were also used as a starting point to determine the optimum pressure and temperature setting on the continuous system.

The objectives of the experiments in the continuous microwave vacuum dehydration system were to:

1. Use results of the experiment sets described in Sections 2 and 3 to determine the optimum process parameters for operation of the continuous microwave vacuum and liquid media dehydration systems,
2. Conduct experiments using grapes in the continuous process liquid media system,

3. Conduct experiments using grapes in the continuous process microwave vacuum system, and
4. Conduct experiments using the combination of both systems to produce puffed dried grapes.

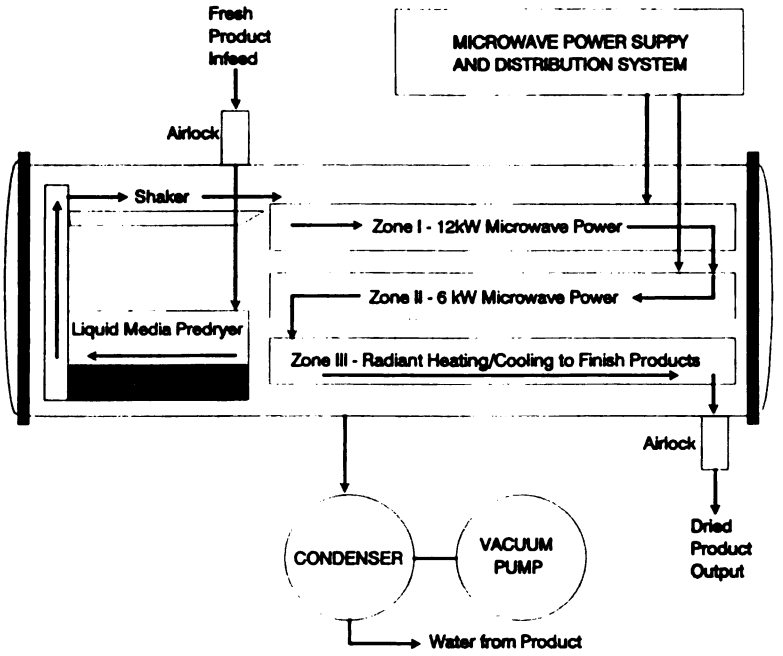
4.3. DESCRIPTION OF THE CONTINUOUS LIQUID MEDIA, MICROWAVE VACUUM DEHYDRATION SYSTEM

4.3.1. Process Flow.

The vacuum vessel (Figure 4.2) contained a liquid media dryer system, and a zoned microwave dehydration system (McKinney and Wear, 1989; Bertha, 1991). The grapes followed one of three process routes through the system:

a. **Full Process Flow.** The grapes were transported through the liquid media and the microwave dehydration systems.
b. **Microwave Only.** The grapes fed directly into the microwave system.
c. **Liquid Media Only.** The grapes entered the liquid media dehydration system and were discharged through the microwave conveyer system without being heated by microwave.

Full process flow consisted of processing grapes in the liquid media predryer for a time sufficient to reduce moisture content from about 80 percent to an estimated 50 percent. The grapes then entered the zoned microwave dehydration system. Microwave heating in zone I further reduced moisture content from an estimated 50 percent to about 20 percent. Subsequent exposure to heating in zone II



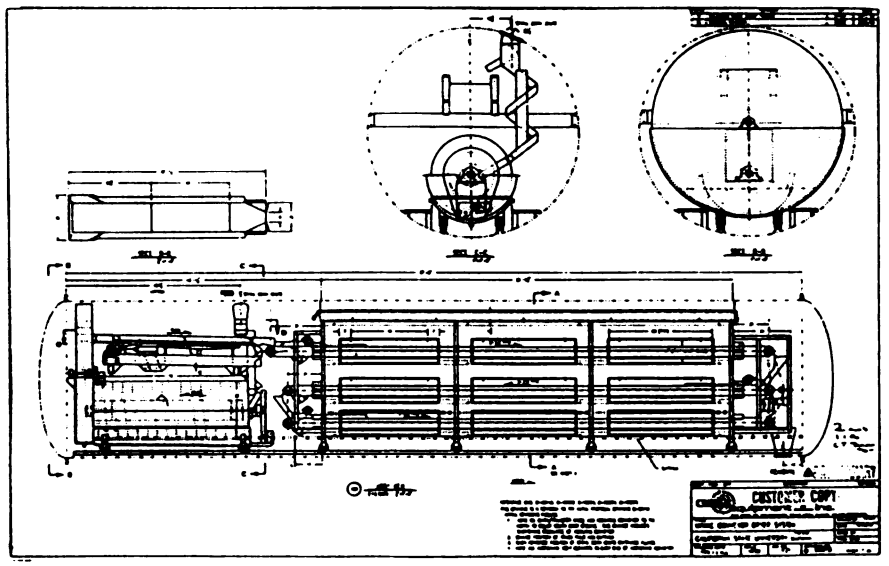


Figure 4.2. MIVAC Continuous Pilot Plant Process Flow and System Configuration.

dehydrated the grapes to about 7 percent. In zone III, the grapes passed under two steam heated infrared panels that induced more moisture loss and moisture equalization. A third panel was used to cool and harden the sugars in the dried grapes before discharge from the system. No microwaves were used in zone III.

Exposure of grapes to **microwave only** demonstrated application to dehydration of products with a low intermediate moisture content in the fresh state, products that had been predried by a method other than the liquid media dryer, or products with geometry and water loss potential greater than grapes, such as fruit or vegetables that had been sliced or diced, exposing the internal tissue.

The **liquid media** dehydration system was designed for predrying grapes for processing in the microwave system. In this process, the grapes remained in the liquid media for the duration of the dehydration process. Laboratory bench experiments had shown that low temperature and pressure treatments induced collapse of the fruit tissue upon itself, yielding wrinkled dried fruit that maintained a golden color resembling golden seedless raisins.

4.3.2. Description of System Components.

Vacuum Chamber. The vacuum chamber consisted of a horizontally mounted cylindrical vessel, 11.3 m (37 ft) long from flange to flange, and about 2.5 m (8 ft) in diameter. The ends of the vessel were sealed with dished heads that were removable using overhead monorails. The vessel was

constructed of type 304 stainless steel with a design pressure of one atmosphere external at 65 °C (150 °F). The chamber was mounted over an access area that contained equipment and piping.

Vacuum Pumping System. Gases and vapors were removed from the vacuum chamber by a vacuum pumping system piped through a modulating valve and a 15 cm (6 in.) PVC foreline. The pumping system was comprised of a Roots impeller pump, a water cooled condenser, and a rotary vane pump. This system was manufactured by Leybold Vacuum Products, Inc. Water and other condensed vapors were collected from the condenser into a receiving tank. Design specifications required a pumping capability of 8.2 kg/h (18 lb/h) of air and 36 kg/h (80 lb/h) of water vapor while maintaining a chamber pressure of 2.7 kPa (20 Torr). Pump down of the 60 m^3 (2100 ft^3) chamber from atmospheric pressure to 0.1 kPa (1 Torr) required less than 45 minutes under no gas load.

Infeed Airlock. Fresh grapes were delivered to the infeed airlock by an incline feed conveyer. The airlock consisted of two 15 cm (6 in.) diameter knifegate valves separated by a 15 x 15 cm clear Lexan interstage. With the lower valve in the closed position, the upper valve opened to admit fresh grapes into the airlock interstage. After a designated time, the feed conveyer stopped and the upper valve closed, isolating the grapes in the interstage. The interstage was evacuated to equalize the interstage pressure to that of the vacuum chamber, the lower valve opened, and

the grapes dropped into the chamber handling system. The lower valve closed, the interstage equalized with atmosphere, and the upper valve opened, ready to receive more grapes. Timing of the infeed airlock and feed conveyer was controlled by a timer and logic controller (PLC) at the panel. At a fresh product feed rate of 55 kg/h, about 1 kg of single grapes was discharged into the vessel each 1 min airlock cycle.

Liquid Media Dryer. The liquid media dryer, manufactured by GEM Equipment, Inc., consisted of four components. A spiral down chute was used to convey grapes from the infeed airlock to the media bath. A reel conveyer carried the grapes through the steam heated media bath. The grapes were collected at the end of the reel conveyer and transported to a shaker conveyer to remove excess media. Radiant panels were used to keep the grapes warm. The shaker discharged the grapes into zone I of the microwave drying system.

The liquid media dryer was designed to remove moisture from 55 kg/h (120 lb/h) of fresh grapes. The steam heated media bath and the radiant panel above the shaker conveyer were controlled in range of 55 to 95 °C and 95 to 200 °C (130 °F to 200 °F and 200 °F to 400 °F), respectively. Product residence time in the media dryer was adjustable from 60 to 180 minutes based on the rotational speed of the reel. The liquid media (Durkex 500) was circulated through

filters to remove any particles or contaminants. The media used in this system was Durkex 500.

Zoned Microwave Dryer. The zoned microwave dryer was also manufactured by GEM Equipment, Inc. It consisted of three separate conveyer systems (6 m long by 60 cm wide) stacked on top of each other to form a single module. The conveyers carried the grapes through three zones in a serpentine pattern.

Microwave chokes permitted the belt and grapes to enter and exit each zone without the microwave leakage from the zone into the chamber area. At the exit of zone I, the grapes dropped onto the inlet to zone II and travelled in the opposite direction to the transfer to zone III. The finished product dropped from the end of the Zone III conveyer into the outfeed airlock. The three belt conveyers were driven by a single hydraulic drive adjustable from 6 to 60 cm/min.

Microwave energy was used as a heat source in zones I and II at maximum levels of 12 and 6 kW, respectively. Steam heated infrared panels were used in zone III for finish drying. In addition, zone III incorporated a water cooled panel for cooling and setting Grape Puffs$_{tm}$ before discharge through the outfeed airlock.

Microwave Power and Distribution. The microwave power generators were manufactured by Gerling Laboratories. The distinctive characteristic of these power sources was that each used two separate 3 kW, medium ripple power sources in

a single NEMA 12 rated enclosure. The power sources had a cumulative output of 18 kW.

The forward power from the microwave power generators was distributed to the respective zones via waveguides. Power to zone I was distributed using four waveguides directed though the top of the chamber. A polypropylene window was mounted at each vessel penetration to preserve the vacuum boundary, and allowed passage of the microwave energy into each zone. Similar distribution of microwave energy was accomplished in zone II using waveguides and microwave windows through the side of the vacuum chamber.

Product Outfeed Airlock. In the rest position, the outfeed airlock upper valve remained open to receive grapes, and the lower valve closed to maintain a vacuum boundary. A small vent and valve let air into the airlock interstage and the airlock receiving hopper to purge stray water vapor from the finished product. When the interstage was filled with dried grapes, the upper valve closed, the interstage was vented to atmosphere, and the lower valve opened discharging the dried grapes from the system. The airlock returned to the rest position by closing the lower valve, venting the interstage to vessel pressure, and opening the upper valve. The timing of the airlock was controlled by a timer and PLC at the panel.

Auxiliary Systems. The process was supported by a cooling tower designed to provide 260 L/min at 27 °C and 241 kPa (71 gal/min at 80 °F and 35 psig) for use by the vacuum

pumping system condenser, the zone III cooling panel, hydraulic power unit cooling, and cooling of the microwave power generators.

A gas fired steam system was used to produce 45 kg/h (100 lb/h) of steam at 90 kPa (13 psig) for use by the liquid media dryer, Zone III radiant panels, vacuum chamber preheating, and cleaning stations. Condensate from several systems was returned to the steam generator.

Control System. Control at the panel included inclined feed conveyer speed, airlock timers, vessel pressure, cooling tower, hydraulic conveyers, and liquid media temperature. Process conditions were monitored at the control panel including temperature measured by infrared detectors as the grapes emerged from each zone, zone III panel temperatures, vessel pressure, and alarm status including stopped belts, infrared panel high temperature, vacuum system high temperature, high condensate at the vacuum pump, and boiler low water level. The microwave power supplies were operated at their respective consoles.

The infrared detectors used in the continuous system were similar to the detector used in the batch unit, however these detectors viewed the grapes as they emerged from each microwave zone. It was anticipated that the temperature readings would be representative of actual temperature of the grapes since there was no interference from the microwaves.

System safety included alarms and a key interlock system that prompted a procedure for inspecting and preparing the vacuum chamber for closure and evacuation. Following the completion and sign off on this procedure, the chamber doors were closed and locked, allowing the keys to be removed and placed in the control panel to allow system operation.

Each microwave power generator was equipped with several interlocking devices to prevent inadvertent power output in non-process conditions. The interlock system required that cooling water be supplied, the vacuum chamber pressure be below 13 kPa (100 Torr), and the zoned microwave conveyer system be in operation.

Energy Monitoring System. Pacific Gas and Electric Co. installed a data logging system and related current transducers to monitor major natural gas and electrical power systems including the steam generator, vacuum pumping system, and the microwave power supplies. This system recorded data to calculate the operating costs and efficiencies of the continuous pilot scale MIVAC facility. The energy logging system scanned power and gas use 120 times per minute, averaged the values, and stored them on disk. The specific points of measurement included:

Metered natural gas at steam generator.

Main electrical service feed.

Each microwave electrical disconnect.

Microwave power (forward and reflected).

Vacuum pumping system.

Office and laboratory.

4.4. MATERIALS AND METHODS

4.4.1. Test Procedures.

The experiments included evaluation of the liquid media system, the zoned microwave system, and a combination process using the liquid media as a predrying step and the microwave system as a finish dryer. Specifically, the experiments included:

a. Tests using microwave only based on the specific energy defined in the laboratory experiments to produce puffed dried grapes,

b. Tests based on laboratory experiments using the liquid media system only to produce puffed dried grapes,

c. Tests using the liquid media system to produce golden raisins without sulfur based on laboratory experiments, and,

d. Tests using a combination of the liquid media and microwave systems to produce a puffed dried grape.

Hand harvested, natural Thompson Seedless grapes were used in all the experiments. The grapes were separated from the cluster stems, washed, and metered into the infeed conveyer. At the start of each experiment, the product handling system was set to the desired infeed rate, including the rotational speed of the liquid media auger and

microwave system belt speed. The vessel was carefully inspected, closed and sealed, and the vacuum system pumped down the vessel to 2.7 kPa. Depending on the experiment, the liquid media system and zone III radiant panels were heated to specified temperatures.

As the grapes entered the system, key events were noted including the time the grape sample emerged from each process. Vessel pressure, liquid media temperature, the grape temperature at the exit of each zone, and zone III panel temperature were recorded.

In tests using the microwave system, a ramp up procedure was used to minimize overheating. Since microwaves require grapes to absorb the energy, the microwave power was increased in steps as the conveyer system filled each zone with grapes. Once each zone was full, the treatment level of microwave power was set and maintained at a constant level.

At the end of the experiment, all systems were stopped and the vessel was vented to atmosphere and opened. This procedure permitted examination of grape samples at various stages in the process. Depending on the experiment, grape samples were collected from the infeed conveyer, at the discharge from the liquid media system, and at the beginning, middle, and end of each zone. The samples were analyzed for moisture content by vacuum oven. These data were used to determine the effect of the liquid media treatments including temperature and process time, and the

microwave treatments including the specific energy in each zone, on the moisture content of the samples.

4.4.2. Treatment Plan.

The treatment plan using the liquid media and microwave systems was based on the results of the laboratory experiments. Treatments are shown in Table 4.1. The following measurements were recorded for each experiment depending on the treatment plan.

Independent Variables.

Initial Moisture Content (IMC).

Initial Grape Sugar Content (°Brix).

Liquid Media Temperature.

Liquid Media Residence Time (min).

Forward and Reflected Microwave Power Level (W).

Microwave Residence Time (min).

Specific Energy (W-h/g fresh grapes).

System energy use.

Dependent Variables.

Moisture Content Profile.

Final Moisture Content (FMC).

Product Description (color, shape, texture).

4.5. RESULTS AND DISCUSSION

4.5.1. Microwave Vacuum Dehydration Test.

Production of puffed dried grapes using the microwave vacuum dehydration system only was accomplished on a continuous basis in two tests lasting 8.7 and 11.6 hours.

Table 4.1

Microwave Vacuum - Liquid Media
Continuous Process Treatments

Test	Type	Dried Product	Media Temperature (°C)	Vessel Pressure (kPa)	Feed Rate (kg/h)	Process Time (min)
1	MW	Puffed	--	2.6	13.6	90
2	MW	Puffed	--	2.6	13.6	90
3	LM	Puffed	74	12.0	27.2	180
4	LM	Puffed	71	12.0	13.6	150
5	LM	Raisin	71	12.0	13.6	150
6	LM	Raisin	68	12.0	13.6	120
7	LM/MW	Puffed	66	2.6	32.7	60/90
8	LM/MW	Puffed	66	2.6	32.7	60/90
9	LM/MW	Puffed	66	2.6	36.3	60/90

LM = Liquid Media
MW = Microwave

Fresh single grapes were fed into the microwave system at a rate of 13.6 kg/h. Based initially on the results of the laboratory batch microwave vacuum experiments, microwave power was applied in the continuous system at an initial specific energy of 0.86 W-h/g fresh grapes. In both tests, product overheating was observed, and microwave power was reduced to 0.81 W-h/g fresh grapes for tests 1 and 2 (Table 4.2). This reduction in specific energy may have been offset by the heat energy applied in the zone III infrared panels. The results of these tests was dehydration of grapes from a fresh initial moisture content of 75 to 76 percent, to a final moisture content of 3 to 4.5 percent. It took 1.5 hours for product to enter zone I and exit zone III. The dried puffed grapes were similar to the fresh grapes used, exhibiting a natural color, berry shape, flavor, and a crunchy, crisp texture. Based on an electric rate of $0.135 per kW·h, and a gas rate of $0.565 per therm, cost to produce the dried grape was under $2.00/kg.

Table 4.2

Microwave Vacuum Continuous Process Tests for Production of Grape Puffs

Test	Vessel Pressure (kPa)	Feed Rate (kg/h)	IMC (%)	FMC (%)	Specific Energy (W-h/g)	Energy Cost ($/dry kg)
1	2.6	13.6	76.5	4.5	0.808	1.93
2	2.6	13.6	75.4	3.0	0.812	1.99

Observation of the temperature of the grapes as they emerged from microwave zone I indicated a temperature of about 26.6 °C (80 °F). This temperature was representative of the boiling point of pure water at the pressure used in the process.

Since the grapes were almost dry at the exit of zone II, the temperature of the grapes was about 48.9 to 54.4 °C (120 to 130 °F). If the temperature exceeded 55 °C, burning was observed.

Since the infrared detectors used in the continuous system monitored the grapes as they emerged from each zone, it is suggested that temperatures of 66 to 71 °C (150 to 160 °F) observed during tests in the laboratory batch system were shifted upward 11 to 17 °C (20 to 30 °F) from the actual temperature of the grapes. The shift in the temperature reading may have been caused by using the infrared detector in the microwave field.

4.5.2. Grape Puffs Produced in Liquid Media.

The information collected in tests 3 and 4 focused on product handling. Initial and final moisture contents were not evaluated. Nevertheless, dried puffed grapes were produced successfully. At feed rates of 27.2 and 13.6 kg/h, Perlette and natural Thompson Seedless grapes were dried in the liquid media system from an estimated 78 percent initial moisture content to under 5 percent final moisture content. The process time was 3 hours and 2.5 hours, and the test duration was 3.3 and 3.5 hours, in tests 3 and 4,

respectively. The grapes exhibited a crisp, somewhat caramelized texture with a light residue of oil evident. Based on an electric rate of $0.135 per kW·h, and a gas rate of $0.565 per therm, cost to produce the dried grape was $0.458 and $1.037/kg of dried product in tests 3 and 4, respectively (Table 4.3).

Table 4.3

Liquid Media Continuous Process Tests for Production of Puffed Grapes

Vessel Pressure 12.0 kPa

Test	Media Temperature (°C)	Feed Rate (kg/h)	IMC (%)	FMC (%)	Process Time (h)	Energy Cost ($/dry kg)
3	74	27.2	78.0	5.0	3.0	0.458
4	71	13.6	80.4	5.0	2.5	1.037

4.5.3. Liquid Media Continuous Process Tests for Production of Golden Raisins.

Production of dried grapes exhibiting the character of Golden Seedless raisins was accomplished at a pressure of 12.0 kPa and a feedrate of 13.6 kg/h (Table 4.4). The dried product was collapsed with a wrinkled appearance and a leathery texture typical of conventional dried fruit. Although no sulfites were used, this product had a bright yellow-golden color. As in tests 3 and 4, initial and final moisture content was not recorded, but was estimated to be about 78 and 10 percent, respectively. Process time was 2.5 hours in test 5 and 2 hours in test 6. The duration of the

tests was 4 and 3 hours, respectively. Cost of production based on the same electric and gas rates as earlier tests was about $1.00/kg. As a reference, the energy cost for production of grapes treated with sulfites, and dried using heated air was about $0.365/kg of dried product (Clary and Moso, 1983). This difference in cost may be offset by the benefit of producing the golden raisin product without the use of sulfites, although color retention over the life of the product must be considered.

Table 4.4

Liquid Media Continuous Process Tests for Production of Golden Raisins

Vessel Pressure 12.0 kPa

Test	Media Temperature (°C)	Feed Rate (kg/h)	IMC (%)	FMC (%)	Process Time (h)	Energy Cost ($/dry kg)
5	71	13.6	78	10	2.5	1.049
6	68	13.6	78	10	2.0	0.985

4.5.4. Combination Liquid Media, Microwave Vacuum Continuous Process Tests for Production of Puffed Grapes.

In tests 7, 8, and 9, processing through the liquid media and microwave systems at 33 to 36 kg/h produced a puffed, dried grape with a crisp texture and original color. There was no difference in product character between the tests. This product was comparable to grapes dried only in the microwave system except for a residue of oil from the

liquid media processing. The oil made the dried grapes less sticky and more free-flowing.

In the original design, it was estimated that the liquid media system removed about half of the moisture. In tests 7 and 8, the liquid media system reduced the moisture content of the grapes to 8.5 percent (wet basis), and the microwave system finish dried the grapes to a final moisture content of 1.9 and 1.5 percent in tests 7 and 8, respectively (Table 4.5). In test 9, intermediate moisture content was 29.0 percent and final moisture content was 8.7 percent. Process time was 2.5 hours in all combination tests. The duration of test 7 was 1.8 hours, 3.5 hours in test 8, and 4 hours in test 9.

Energy costs were $0.683 and $0.593/kg in tests 7 and 8, and $0.452/kg in test 9. The lower energy cost in test 9 was mostly likely due to the relatively high final moisture content.

Table 4.5

Combination Liquid Media, Microwave Vacuum Continuous Process Tests for Production of Puffed Grapes

Vessel Pressure 2.6 kPa

Test	Media Temperature (°C)	Feed Rate (kg/h)	Transfer IMC (%)	Transfer MC (%)	Transfer FMC (%)	Process Time (h)	Energy Cost ($/dry kg)
7	66	33	76.2	8.5	1.9	2.5	0.683
8	66	33	73.0	8.5	1.5	2.5	0.593
9	66	36	68.4	29.0	8.7	2.5	0.452

4.5.5. Conclusions of Continuous Process Tests.

The conclusions based on nine tests in the continuous process liquid media, microwave vacuum dehydration system were:

a. Grapes were successfully dehydrated using only microwave energy in a vacuum to produce a puffed, crispy grape.

b. Dried puffed grapes were also produced using only the liquid media dehydration system. This product was similar to the grapes processed in the microwave system, except they had a slight oil residue and a caramelized flavor.

c. Golden raisins were produced using only the liquid media dehydration system. This product exhibited a wrinkled raisined character and a yellow-golden color without the use of sulfites.

d. The combination liquid media and microwave vacuum dehydration system performed successfully in producing puffed grapes in a continuous process.

5. SUMMARY AND CONCLUSIONS

5.1. SUMMARY

5.1.1. Microwave Vacuum Dehydration of Grapes.

Results from experiment sets in a laboratory batch microwave vacuum dehydration system indicated a relationship of microwave power level, application time, product temperature, and final moisture content. It was determined that microwave power should be reduced in stages as the moisture content of the grapes decreased over time. Application of microwave power based on time provided moderate results in drying grape samples. Controlling microwave power levels based on product temperature resulted in successfully producing a dried grape resembling fresh grapes including preservation of shape, color, and flavor without the use of preservatives.

The optimum specific energy to dry grapes from an initial moisture content of 78 percent to a final moisture content of less than 5 percent ranged from 0.80 to 0.90 W-h/g in 70 to 90 min. This specific energy was applied based on a maximum grape temperature of 65 °C as indicated by an infrared detector. Further analysis indicated that due to interaction with the microwave environment, the infrared detector reading was shifted upward about 10 °C. The actual

product temperature was about 55 °C based on observations during experiments in which infrared detectors were mounted outside the microwave environment.

5.1.2. Evaluation of Liquid Media Immersion on Moisture Loss in Grapes.

Durkex 500 was the most effective liquid media material evaluated for dehydration of grapes. This process proved successful in drying grape samples for finish drying in the microwave vacuum dehydration system using a laboratory configuration. Regression analysis indicated temperature and pressure were the most significant factors in determining the texture and final moisture content of the grape samples. Grape dehydration in liquid media heated to 80 °C at a pressure of 2 to 3 kPa resulted in a crisp, puffed grape. At 60 °C and 10 kPa, the dried grape product exhibited a wrinkled, collapsed texture resembling golden seedless raisins. Drying time ranged from 60 to 120 min.

5.1.3. Continuous Process Liquid Media and Microwave Vacuum Dehydration.

Application of microwave vacuum and liquid media dehydration proved successful using a continuous process in a commercial prototype system. The liquid media system performed as a predrying step for microwave finish drying and also fulfilled expectations as a technique for producing golden raisins without the use of sulfites. In combination with the microwave vacuum process, this continuous system processed 55 kg/h of fresh grapes into a dried grape product of less than 5 percent final moisture content. Processing

time was 2.5 hours. Based on an electric rate of $0.135 per kW·h, and a gas rate of $0.565 per therm, energy cost to produce the dried grape products ranges from $0.49 to $1.99/kg of dried product.

5.1.4. Commercial Application of Microwave Vacuum and Liquid Media Dehydration Technology.

Liquid media dehydration technology exhibits some potential for production of grapes and other fruit products. Several fruit products dried in this vacuum process are currently available. The residue of oil on the dried products presents considerations in light of public opinion related to dietary intake of fats. Nevertheless, this method of dehydration offers the advantage of preservation of many fresh product characteristics without the use of sulfites or other preservatives.

Use of liquid media dehydration for production of grapes finish dried using microwave vacuum dehydration has a significant impact on reducing the cost of the process. However, oil residue on the dried product remains a factor.

Although grapes discolor during dehydration in heated air, microwave vacuum dehydration technology used in conjunction with heated air dehydration offers distinct possibilities for dehydration of other fruits and vegetables. Predrying products to about 50 percent moisture content using heated air followed by finish drying using microwave vacuum processing reduces energy costs by more than 50 percent.

Initial commercial application of microwave vacuum dehydration technology is contingent on the capability of producing finished dried fruits, vegetables, and other food products with quality and character that justifies any premium in cost of production. The benefits of the technology include rapid dehydration and preservation of fresh product character including color, flavors, and appearance without the use of preservatives.

5.2. CONCLUSIONS

5.2.1. Microwave Vacuum Dehydration of Grapes.

Results from experiment sets in a laboratory batch microwave vacuum dehydration system indicated:

a. A relationship existed between microwave energy and time of exposure and their effect on product temperature and final moisture content of grapes. The total specific energy was 0.84 to 0.88 W-h/g for 90 minutes.

b. This range of specific energy based on time dried grapes to less than 5 percent that exhibited the integrity, shape, and color of the fresh grape.

5.2.2. Evaluation of Liquid Media Immersion on Moisture Loss in Grapes.

The conclusions of liquid media laboratory experiment sets 1 - 5 were:

a. Temperature and pressure were the primary factors in determining the texture and final moisture content of the dried grape product,

b. Liquid media dehydration showed potential for dehydration of grapes to a moisture content sufficient for processing in the microwave vacuum system.

5.2.3. Continuous Process Liquid Media and Microwave Vacuum Dehydration.

Tests completed using a continuous process liquid media and microwave vacuum dehydration system indicated:

a. Grapes were successfully dehydrated using only microwave energy in a vacuum to produce a puffed, crispy grape.

b. Dried puffed grapes were also produced using only the liquid media dehydration system. This product was similar to the grapes processed in the microwave system, except they had a slight oil residue and a caramelized flavor.

c. Golden raisins were produced using only the liquid media dehydration system. This product exhibited a wrinkled raisined character and a yellow-golden color without the use of sulfites.

d. The combination liquid media and microwave vacuum dehydration system performed successfully in producing puffed grapes in a continuous process.

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6. LITERATURE CITED

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APPENDICES

APPENDIX 7.1

THE ELECTROMAGNETIC SPECTRUM

A table of the electromagnetic spectrum (Table 7.1) is included as a reference. A microwave frequency of 2450 MHz was selected in the experiments described in this dissertation. This frequency falls in the range of radio frequencies in the ultra high frequency band (UHF). The wavelength of 2450 MHz is 12.2 cm which is designated as being within the S band.

APPENDIX 7.1

THE ELECTROMAGNETIC SPECTRUM

Table 7.1.1
The Electromagnetic Spectrum
(Thuery, 1991)

Region	Frequency Range	Wavelength
Audiofrequencies	30 Hz - 30 kHz	10 Mm - 10 km
Radiofrequencies	30 kHz - 300 GHz	10 km - 1 mm
Infrared	3×10^{11} - 4.1×10^{14} Hz	1 mm - 730 nm
Visible	4.1×10^{14} - 7.5×10^{14} Hz	730 nm - 400 nm
Ultraviolet	7.5×10^{14} - 10^{18} Hz	400 nm - 0.3 nm
X rays	>10^17 Hz	<3 nm
Y rays	>10^20 Hz	<3 pm
Cosmic rays	>10^20 Hz	<3 pm

Frequency Bands
(Thuery, 1991)

Band	Designation		Frequency limits
4	VLF	very low frequency	3 kHz - 30 kHz
5	LF	low frequency	30 kHz - 300 kHz
6	MF	medium frequency	300 kHz - 3 MHz
7	HF	high frequency	3 MHz - 30 MHz
8	VHF	very high frequency	30 MHz - 300 MHz
9	UHF	ultra high frequency	300 MHz - 3 GHz
10	SHF	super high frequency	3 GHz - 30 GHz
11	EHF	extremely high frequency	30 GHz - 300 GHz

Microwave Bands
(Thuery, 1991)

Designation	Frequency Limits (GHz)	Wavelength (cm)
P	0.225 - 0.39	133.3 - 76.9
L	0.39 - 1.55	76.9 - 19.3
S	1.55 - 5.20	19.3 - 5.77
X	5.20 - 10.90	5.77 - 2.75
K	10.90 - 36.00	2.75 - 0.834
Q	36.00 - 46.00	0.834 - 0.652
V	46.00 - 56.00	0.652 - 0.536
W	56.00 - 100.00	0.536 - 0.300

APPENDIX 7.2

ENERGY CALCULATION FOR MICROWAVE POWER APPLICATION TO GRAPES

The following Tables 7.2.1 - 7.2.4 summarize the estimation of the amount of microwave energy that is theoretically required to remove water from grapes. The calculation for the energy needed is based on energy to warm the water and solids in the grape sample, and the energy required to induce vaporization of the water from the grapes. These calculations are based on the assumptions outlined below and shown in the Table 7.2.1.

Tables 7.2.5 - 7.2.8 show the same calculations based on the results of the temperature based experiment sets described in Section 2.

These calculations were based on the following factors.

1. Initial moisture content (IMC).
2. Sensible heat energy necessary to warm the water and dry matter components of the grape sample.
3. The energy required to induce vaporization of water.
4. The additional energy needed to vaporize water from the matrix of soluble solids.
5. The coupling efficiency of the microwave power with the grapes.
6. The power application regime consisting of adjusting the level of microwave power based on either time or temperature of the grape sample.

APPENDIX 7.2

ENERGY CALCULATION FOR MICROWAVE POWER APPLICATION TO GRAPES

Table 7.2.1

Assumptions for Calculation of Energy Required to Dehydrate Grapes

Product Mass (grapes) =	1.8 kg
Initial Moisture Content (IMC) =	78 %
Final Moisture Content (FMC) =	3 %
Initial Temperature =	21 °C
Final Temperature =	49 °C
Specific Heat of Dry Matter =	0.40
Estimated latent heat of water in product =	2559 kJ/kg
Estimate Microwave Coupling Efficiency =	0.40
kJ to W-h conversion =	3600 kJ/kW-h

Table 7.2.2

Calculation of the Quantity of Water to be Removed from a Grape Sample

(1.8 kg fresh grapes) x (0.78 IMC) = 1.4 kg water content

(1.8 kg fresh grapes) - (1.4 kg water) = 0.4 kg dry matter

$$\frac{0.03\ FMC}{(1 - 0.03)} \times 0.40 \text{ kg dry matter} = 0.012 \text{ kg water in product}$$

(1.8 kg fresh grapes) - (0.40 kg dry matter) -
- (0.012 kg water in product) = 1.39 kg water removed

APPENDIX 7.2

ENERGY CALCULATION FOR MICROWAVE POWER APPLICATION TO GRAPES

Table 7.2.3

Calculation of the Energy Needed to Warm the Grape Sample and Induce Vaporization of Water

Sensible Heat of Water in Product:	
Delta T = (49 - 21 °C) = 28 °C	
28 °C x $\frac{1\ kJ}{°C\ kg}$ x 1.40 kg water in product =	39.3 kJ
Sensible Heat of Water in Dry Matter:	
28 °C x $\frac{1\ kJ}{°C\ kg}$ x 0.4 x 0.40 kg dry matter =	4.4 kJ
Latent Heat of Water Removed:	
1.39 kg water removed x $\frac{2559\ kJ}{kg}$ =	3561.5 kJ
Energy Required to Remove 1.39 kg water =	3605.2 kJ
3605.2 kJ x (kW/3600 kJ) =	1.0 kW-h
Microwave Energy @ 0.4 Coupling Efficiency =	2.5 kW-h

Table 7.2.4

Theoretical Specific Energy Required to Dehydrate Grapes

SPECIFIC ENERGY - W-h/g FRESH GRAPES		
2500 W-h / 1.8 kg	=	1390.0 W-h/kg
	=	1.4 W-h/g

APPENDIX 7.2

ENERGY CALCULATION FOR MICROWAVE POWER APPLICATION TO GRAPES

Table 7.2.5

Calculation of Energy Using the Results Temperature Based Experiments Described in Section 2

Product Mass (grapes) =	1.8 kg
Initial Moisture Content (IMC) =	**76.9%**
Final Moisture Content (FMC) =	**4.7%**
Initial Temperature =	**25 °C**
Final Temperature =	**71 °C**
Specific Heat of Dry Matter =	0.40
Estimated latent heat of water in product =	2559 kJ/kg
Estimate Microwave Coupling Efficiency =	**0.65**
kJ to W-h conversion =	3600 kJ/kW-h

Table 7.2.6

Calculation of the **Actual** Quantity of Water to be Removed from a Grape Sample

(1.8 kg fresh grapes) x (0.77 IMC) = 1.4 kg water content
(1.8 kg fresh grapes) - (1.4 kg water) = 0.42 kg dry matter

$$\frac{0.04\ \text{FMC}}{(1 - 0.04)} \times 0.42 \text{ kg dry matter} = 0.021 \text{ kg water in product}$$

(1.8 kg fresh grapes) - (0.42 kg dry matter) -
- (0.02 kg water in product) = 1.37 kg water removed

APPENDIX 7.2

ENERGY CALCULATION FOR MICROWAVE POWER APPLICATION TO GRAPES

Table 7.2.7

Calculation of the Actual Energy Needed to Warm the Grape Sample and Induce Vaporization of Water

Sensible Heat of Water in Product:
Delta T = (71 - 25 °C) = 46 °C

46 °C x $\frac{1\ kJ}{°C\ kg}$ x 1.4 kg water in product = 64.2 kJ

Sensible Heat of Water in Dry Matter:

46 °C x $\frac{1\ kJ}{°C\ kg}$ x 0.4 x 0.42 kg dry matter = 7.7 kJ

Latent Heat of Water Removed:

1.38 kg water removed x $\frac{2559\ kJ}{kg}$ = 3517.0 kJ

Energy Required to Remove 1.38 kg water = 3588.9 kJ
3588.9 kJ x (kW/3600 kJ) = 1.0 kW-h

Microwave Energy @ 0.65 Coupling Efficiency = 1.5 kW-h

Table 7.2.8

Actual Specific Energy Required to Dehydrate Grapes

ACTUAL SPECIFIC ENERGY - W-h/g FRESH GRAPES
1500 W-h / 1.8 kg = 845.3 W-h/kg
= 0.85 W-h/g

APPENDIX 7.3

RESULTS OF EXPERIMENT SETS 1 TO 6

These data are discussed in Section 2 and presented here as reference. Tables 7.3.1 and 7.3.2 show the actual levels of power applied, the time the power was applied in each stage, the specific energy resulting from the power-time application, and the fresh fruit sugar and moisture content. These are treatment means of 3 replications. Tables 7.3.3 and 7.3.4 summarize the weight loss, the final moisture content and character of the dried grape samples.

APPENDIX 7.3

RESULTS OF EXPERIMENT SETS 1 TO 6

Table 7.3.1
Results of Experiment Set 1 - Microwave Power was Applied at the Levels and Times Indicated (3 replications per treatment) (Sample Weight: 907g)

Microwave Power (W)	Time (min)	Watt Density (w/gm)	Sugar (Brix)	IMC (%)	Final Temperature (°C)	Final Weight (g)	FMC (%)
500	30	0.28	16.5	83.3	43	675	74.7
500	60	0.55	19.0	79.5	54	420	58.4
500	90	0.83	17.0	82.1	77	215	20.2
750	30	0.41	17.0	82.6	52	540	66.7
750	60	0.83	18.5	81.4	85	215	18.3
750	90	1.24	20.0	81.0	113	195	10.9
1000	30	0.55	18.5	81.6	54	245	46.4
1000	60	1.10	18.6	84.9	102	195	15.7
1250	30	0.69	16.6	83.1	60	325	43.6
1250	60	1.38	17.9	80.7	96	190	16.1
1500	30	0.83	18.2	81.2	88	220	19.5

Table 7.3.2
Results of Experiment Set 2 - Microwave Power was Applied at the Levels and Times Indicated (3 replications per treatment) (Sample Weight: 907g)

Microwave Power (W)	Time (min)	Watt Density (w/gm)	Sugar (Brix)	IMC (%)	Final Temperature (°C)	Final Weight (g)	FMC (%)
500	30	0.275	18.6	79.3	49	752	75.5
500	60	0.551	19.0	78.5	38	549	65.3
500	90	0.826	20.0	79.1	35	254	24.3
750	30	0.413	20.1	80.9	32	91	67.4
750	60	0.826	18.1	81.0	46	235	21.8
750	90	1.239	19.2	81.4	49	222	20.6
1000	30	0.551	19.0	79.3	43	367	50.4
1000	60	1.101	19.1	81.7	46	218	17.0
1250	30	0.688	18.0	79.6	49	299	37.8
1250	60	1.377	16.1	80.7	63	191	15.4
1500	30	0.826	16.1	83.1	66	218	19.8

APPENDIX 7.3

RESULTS OF EXPERIMENT SETS 1 TO 6

Table 7.3.3

Results of Experiment Set 3 - Microwave Power was Applied in Stages of 3000, 1500, and 500W for the Times Indicated (1 replication per treatment) (Sample Weight: 1814g)

Power Application				Specific Energy				Product Character		
Stage1 Time@ 3000W	Stage2 Time@ 1500W	Stage3 Time@ 500W	Total Time (min)	Stage1 W-h/g	Stage2 W-h/g	Stage3 W-h/g	Total W-h/g	Brix (%)	Moisture (%) Initial	Final
5	44	0	49	0.14	0.61	0	0.74	13.6	81.6	18.0
10	32	0	42	0.28	0.44	0	0.72	17.0	80.1	24.0
15	24	0	39	0.41	0.33	0	0.74	14.6	85.4	54.8
20	14	0	34	0.55	0.19	0	0.74	16.8	81.9	22.9
25	10	0	35	0.69	0.14	0	0.83	14.6	85.6	20.9
28	0	0	28	0.77	0.00	0	0.77	17.4	81.9	28.7

APPENDIX 7.3

RESULTS OF EXPERIMENT SETS 1 TO 6

Table 7.3.4

Results of Experiment Set 4 - Microwave Power was Applied in Stages of 3000, 1500, and 500W for the Times Indicated (1 replication per treatment) (Sample Weight: 1814g)

Power Application				Specific Energy				Product Character		
Stage1 Time@ 3000W	Stage2 Time@ 1500W	Stage3 Time@ 500W	Total Time (min)	Stage1 W-h/g	Stage2 W-h/g	Stage3 W-h/g	Total W-h/g	Brix (%)	Moisture (%) Initial	Final
10	20	78	108	0.28	0.28	0.36	0.91	16.2	80.6	7.7
10	30	32	72	0.28	0.41	0.15	0.84	18.8	81.2	8.0
10	40	37	87	0.28	0.55	0.17	1.00	17.5	81.7	11.5
20	10	40	70	0.55	0.14	0.18	0.87	16.8	82.4	16.7
20	18	0	38	0.55	0.25	0	0.80	19.0	80.9	23.4
20	16	0	36	0.55	0.22	0	0.77	16.0	83.2	21.7

APPENDIX 7.3

RESULTS OF EXPERIMENT SETS 1 TO 6

Table 7.3.5

Results of Experiment Set 5 - Microwave Power was Applied in Stages of 3000, 1500, and 500W for the Times Indicated (3 replications per treatment) (Sample Weight: 1814g)

Power Application					Product Character					
Stage1 Time@ 3000W	Stage2 Time@ 1500W	Stage3 Time@ 500W	Total Time (min)	Specific Energy W-h/g	Brix (%)	IMC (%)	Puffed (%)	Burnt (%)	Chewy (%)	FMC (%)
5	20	80	105	0.78	21.6	76.6	5.8	0	94.2	17.8
5	30	72	107	0.88	20.9	77.7	63.3	11.6	25.1	7.1
5	40	49	94	0.91	19.7	78.4	70.1	15.7	14.2	3.5
10	20	73	103	0.89	20.5	77.6	60.0	11.5	28.5	6.7
10	30	29	69	0.82	22.4	77.1	69.0	4.9	26.1	7.1
15	25	28	68	0.88	22.1	76.4	60.9	10.0	29.2	7.2
15	30	8	52	0.86	19.1	82.7	34.9	41.8	23.3	10.0
20	10	5	35	0.71	20.7	78.1	0	0	100.0	36.5

APPENDIX 7.3

RESULTS OF EXPERIMENT SETS 1 TO 6

Table 7.3.6

Results of Experiment Set 6 - Microwave Power was Applied in Stages of 3000 W Until the Temperature Approached the Treatment Level and the Power was Reduced to 1500 and 500W as Needed (3 replications per treatment) (Sample Weight: 1814g)

Treatment Temperature (°C)	Total Time@ (min)	Specific Energy W-h/g	Brix (%)	IMC (%)	Puffed (%)	Burnt (%)	Chewy (%)	FMC (%)	Texture
54	103	0.784	23.3	76.5	4.4	2.0	93.6	88.3	Chewy
60	81	0.786	22.1	77.2	20.1	3.8	76.1	66.4	Chewy
66	91	0.875	22.1	76.5	80.3	5.7	14.0	67.1	Crisp
71	70	0.840	21.8	76.9	80.3	11.4	8.3	66.7	Crisp
77	66	0.881	21.9	77.2	67.2	20.6	12.2	53.1	Crisp

all samples puffed and golden

APPENDIX 7.4

PROPERTIES OF SATURATED WATER VAPOR

Figure 7.1 describes the relationship of the boiling point of pure water and pressure. Figure 7.1 presents the basic relationship of absolute pressure and boiling point of water.

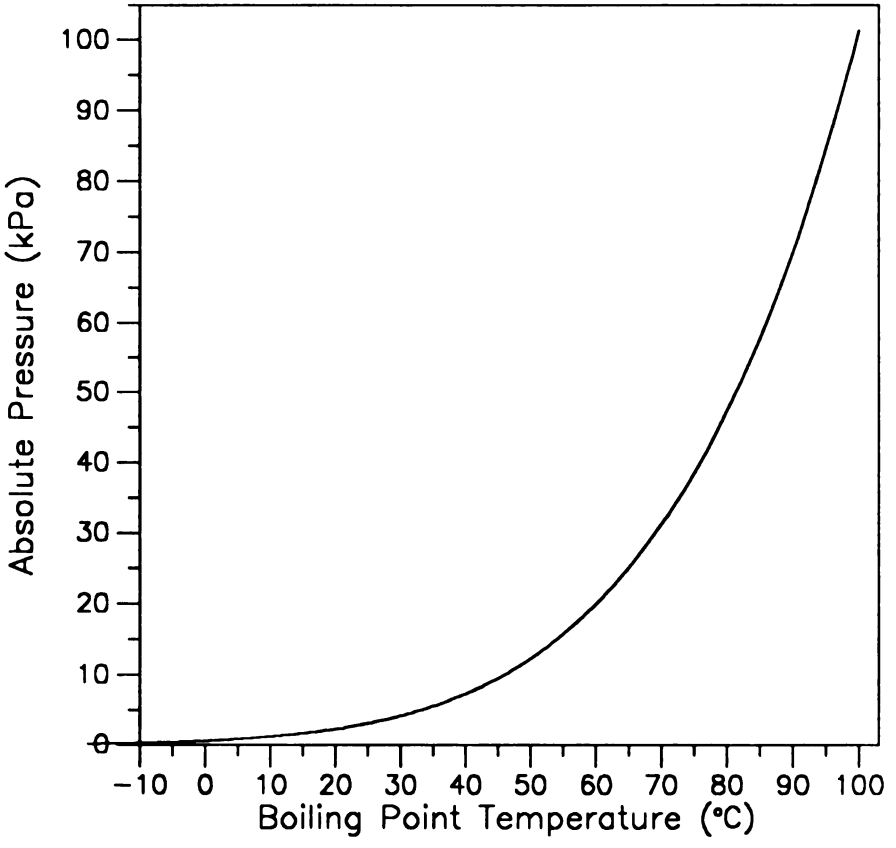

Figure 7.1. Properties of Saturated Water Vapor. Source: Handbook of American Society of Heating and Ventilating Engineers, 1951, Table 3, page 43. Compiled by J. Goff and S. Gratch.

APPENDIX 7.5

CONTINUOUS PROCESS ENERGY LOGS

The following energy log presents records for each of the tests conducted in the continuous microwave vacuum and liquid media dehydration systems. This information includes initial and final moisture content, feedrate, and total process time. Energy used is summarized for the major system components including microwave power supplies, the vacuum pumping system, and other systems to provide a total of gas and electric use. Based on the utility rates and the quantity of product dried and water removed, a processing cost is shown.

Electric Rate	$0.135/kWh
Gas Rate	$0.565/kWh

APPENDIX 7.5

CONTINUOUS PROCESS ENERGY LOGS
MIVAC Pilot Plant System Energy Summary - 1992-1993

Test Number	1	2	3	4	5	6	7	8	9
Date	9/15	9/17	6/18	9/5	8/14	9/12	9/23	9/24	9/30
Process Method MW,LM,Both	MW	MW	LM	LM	LM	LM	BOTH	BOTH	BOTH
Initial Moisture (%)	78.0	78.0	78.0	78.0	78.0	78.0	76.2	73.0	68.4
Final Moisture (%)	4.5	3.0	5.0	5.0	10.0	10.0	1.5	1.5	8.7
Feedrate (lb/h)	30	30	60	30	30	30	72	72	80
Test Duration (h)	8.7	11.6	3.3	3.5	4.1	2.9	1.8	3.5	3.9
Microwave (kW)	172	231	0	0	0	0	19.4	32.0	51.3
Vacuum Pump (kW)	121	168	36	39	42	34	26.4	50.3	56.5
Auxillary Systems (kW)	93	127	34	45	61	35	25.4	51.1	54.2
Total Electrical (kW)	386	526	71	84	103	69	71.2	133	162
Total Gas Use (kBTUh)	651	913	271	288	387	273	320	812	754
Total Elect. Energy (kWh)	45	45	21	24	25	24	39	38	41
Total Gas Energy (kBTU)	75	79	82	82	96	95	177	233	192
Electric Cost ($/h)	6.01	6.12	2.89	3.23	3.44	3.23	5.31	5.17	5.56
Gas Cost ($/h)	0.04	0.04	0.04	0.05	0.05	0.05	0.10	0.13	0.11
Dry Matter Rate (lb/h)	6.6	6.6	13.2	6.6	6.6	6.6	17.2	19.4	25.3
Water Removal Rate (lb/h)	23.1	23.2	46.1	23.5	22.7	22.7	54.6	52.3	52.3
Specific Energy (W-h/g)	.808	.812	n/a	n/a	n/a	n/a	.145	.113	.179
Cost/lb Fresh Grapes	.202	.205	.048	.109	.116	.109	.075	.074	.071
Cost/lb Water Removed	.262	.266	.063	.142	.154	.145	.099	.101	.108
Cost/lb Dried Grapes	.876	.905	.208	.471	.476	.447	.310	.269	.205