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# VEGETABLE DRYING IN TWO NOVEL FOOD DRYERS

by

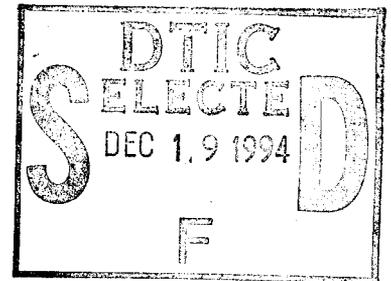
**Joseph Cohen, Christopher Rees, Linnea Hallberg,  
and Tom C.S. Yang**

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## **PREFACE**

A portion of the information in this report on parameters that affect drying of vegetables was presented at the 54th Annual Meeting of the Institute of Food Technologists, 1994, Atlanta, GA. The investigation took place during the period January 1993 to March, 1994. The research was funded by FTBB1313, Program ID:TB-PST.

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## VEGETABLE DRYING IN TWO NOVEL FOOD DRYERS

### Summary

The parameters that affect the drying of vegetables in a centrifugal fluidized bed dryer (CB) and a ball dryer (BD) were studied.

For the CB those parameters were: temperature of the drying air, air speed, rotational speed of the drying chamber. For the BD the parameters were: rotational speed of the drying balls, temperature of the drying chamber, feed rate to the chamber.

For the CB the only parameter that significantly affected the drying rate was the air temperature. For the BD the parameters of significant importance to the drying rate were the temperature of the drying chamber and the rotational speed of the drying balls.

Peas, green beans and carrots that were dried by these two methods as well as by freeze-drying (FD) and microwave augmented freeze-drying (MW) were compared to frozen, undried product for rehydration, texture and reflectance color.

The rehydration ratio values varied with the product. With peas the BD values were less than all the others. With beans the BD values were greater than all the others. This might be a reflection of the size and shape of the vegetable, relative cellular damage and the surface area covered by intact exterior tissue.

All the dried products were generally softer than the frozen control, except that the ball dried carrots were tougher. This reflects the severity of the drying process on the structural deterioration of the vegetables. The BD carrots seemed to exhibit a case-hardening effect.

There were generally no significant color differences shown except for slight differences for the "a" value of peas. The FD, both conventional and microwave, were less green. The frozen control and BD were more green, although differences were not great.

### Introduction

Fluidized bed dryers were first commercialized on a large scale by U.S. petroleum companies during World War II. The technique was first used for catalytic cracking to manufacture gasoline. The industry soon realized that the method was very

versatile and adapted it for such unit operations as fluid-bed coking, catalyst regeneration, platforming and ethylene manufacture. It also was used by the metallurgical and other elements of the chemical processing industry. The technique has the important characteristic of uniformity of both particle size distribution and temperature. This allows the operating conditions to be set within narrow limits, thus allowing scale-up from the laboratory to large commercial units. (Priestley, 1962).

The technique involves levitating particulate solids in an upward-flowing gas stream, usually hot air. The method mobilizes the solid particulates, thus creating intimate contact between the dry, hot carrier gas and the solids. At the proper gas flow rate the solids behave as liquids. Fluidization is dependent on the characteristics of the particles, i.e, size distribution, density, shape and viscosity. Carrier gas properties that contribute to fluidization include density and viscosity. (Rossi, 1984).

A typical commercial fluidized bed dryer used by the chemical industry has a reaction chamber that is fixed in place and is usually cylindrical in shape. The hot gas is typically introduced into the bottom of the preloaded bed and exits at the top. It is usually run as a batch process.

The design of such fluidized beds is well known (Frantz, 1962; Clark, 1967; Zenz, 1977). However, these designs were based on the chemical industry fixed bed reactor. The CB for food items uses a rotating rather than a fixed chamber. This should have the advantage of even more intimate contact between the particles and the carrier gas.

The CB has not been studied with foods in great depth. Farkas et al. (1969) determined that the pressure drop across the fluidized bed increased in proportion to the centrifugal force. Using diced carrots, they determined an equation for the air flow at minimum fluidization. Lazar and Farkas (1971) studied potato, apple and carrot pieces and determined that a skin layer developed during the early stages of drying that became increasingly resistant to heat and moisture transfer. Brown et al. (1972) used a CB to dry various piece-form foods, such as dried vegetables. Carlson et al. (1976) described a method for preparing quick-cooking rice products with a CB.

A well-designed CB would allow air flow rates to be much higher than conventional practical levels that are limited by the moisture migration rate of the

particles that are to be dried. This is because the centrifugal force would effectively counteract the force of the air that flows past the particles. Farkas et al. (1969) found that the new limits on the air flow would be a function of the centrifugal force, the pressure and volume of the air, the available heating capacity of the chamber, and the moisture diffusion rate in the piece.

Ball dryers have been less characterized. Best (1988) stated that the enhanced heat transfer rates that occur with the large surface area of the balls would allow a dryer to be run at a relatively low temperature, 140 °F (60 °C), and thus this method should have less food quality degradation than other drying techniques that occur at higher temperatures.

### **Equipment**

The CB used was an APV Mitchell™ (Dryers) Ltd centrifugal fluidized bed dryer. A schematic diagram of the dryer is shown in Fig. 1.

The product to be dried is placed in the drying chamber (A) and the door closed. The chamber is a rotating drum of 30 cm (12 in) diameter and 33 cm (13 in) in depth for a total volume of 23,300 cm<sup>3</sup> (1,470 in<sup>3</sup>). A steam preheater (B) heats outside air that is then sent through the blower (C) and up the inlet tube (D) prior to reaching the chamber. The temperature of the process air is controlled at (E). The rotational speed of the chamber is controlled with a variable speed drive (F). The flow rate of the inlet air is controlled with an opening (G) on the bottom of the column that can be varied to allow different amounts of the process air to escape. There is an additional vent on the top (H), an inlet (I) on the side of the column, and a damper (K) to allow or restrict recirculation of the process air. Air is returned to the preheater through the return line (J). The rotational speed and the temperature is continuously monitored during the actual processing. Temperature can be controlled to  $\pm 2$  °C under most conditions. Rotational speed can be controlled to  $\pm 1$  rpm. The flow rate is much more difficult to determine and control as explained below but it is estimated to fall within a range of  $\pm 0.14$  m<sup>3</sup>/s ( $\pm 5$  ft<sup>3</sup>/s). After each run the mass of the finished product was weighed with a scale that could measure  $\pm 0.05$  g ( $\pm 0.01$  lb).

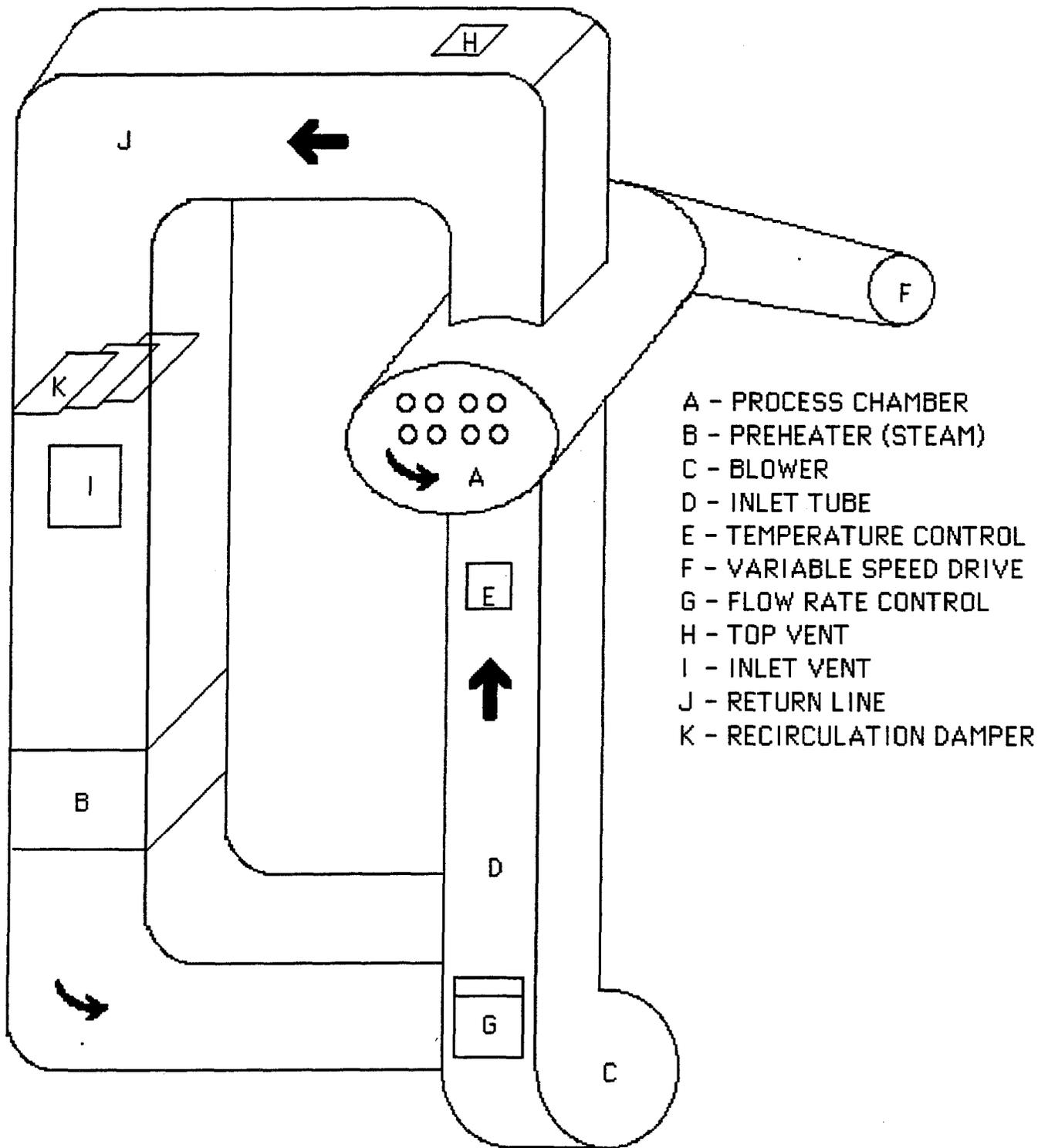


Figure 1 - SCHEMATIC DIAGRAM OF CENTRIFUGAL FLUIDIZED BED DRYER

The BD used was a Precision Drying Systems Model 25N™ ball dryer. A schematic diagram of this dryer is shown in Fig. 2. The material to be dried is added at the top of the drying chamber through a screw conveyor. It falls into the chamber and comes in contact with rotating heated Teflon™ balls. Heated air is continuously added to the chamber. Upon completion of the drying, the product is separated from the balls and is collected at the bottom of the chamber.

The variation in operating parameters can be controlled closely. Temperature can be controlled to  $\pm 2$  °C. Rotational speed can be controlled to less than 0.2 rpm. The feed rate is more difficult to control and care must be taken to insure that product does not jam up on the screw.

### **Control of Flow Rate of Air with the CB**

It was realized at the start of this study that the flow rate would be very important to the drying process. The temperature and rotational speed could both be measured continuously during the drying process, but the flow rate could not. The flow rate would change with the temperature of the inlet air and with position within the inlet tube. The rate is a function of the amount of air entering, but this could not be easily measured.

The solution to this problem was to cut a rectangular hole in the bottom of the inlet tube with a covering that could be varied. The size of the hole could then be changed to allow different amounts of process air to escape. The flow rate at different points of a cross section within the inlet tube (Fig. A-1) was then measured, at different temperatures, and then numerically integrated to determine an estimate of the total flow rate. (This is shown in the Appendix.)

### **Procedure**

Frozen whole peas of 0.8 to 1.0 cm (0.3 to 0.4 in) diameter, diced carrots of 0.8 to 1.0 cm on a side and cut green beans of 0.8 to 1.0 cm diameter and 2.8 to 3.0 cm (7.1 to 7.6 in) in length were used in this study. The initial moisture content of the vegetables was as follows: Peas - 74%, carrots - 93%, and beans - 90%.

### **Centrifugal Fluidized Bed Dryer**

To determine the significance of the operating parameters, 1.82 kg (3.96 lb) of

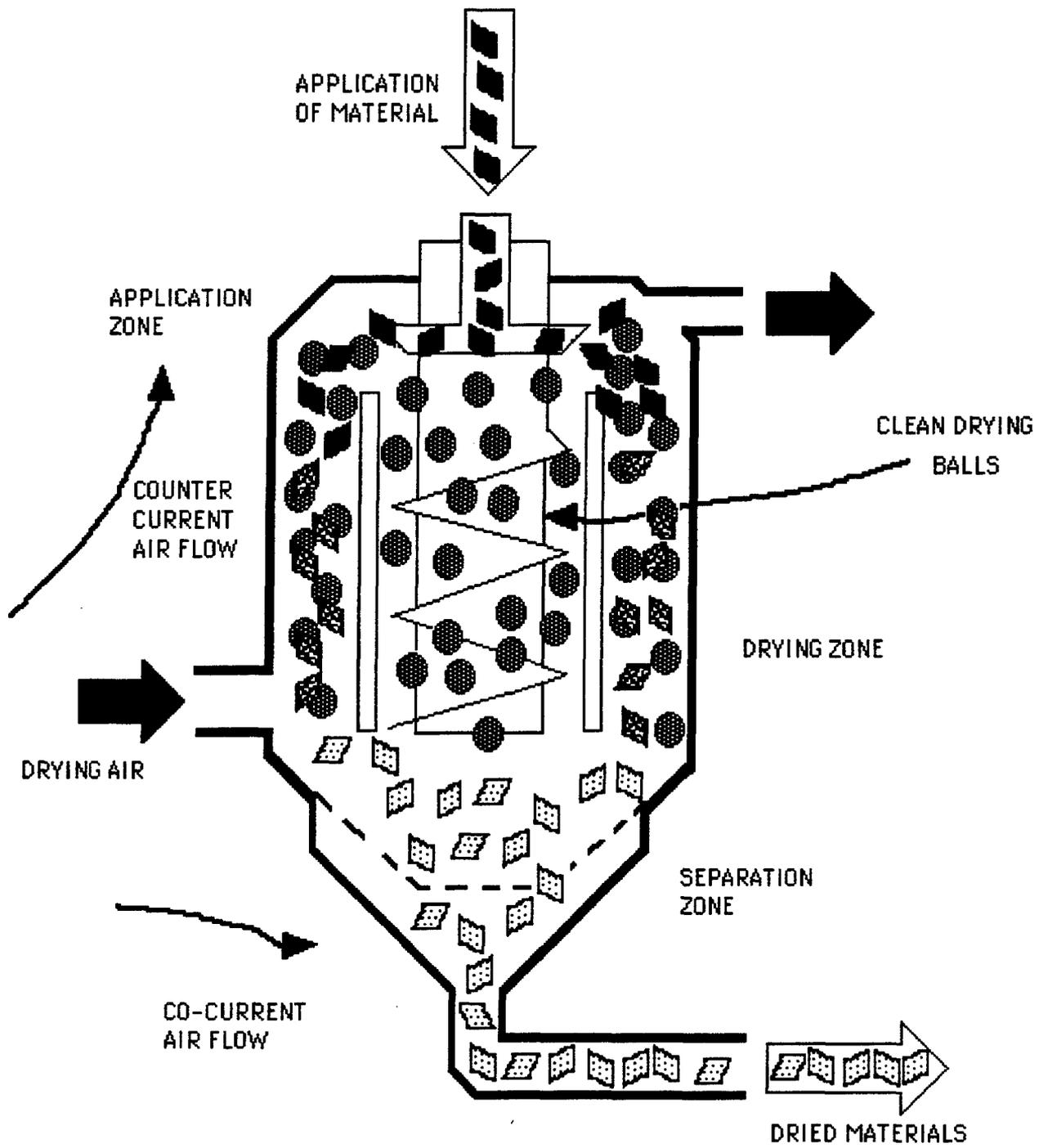


Figure 2 - SCHEMATIC DIAGRAM OF BALL DRYER

frozen vegetables were placed in the preheated chamber after the inlet tube opening was set. The chamber temperature control was preset. The individual runs were made beginning with the lowest temperature and finishing at the highest. Depending on the temperature, the time to achieve the operating temperature was typically 2 to 5 minutes. The operating conditions were maintained during each individual run. Each run was terminated after 15 minutes. The vegetables were then removed from the chamber and weighed. A sample of the vegetable was removed for moisture determination and maintained in a closed container at refrigerated conditions. This procedure for determining moisture was done for all the samples within 48 hours of completion of the run. The determinations were done with a Computrac Max 50<sup>TM</sup> instrument.

For the drying time comparison study, 1.5 kg (3.3 lb ) of vegetables was used for each run.

#### **Ball Dryer**

For all the studies with this dryer, 1.5 kg (3.3 lb) of vegetables were used. The chamber was preheated to the desired temperature. The other parameters were set. The entire product was placed in the feed hopper. The run was terminated when no further product emerged. The beans were too large to be fed through the screw so they had to be added by hand through the top of the drying chamber at a rate that simulated that of the feed screw. When collected they were shredded in strips lengthwise and had the appearance of French-style beans

#### **Freeze-Dryer**

For purposes of drying rate comparison, additional peas were freeze-dried (FD) and freeze-dried with microwave power augmentation. A Cober Electronics <sup>TM</sup> microwave freeze-dryer was used. A schematic diagram of this equipment is shown in Fig. 3. The microwave power was set at 500 watts. Again, 1.5 kg (3.3 lb ) were used for each run.

#### **Quality Analyses**

Various instrumental studies were made on the rehydrated products to determine quality differences.

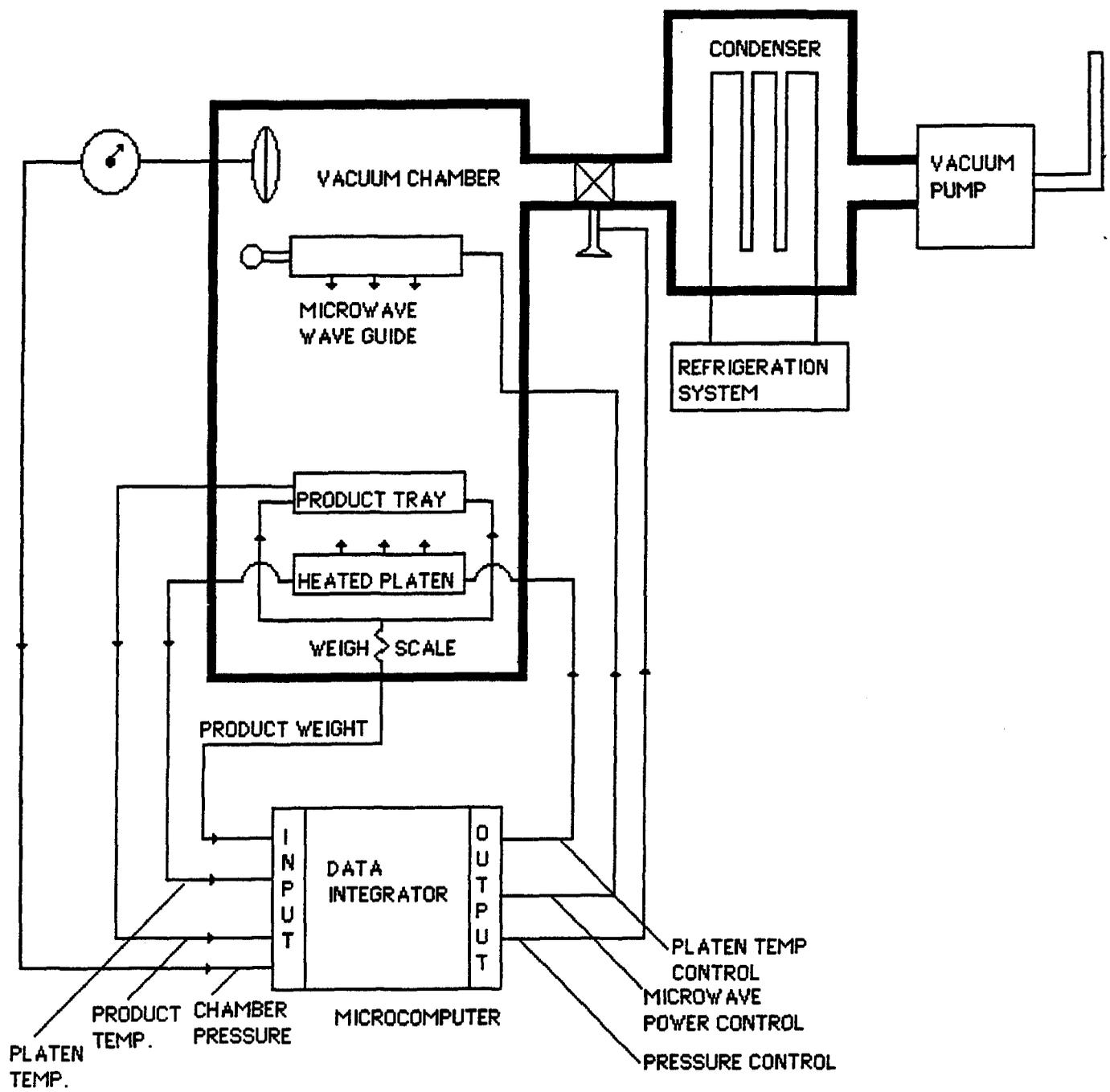


Figure 3 - SCHEMATIC DIAGRAM OF MICROWAVE AUGMENTED FREEZE-DRYER

### **Rehydration Ratio**

The product to be measured was placed in 600 to 800 mL of boiling water. It was continuously stirred for two minutes while in the boiling water. The water was then drained off through a No. 150 mesh metal screen, the product cooled and the mass of the drained product measured. The rehydration ratio is defined as the ratio of the increase in mass divided by the initial mass.

### **Shear Force**

An SMS-TAXT2 Texturometer™ was used for these measurements. A single 0.3 x 6.5 cm (0.12 x 2.4 in) blade was used. Individual rehydrated vegetables were placed over the entire length of the slit. Seven to eight whole peas, carrot cubes, or green bean slices were used for each measurement. The beans were placed so that the cross section was over the slit.

### **Reflectance Color**

A Pacific Systems Spectrogard Reflectometer, Model 96™ was used to measure the color of rehydrated vegetables. A 3.3 cm (1.3 in) thick quartz cell was used to hold the samples being measured. A single reading was taken on each side of the cell through an aperture of 0.5 cm<sup>2</sup> (0.04 in<sup>2</sup>). Hunter "L", "a" and "b" measurements were made. A greater "L" value indicates a lighter color. A greater "a" value indicates more red, less green. A greater "b" value indicates more yellow, less blue.

## **Results and Discussion**

### **Centrifugal Fluidized Bed Dryer**

The experimental data for the first series of experiments is shown in Table 1. This data consists of the final mass of partially dried vegetables and the final measured moisture level for each of the 19 sets of processing conditions.

### **Experimental Design for CB Drying**

A response surface methodology was used to determine the optimum parameters for drying rate with this equipment. Three variables (air flow rate, drying temperature and drum rotational speed) were used to change the operating conditions in a set of 19 runs. The temperatures ranged from 40 to 90 °C

(104 to 194 °F), the rotational speed from 30 to 180 rpm, the flow rate from 0.42 to 0.84 m<sup>3</sup> (15 to 30 ft<sup>3</sup>) per second. The data for the percent of the initial moisture removed is calculated from the initial moisture and the final mass.

**TABLE 1 - EXPERIMENTAL DATA FOR FIRST SET OF CB RUNS**

Run	Temp. °C	RPM	Flow m <sup>3</sup> /s	Final Mass kg		Final % Moisture (% initial Moisture Removed)	
				Peas	Carrots	Peas	Carrots
1	40	105	0.56	1.17	1.38	64.42 (48)	90.04 (26)
2	50	60	0.42	1.19	1.07	66.42 (47)	87.27 (44)
3	50	150	0.42	1.31	1.29	69.14 (38)	90.18 (31)
4	50	60	0.70	1.09	0.92	62.94 (54)	85.27 (53)
5	50	150	0.70	1.20	1.19	67.08 (46)	89.54 (37)
6	65	30	0.56	1.02	0.73	60.38 (59)	82.29 (64)
7	65	105	0.28	1.01	1.05	60.57 (60)	78.38 (44)
8	65	105	0.56	1.01	0.98	60.57 (60)	88.13 (50)
9	65	105	0.56	1.00	1.05	61.33 (61)	86.89 (46)
10	65	105	0.56	1.01	0.95	60.08 (60)	85.91 (51)
11	65	105	0.84	1.01	0.88	57.94 (60)	86.47 (56)
12	65	180	0.56	1.04	0.80	61.55 (58)	82.99 (60)
13	80	60	0.42	0.91	0.58	56.29 (67)	78.83 (75)
14	80	150	0.42	1.06	0.75	64.59 (56)	84.59 (63)
15	80	60	0.70	0.88	0.57	55.07 (70)	75.72 (75)
16	80	150	0.70	0.97	0.74	58.90 (63)	82.69 (64)
17	90	105	0.56	0.89	0.68	54.33 (69)	77.31 (67)
18	50	105	0.56	1.04	1.15	60.13 (58)	89.20 (40)
19	80	105	0.56	0.88	0.63	54.90 (70)	77.68 (70)

The mass had a correlation with the percent moisture of -0.963 with the peas and -0.832 with the carrots. Since the final mass measured the mass of all the vegetables while the moisture was determined from a sample of the vegetables, the data for the final mass was that used for the statistical analyses.

Table 2 presents the analysis of a subset of the data, based on two conditions of each of the variables.

**TABLE 2 - ANALYSIS OF VARIANCE FOR FIRST SET OF CB RUNS  
(RUNS 2 - 5, 13 - 16)**

Factor	Peas		Carrots	
	F	Signif.	F	Signif.
Temperature	32.64	89.0	102.65	93.7
rpm	5.58	74.5	18.32	85.4
Flow Rate	4.91	73.0	30.35	88.6
Temperature x rpm	0.04	12.6	9.00	79.5
Temperature x Flow Rate	3.24	67.8	21.16	86.4
rpm x Flow Rate	1.96	60.5	1.00	50.0

Table 3 is the response surface analysis of the first set of CB data.

**TABLE 3 - RESPONSE SURFACE FOR FIRST SET OF CB RUNS  
(RUNS 1 - 17)**

Factor	Peas		Carrots	
	F	Signif.	F	Signif.
Temperature	18.61	>99.9%	80.0	>99.9%
rpm	1.35	nsd	20.5	>99.9%
Flow Rate	0.99	nsd	3.54	nsd

These analyses showed that the most significant factor governing the drying rate was that of temperature. The other primary factors of RPM and flow rate can also affect the drying rate, but these are not as important as the temperature. The interaction of temperature and flow rate was the most important, but again, not significant.

No factor was statistically significant with the analysis of variance, primarily because of the small amount of data used in the calculations although temperature was the most important. Temperature was statistically significant with the response surface analysis.

The data from runs 1, 18, 8, 19 and 17 were used to determine a correlation between the processing temperature and the final mass, since this was the most

important factor. All these runs were made at 105 rpm and 0.56 ft<sup>3</sup>/s. The correlation was -0.954 for the peas and -0.970 for the carrots, which were highly significant. There was a leveling off of the final mass at the very highest temperatures. These data are shown in Table 4.

**TABLE 4 - CORRELATION BETWEEN PROCESSING TEMPERATURE AND FINAL MASS**

Temperature °C	Final Mass, kg	
	Peas	Carrots
40	1.17	1.38
50	1.04	1.15
65	1.00	1.00
80	0.88	0.63
90	0.89	0.68

Calculations were made that used the initial moisture values of 74% for the peas and 93 % for the carrots and the known moisture loss to determine a calculated final moisture to compare to the actual measured final moisture. These figures are shown in Table 5.

**TABLE 5 - FINAL PERCENT MOISTURE**

Run	Peas			Carrots		
	Measured	Calculated	Difference	Measured	Calculated	Difference
1	64.42	60.08	+4.34	90.04	90.08	-0.04
2	66.42	60.69	+5.73	87.27	88.14	-0.87
3	69.14	64.24	+4.90	90.18	90.14	+0.04
4	62.94	57.08	+5.87	85.27	86.13	+0.86
5	67.08	60.98	+6.10	89.54	86.13	-0.90
6	60.38	54.02	+6.36	82.29	82.50	-0.21
7	60.57	53.60	+6.97	78.38	78.46	-0.08
8	59.14	53.40	+5.74	88.13	87.04	+1.09
9	61.33	53.18	+8.15	86.89	87.93	-1.04
10	60.08	53.60	+6.48	85.91	86.67	-0.76
11	57.94	53.60	+4.34	86.47	85.56	+0.91
12	61.55	54.82	+6.73	82.99	84.95	-1.96
13	56.28	48.50	+7.78	78.83	79.71	-0.88
14	64.59	55.98	+8.61	84.59	83.13	+1.46
15	55.07	46.91	+8.16	75.72	77.78	-2.06
16	58.90	51.87	+7.03	82.69	82.72	-0.03
17	54.33	47.45	+6.88	77.31	81.33	-4.02
18	60.13	54.82	+5.31	89.20	88.98	+0.65
19	54.90	46.91	+7.99	77.68	79.71	-2.03

The calculated final moistures were slightly different from the actual final moistures. This fact indicates that there were probably sampling differences within the final products. At any rate, all the other data analyses were based on the values for the final mass.

The processing conditions used for the second set of experimental runs corresponded to Runs 2 to 5 and 13 to 16. These data are shown in Table 6. These runs were all made with 1.5 kg of vegetables and 20 minutes processing time.

**TABLE 6 - EXPERIMENTAL DATA FOR SECOND SET OF CB RUNS**

<u>Product</u>	<u>Temp. °C</u>	<u>Flow Rate m<sup>3</sup>/s</u>	<u>Rotat. Speed rpm</u>	<u>Final Mass kg</u>	<u>% Initial Moisture Removed</u>	<u>Final % Moisture</u>
A. Beans	50	0.42	60	0.56	58	83
Beans	50	0.42	150	0.75	34	87
Beans	50	0.70	60	0.47	73	79
Beans	50	0.70	150	0.70	42	86
Beans	80	0.42	60	0.32	49	69
Beans	80	0.42	150	0.37	87	74
Beans	80	0.70	60	0.30	97	68
Beans	80	0.70	150	0.44	78	78
B. Peas	50	0.42	60	0.63	49	61
Peas	50	0.42	150	0.60	53	60
Peas	50	0.70	60	0.56	58	57
Peas	50	0.70	150	0.57	56	58
Peas	80	0.42	60	0.47	70	49
Peas	80	0.42	150	0.47	70	49
Peas	80	0.70	60	0.48	68	50
Peas	80	0.70	150	0.46	71	48
C. Carrots	50	0.42	60	0.47	58	81
Carrots	50	0.42	150	0.58	46	85
Carrots	50	0.70	60	0.35	72	75
Carrots	50	0.70	150	0.52	53	83
Carrots	80	0.42	60	0.22	86	60
Carrots	80	0.42	150	0.29	78	70
Carrots	80	0.70	60	0.19	89	54
Carrots	80	0.70	150	0.27	80	68

The data for all three products was combined for the percent mass removed and the percent moisture removed. The analysis of variance for these data are shown in Table 7.

**TABLE 7 - ANALYSIS OF VARIANCE FOR SECOND SET OF CB RUNS  
LEADING TO**

Factor	% Mass Removed			% Moist. Removed	
	F	Signif.	df	F	Signif.
Temperature	308	95%	1/2	613	95%
Flow Rate	9.9	nsd	1/2	17.9	nsd
Rotational Speed	52.1	95%	1/2	94.3	95%
Product	76.9	95%	2/2	28.0	95%
Temp. x Flow Rate	9.9	nsd	1/2	20.6	95%
Temp. x Rotational Speed	7.4	nsd	1/2	11.9	nsd
Temp. x Prod.	14.9	nsd	2/2	68.1	95%
Flow Rate x Rotational Speed	22.3	95%	1/2	5.5	nsd
Flow Rate x Product	1.0	nsd	2/2	1.0	nsd
Rotational Speed x Product	17.4	nsd	2/2	34.6	95%
Temp. x Flow Rate x Rot. Speed	0.2	nsd	1/2	0.6	nsd
Temp. x Flow Rate x Product	0.4	nsd	2/2	1.3	nsd
Temp. x Rot. Speed x Product	2.0	nsd	2/2	3.6	nsd
Flow Rate x Rot. Speed x Product	0.4	nsd	2/2	1.2	nsd

The results from this data is similar to that from the first set. Temperature is the most important factor of the three variables. Rotational speed was also significant. Of course, the product used was significant to the data. Some of the interactions were also significant, specifically flow rate and rotational speed on % mass removed and temperature and flow rate, temperature and product and rotational speed and product on % moisture removed.

#### **Ball Dryer**

Conditions were chosen so a three-way analysis of variation could be used to determine the effect of the different operating conditions. The results are shown in Table 8.

**TABLE 8 - EFFECT OF OPERATING PARAMETERS ON THE FINAL MOISTURE CONTENT AND DRYING TIME WITH PEAS IN THE BALL DRYER**

Run	Temp. °C	Feed Rate %	Rotational Speed rpm	Final % Moisture	Drying Time min.
1	60	10	1.5	24.3	105
2	60	10	8.0	62.0	60
3	60	15	1.5	24.6	105
4	60	15	8.0	56.1	65
5	71	10	1.5	12.8	155
6	71	10	8.0	43.0	100
7	71	15	1.5	20.4	145
8	71	15	8.0	42.1	100
9	82	10	1.5	5.8	165
10	82	10	8.0	49.3	50
11	82	15	1.5	13.5	150
12	82	15	8.0	52.4	30

Table 9 is the analysis of variance of the data in Table 8.

**TABLE 9 - ANALYSIS OF VARIANCE FOR FINAL % MOISTURE FOR BALL DRYER**

Factor	F	Signif.	Differences *
Temperature	189.3	99%	60 <u>71</u> <u>82</u>
Feed Rate	12.2	nsd	<u>10%</u> <u>15%</u>
Rotational Speed	3588.6	99%	1.5 8.0
Temp. x Feed Rate	18.9	95%	
Temp. x Rotational Speed	58.5	95%	
Feed Rate x Rot. Speed	31.0	95%	

\* Conditions underlined are not significantly different from each other.

The temperature and ball speed were significant in their effect on the final moisture content, as were all the interactions. The feed rate was not significant. The most significant factor was the ball rotational speed. This is not surprising as

the ball speed controls the residence time within the drying chamber. There was no difference in the final % moisture between 71 and 82 °C. The lowest temperature, 60 °C, removed significantly less moisture at the end of the run. Unless there were significant quality differences, it would probably be best to run at 71 °C and the lower rotational speed. However, the operating conditions can be varied to give a desired final moisture content.

### **Quality Comparison**

The rehydration ratio values are shown in Table 10.

The texture values are shown in Table 11.

The reflectance color values are shown in Table 12 a, b and c.

The rehydration ratio values varied with the product. With peas the BD values were less than all the others. With beans the BD values were greater than all the others. With carrots, the BD and CB values were less than the others. This might be a reflection of the size and shape of the vegetable, relative cellular damage and the surface area covered by intact exterior tissue.

All the dried products were generally softer than the frozen control, except that the ball dried carrots were tougher. This reflects the severity of the drying process on the structural deterioration of the vegetables. The BD carrots seemed to exhibit a case-hardening effect.

There were generally no significant color differences shown except for slight differences for the "a" value of peas. The FD, both conventional and microwave, were less green. The control and ball dried were more green, although differences were not great. In the tables, samples connected by an underline are not significantly different.

Table 13 shows the drying rate. The CB rate was the fastest, followed by the BD rate. The MW rate was slower than either BD or CB but much faster than FD.

### **Conclusions**

This study showed that for CB drying, all three factors of flow rate, rpm and temperature affected the rate of moisture removal, with temperature being the most important. Some experimental conditions do not promote fluidizing and should not be used. Too high a flow rate may tend to push the product onto the walls of the

**TABLE 10 - REHYDRATION RATIO (RR) OF VEGETABLES**

Process	Data	Average					
<b>A. Peas</b>							
FD	1.1, 1.3	1.2					
MW	1.4, 1.4	1.4					
CB	1.3, 1.6	1.45					
BD	0.7, 0.8	0.75					
Analysis of Variance							
Factor	<i>F</i>	Significance	Isd				
Treatment	12.32	95%	0.25	BD	<u>FD</u>	<u>MW</u>	<u>CB</u>
<b>B. Green Beans</b>							
FD	1.4, 1.4	1.4					
MW	1.3, 1.1	1.2					
CB	1.3, 1.1	1.2					
BD	1.8, 2.4	2.1					
Analysis of Variance							
Factor	<i>F</i>	Significance	Isd				
Treatment	0.088	nsd	NA	<u>CB</u>	<u>MW</u>	<u>FD</u>	<u>BD</u>
<b>C. Carrots</b>							
FD	1.7, 1.6	1.65					
MW	1.9, 2.0	1.95					
CB	0.8, 0.7	0.75					
BD	1.2, 1.2	1.2					
Analysis of Variance							
Factor	<i>F</i>	Isd					
Treatment	165.97	99%	0.46	CB	BD	<u>FD</u>	<u>MW</u>
		95%	0.28	CB	BD	FD	MW

**TABLE 11 - TEXTURE ANALYSIS OF REHYDRATED VEGETABLES**

All readings at 0.5 speed 15.0 mm travel length, single 0.3 x 6.5 cm blade. Seven to eight vegetables were used to completely cover the slit. All values are in Newtons.

Process	Data	Average	Standard Deviation
<b>A. Peas</b>			
Control	66, 67, 59, 61	63.3	3.9
FD	62, 63, 59, 63	61.8	1.9
MW	58, 66, 40, 46	52.5	11.7
CB	47, 53, 57, 43	50.0	6.2
BD	42, 38, 47, 46	43.3	4.1
<b>Analysis of Variance</b>			
Factor	<i>F</i>	significance	lsd
Treatment	6.62	99%	4.3
		95%	3.4
			BD CB MW FD CN
			BD CB MW FD CN
<b>B. Green Beans</b>			
Control	253, 275, 302, 236	266.5	28.6
FD	98, 116, 143, 131	122.0	19.4
MW	106, 86, 118, 104	103.5	13.2
CB	129, 169, 149, 113	140.0	24.3
BD	79, 83, 119, 104	96.3	18.7
<b>Analysis of Variance</b>			
Factor	<i>F</i>	significance	lsd
Treatment	42.05	99%	14.3
			11.1
			BD MW FD CB CN
			BD MW FD CB CN
<b>C. Carrots</b>			
Control	116, 154, 117, 238	156.3	57.3
FD	93, 84, 82, 57	79.0	15.4
MW	68, 35, 87, 109	74.8	31.4
CB	94, 99, 75, 95	73.3	42.6
BD	222, 280, 214, 155	217.8	51.1
<b>Analysis of Variance</b>			
Factor	<i>F</i>	significance	lsd
Treatment	9.13	99%	10.8
			8.3
			CB MW FD CN BD
			CB MW FD CN BD

**TABLE 12a - REFLECTANCE COLOR "L" OF REHYDRATED VEGETABLES**

Process	Data	Average	Standard Deviation
<b>A. Peas</b>			
Control	26.2, 18.3, 17.5, 24.0	21.5	4.3
FD	23.7, 24.6, 22.5, 23.5	23.6	0.9
MW	19.0, 21.6, 21.8, 25.6	22.0	2.7
CB	22.0, 22.5, 17.9, 24.1	21.6	2.6
BD	21.3, 19.1, 25.9, 18.5	21.2	3.4
Analysis of Variance			
Factor	<i>F</i>	significance	lsd
Treatment	0.41	nsd	NA
			<u>BD CN CB MW FD</u>
<b>B. Green Beans</b>			
Control	29.5, 21.1, 16.5, 19.7	21.7	5.5
FD	23.9, 21.1, 26.1, 21.5	23.2	2.3
MW	27.3, 16.0, 17.5, 24.9	21.5	5.4
CB	20.3, 22.0, 24.6, 17.9	21.2	2.8
BD	29.8, 24.1, 22.0, 21.1	24.3	3.9
Analysis of Variance			
Factor	<i>F</i>	significance	lsd
Treatment	0.39	nsd	NA
			<u>FD CB BD MW CN</u>
<b>C. Carrots</b>			
Control	28.1, 26.4, 26.0, 23.4	26.0	1.9
FD	25.8, 27.6, 27.0, 31.7	28.0	2.6
MW	43.0, 32.6, 38.6, 28.9	35.8	6.3
CB	33.3, 23.3, 18.6, 30.4	26.4	6.7
BD	31.1, 28.9, 19.9, 28.8	27.2	5.0
Analysis of Variance			
Factor	<i>F</i>	significance	lsd
Treatment	2.75	nsd	NA
			<u>CN FD BD MW CB</u>

**TABLE 12b - REFLECTANCE COLOR "a" OF REHYDRATED VEGETABLES**

Process	Data	Average	Standard Deviation
<b>A. Peas</b>			
Control	-4.3, -2.3, -1.8, -4.3	-3.2	1.3
FD	-4.3, -5.3, -4.0, -5.4	-4.7	0.7
MW	-3.5, -4.6, -4.8, -5.5	-4.6	0.8
CB	-4.6, -4.3, -3.1, -3.8	-4.0	0.7
BD	-3.3, -3.3, -3.3, -3.1	-3.2	0.1
Analysis of Variance			
Factor	<i>F</i>	significance	lsd
Treatment	3.2	95%	1.8
			<u>CN BD CB MW FD</u>
<b>B. Green Beans</b>			
Control	-0.4, -0.4, -0.3, -0.3	-0.3	0.1
FD	-1.8, -1.1, -2.3, -1.5	-1.7	0.5
MW	-2.5, -0.7, -1.3, -2.5	-1.8	0.9
CB	-3.0, -7.7, -2.3, -1.1	-3.5	2.9
BD	-1.1, -1.7, -2.1, -2.1	-1.8	0.5
Analysis of Variance			
Factor	<i>F</i>	significance	lsd
Treatment	2.7	nsd	NA
			<u>CN FD MW B D CB</u>
<b>C. Carrots</b>			
Control	5.5, 6.6, 7.0, 7.2	6.6	0.8
FD	1.7, 5.7, 3.0, 9.1	4.9	3.3
MW	0.3, 5.0, 0.9, 1.8	1.9	2.2
CB	3.9, 6.0, 4.2, 2.1	4.0	1.6
BD	6.5, 1.4, 2.7, 3.2	3.4	2.2
Analysis of Variance			
Factor	<i>F</i>	significance	lsd
Treatment	2.6	nsd	NA
			<u>MW BD CB FD CN</u>

**TABLE 12c - REFLECTANCE COLOR "b" OF REHYDRATED VEGETABLES**

Process	Data	Average	Standard Deviation
<b>A. Peas</b>			
Control	9.4, 4.4, 3.5, 8.6	6.5	2.9
FD	10.2, 10.1, 9.0, 10.0	9.9	0.3
MW	6.7, 7.9, 8.4, 10.8	8.4	1.7
CB	8.8, 8.9, 6.5, 8.6	8.2	1.1
BD	7.0, 6.7, 7.6, 6.6	7.0	0.4
<b>Analysis of Variance</b>			
Factor	<i>F</i>	significance	lsd
Treatment	2.8	nsd	NA
			<u>FD BD CB MW CN</u>
<b>B. Green Beans</b>			
Control	9.4, 4.0, 3.4, 5.6	5.6	2.7
FD	8.0, 5.2, 7.8, 5.0	6.5	1.7
MW	6.7, 5.1, 4.9, 7.0	5.9	1.1
CB	7.1, 6.8, 7.7, 5.6	6.8	0.9
BD	6.7, 6.0, 6.4, 7.2	6.6	0.5
<b>Analysis of Variance</b>			
Factor	<i>F</i>	significance	lsd
Treatment	0.4	nsd	NA
			<u>CN MW FD BD CB</u>
<b>C. Carrots</b>			
Control	8.5, 9.2, 8.5, 8.7	8.7	0.3
FD	6.0, 10.2, 6.1, 13.0	8.9	3.4
MW	4.6, 11.8, 3.6, 6.4	6.6	3.7
CB	5.3, 8.3, 5.8, 6.9	6.6	1.4
BD	9.4, 6.0, 5.6, 8.1	5.0	3.3
<b>Analysis of Variance</b>			
Factor	<i>F</i>	significance	lsd
Treatment	1.4	nsd	NA
			<u>BD MW</u> <u>CB CN FD</u>

**TABLE 13 - DRYING RATE OF VEGETABLES**  
**All data for a load of 1.5 kg**

Process	Time minutes
<b>A. Peas (43 - 48% final H<sub>2</sub>O)</b>	
FD	260
MW	131
CB	20
BD	100
<b>B. Green Beans (51 - 69% final H<sub>2</sub>O)</b>	
FD	236
MW	183
CB	20
BD	71
<b>C. Carrots (57 - 70% final H<sub>2</sub>O)</b>	
FD	275
MW	246
CB	20
BD	55

chamber. These conditions can be determined when the chamber is opened up at the end of the run. The process removes moisture very quickly. At 65 °C, 58 to 60% of the initial moisture of the peas and 44 to 64% of the initial moisture of the carrots was removed.

For BD drying the only factor that had significance was the rotational speed of the screw conveyor. This is the controlling factor for residence time within the chamber. Temperature of drying was not at all significant, possibly because the conditions chosen were fairly close.

The two processes have significance for use in the development of military rations, many of which have partially dried components of a particle size suitable for CB drying. The studies described here should be followed up with sensory analyses although the quality analyses indicated few differences, if any.

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## APPENDIX - MAPPING OF AIR FLOW WITHIN CB DRYER

One of the operating parameters of the CB dryer that we wanted to control was the air flow rate. As originally designed, the flow rate was largely constant over the range of loads in the drum and also at different positions of the recirculation damper and top vent. This was accomplished by powering the blower impeller with an abnormally large (25 hp) motor. Economics did not allow us to procure and install a variable speed drive on the blower.

Therefore, an adjustable vent was installed at the point where the blower outlet joins the drum inlet tube. This vent can be opened to allow a portion of the process air to escape the system, thereby reducing the total flow to the drum. One disadvantage to this approach is that at low flow rates the system is more sensitive to variation in loads in the drum than the original design.

Air flow rate data were taken at fixed positions on a selected (rectangular) cross section of the inlet tube. This cross section was selected to be a reasonable distance upstream from the drying drum and as far as practical downstream from the blower impeller. This cross section was divided into 16 identically sized cells. The air flow was measured at the center of each cell with a hot-wire anemometer. The positions are shown in Fig. A-1. A second, temperature-compensated hot wire anemometer was mounted in the same cross section in a fixed position as near to the center of the duct as was practical. This position is labeled F in Fig. A-1.

The air flow for the 16 positions as well as the fixed probe was measured while varying the flow control vent at the bottom of the inlet tube at different temperatures. All the data were taken at standard conditions of 65 rpm, top vent open, recirculation damper closed and a load of 1.8 kg peas. The air flow exhibited short-term semicyclic fluctuations on the order of 5 to 10 seconds. Therefore a procedure was adopted to take each data point during the portion of the cycle when the fluctuation decreased and the flow as indicated by the fixed anemometer was approximately repetitive. These data, in feet per minute, are shown in Table A-1.

The results are plotted in Fig. A-2. These are three Mathematica™ contour plots of sets of the 16 data points described above, together with the value read from the contour plot at the location of the fixed velocity probe, F, based on three different flow rates at the center. At a lower flow rate (i.e. 400 cfmin) the gradients were large,

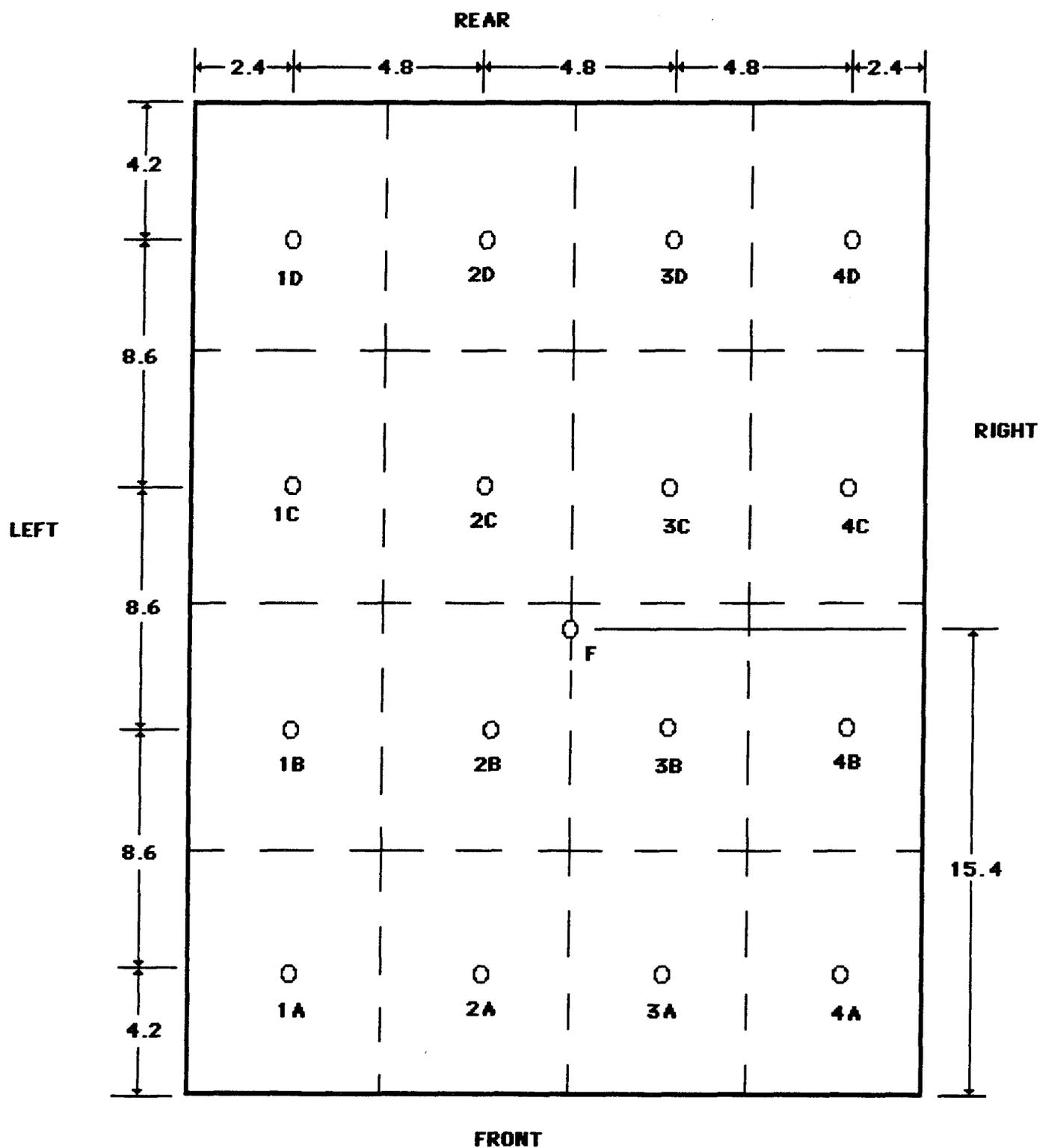


Figure A-1 - Positions for Flow Measurements in Cross Section of Inlet Tube  
 Top View Looking Down (Dimensions in cm). 0 = air flow  
 measurement points; F = fixed probe

**TABLE A-1 - Air Flow Rate (ft/min) as a Function of Opening and Temperature**

<u>Position</u>	<u>Opening (inches/cm)</u>				
	<u>1.0/2.5</u>	<u>2.0/5.0</u>	<u>3.0/7.5</u>	<u>4.0/10.0</u>	<u>5.0/12.5</u>
<b>A. 40 °C</b>					
1A	5270	5290	4735	2010	
1B	4995	4220	3160	1475	
1C	1405	1395	1185	1010	
1D	3140	2850	1555	640	
2A	5010	3925	2480	1055	
2B	3180	2855	1680	840	
2C	1510	1630	1320	685	
2D	3740	2960	2330	620	
3A	5060	4180	2930	1090	
3B	3840	2580	1500	930	
3C	1555	1480	1340	665	
3D	3700	2770	2075	720	
4A	5440	5410	5320	3580	
4B	5265	4910	3610	2460	
4C	1500	1345	1095	655	
4D	3265	2620	1860	710	
<b>B. 50 °C</b>					
1A	4990	5120	3270	2035	1125
1B	4525	4410	2610	1480	1000
1C	1170	1235	1055	970	675
1D	3270	2570	1040	575	335
2A	4870	3590	1755	820	550
2B	2810	2670	1300	535	530
2C	1340	1320	1000	650	435
2D	3215	3105	1090	585	470
3A	4900	3915	2060	1165	1250
3B	3320	2350	1140	720	890
3C	1555	1580	890	730	690
3D	3640	3075	1390	670	715
4A	5290	5070	5040	3560	2775
4B	5170	4300	3010	2030	1790
4C	1340	1200	880	615	570
4D	1450	2530	1710	830	785

**TABLE A-1 Continued**

Position	Opening (inches/cm)			
	<u>1.0/2.5</u>	<u>2.0/5.0</u>	<u>3.0/7.5</u>	<u>4.0/10.0</u>
C. 65 °C				
1A	4440	3830	2010	1045
1B	2080	3065	1630	975
1C	1090	1265	1270	690
1D	2800	1770	680	260
2A	2895	2985	940	500
2B	2215	2280	635	415
2C	1440	1090	605	305
2D	3070	2110	540	835
3A	4120	2855	975	490
3B	2630	2010	870	430
3C	1090	1245	685	400
3D	2755	2310	695	340
4A	4960	4915	2765	1735
4B	3580	990	570	400
4C	2970	2360	675	510
D. 70 °C				
1A	4845	3320	2280	1040
1B	2330	2545	1750	885
1C	900	1060	890	680
1D	2580	1810	620	325
2A	3880	2230	1020	565
2B	2160	1690	760	390
2C	1255	1210	620	350
2D	2740	2290	630	260
3A	4030	2370	1400	760
3B	3030	1990	810	550
3C	1140	1180	840	500
3D	2700	2190	685	240
4A	4910	4880	2990	1770
4B	4605	2810	2300	1375
4C	1410	1130	1080	395
4D	2990	2170	1260	445

**TABLE A-1 Continued**

Position	Opening (inches/cm)			
	<u>1.0/2.5</u>	<u>2.0/5.0</u>	<u>3.0/7.5</u>	<u>4.0/10.0</u>
E. 75 °C				
1A	4205	3345	2430	905
1B	3280	2690	1530	855
1C	1040	1055	1130	550
1D	2430	1675	610	300
2A	3230	2460	1180	445
2B	2220	1615	735	355
2C	1300	955	715	270
2D	2640	2115	620	270
3A	3570	2670	1060	750
3B	2290	2125	765	580
3C	1160	975	605	295
3D	2625	2290	810	450
4A	4950	4910	2810	1750
4B	3580	3380	1870	1315
4C	1140	985	675	345
4D	2545	1695	925	420
F. 80 °C				
1A	3370	3240	1650	865
1B	2240	2775	1355	940
1C	890	960	870	580
1D	2510	1670	425	280
2A	2710	2775	920	415
2B	1945	970	610	315
2C	1020	2380	525	300
2D	2130	2805	475	260
3A	3300	1930	965	640
3B	2655	1280	830	475
3C	1255	900	620	380
3D	2420	2410	540	330
4A	4790	4110	2410	1420
4B	4065	3340	2085	1050
4C	1070	1250	500	330
4D	2615	2040	605	530

**TABLE A-1 Continued**

<u>Position</u>	<u>Opening (inches/cm)</u>			
	<u>1.0/2.5</u>	<u>2.0/5.0</u>	<u>3.0/7.5</u>	<u>4.0/10.0</u>
G. 85 °C				
1A	3290	3370	1325	860
1B	2575	2155	895	875
1C	690	855	745	580
1D	1515	1505	380	305
2A	2315	1835	420	400
2B	1675	1500	370	365
2C	910	965	330	280
2D	1765	1545	255	250
3A	2655	2255	610	820
3B	1760	1375	520	475
3C	920	915	350	385
3D	2140	1830	310	410
4A	4780	3880	1675	1685
4B	2605	2705	1170	1275
4C	870	940	320	285
4D	1830	1345	425	380
H. 90 °C				
1A	4205	3240	2795	
1B	2415	3070	2150	
1C	760	725	985	
1D	2050	1510	1155	
2A	2500	2405	2160	
2B	1960	1355	1355	
2C	850	790	900	
2D	2360	2080	1465	
3A	2640	2125	1900	
3B	2100	1750	1170	
3C	970	875	945	
3D	2360	2080	1465	
4A	4420	3880	4520	
4B	3150	3070	2520	
4C	780	985	730	
4D	1890	2060	1120	

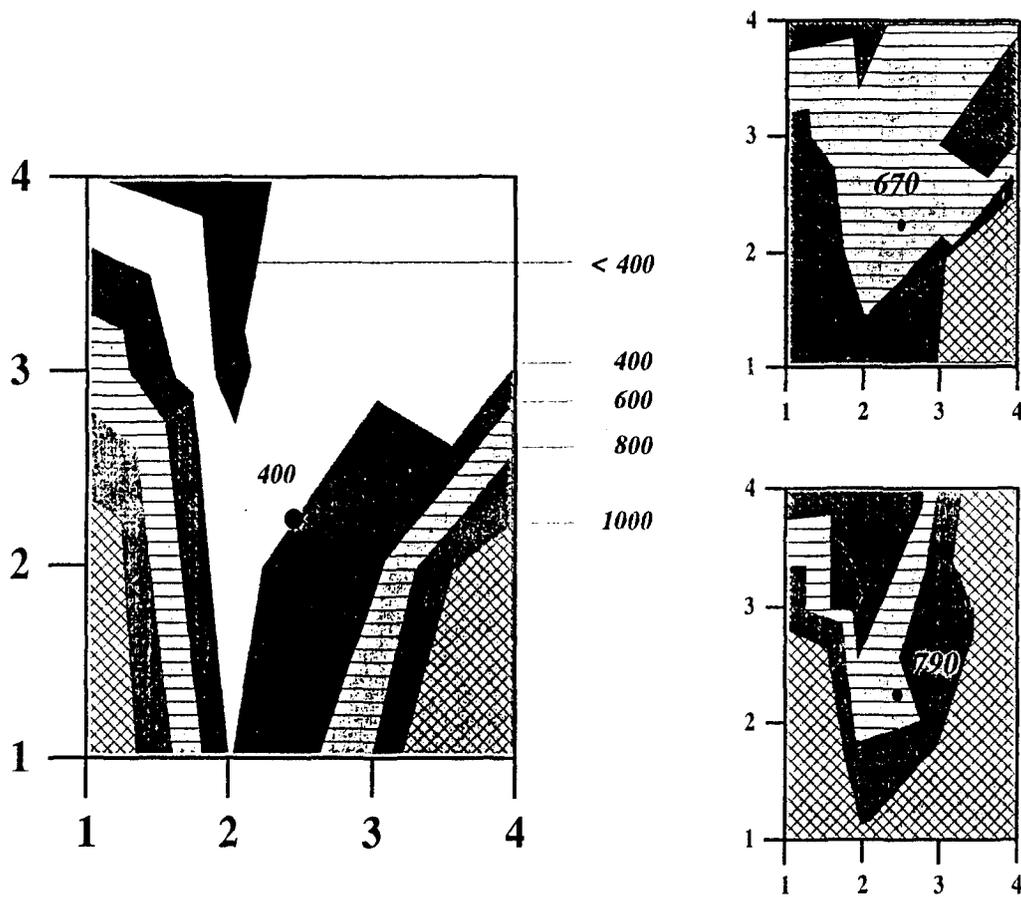


Figure A-2 - Mathematica™ Plot of Anemometer Readings (cf/min) as a Function of Position

ranging from 400 to 1,000 cfmin. As the rate increased (i.e., 670, 790 cfmin), the gradients became smaller (i.e. 600 - 1,000 cfmin) and the higher rate (i.e. 1,000 cfmin) started to engulf the inlet tube. It was also noticed that the flow rate tended to be higher at the front and right side of the tube and lower at the rear, corresponding to the position of the greatest discharge from the blower impeller. For a continuous CB dryer unit, this phenomenon is advantageous, as the higher flow rate would remove moisture faster in the front opening of the rotating drum where the wet ingredients enter. The discharging end of the drum receives less air flow, thus reducing the heat damage of the dry products.

The average velocity for the 16 cells was corrected by the proportion between the value on the contour plot of the location of the fixed probe and the fixed probe reading. The relationship between the flow rate and the adjustable vent opening is presented in Table A-2a. The relationship between the flow rate and the adjustable vent opening is presented in Table A-2b.

The flow as a function of the fixed velocity probe reading is shown in Fig. A-3.

To estimate the integrated value for the flow rate, it was assumed that each point was in the center of a uniform area. An average value for all 16 points was calculated and then multiplied by the total area of that portion of the column. This value of ft<sup>3</sup>/min was then converted to cm<sup>3</sup>/s. These values are shown in Table A-2.

**TABLE A-2 - Flow Rate Data of CB Dryer**

a. Opening (cm) As A Function Of The Flow Rate

<u>Temp. °C</u>	<u>Flow Rate (cm<sup>3</sup>/s)</u>				
	<u>0.28</u>	<u>0.42</u>	<u>0.56</u>	<u>0.70</u>	<u>0.84</u>
40	--	9.8	9.2	8.1	7.0
50	12.7	10.9	8.8	6.7	6.1
65	8.8	6.9	6.3	5.8	4.4
70	9.2	7.3	6.3	5.2	3.7
75	8.8	7.0	6.2	5.4	3.0
80	8.2	6.6	6.3	5.2	--
85	6.6	6.1	5.6	--	--
90	--	--	7.7	3.4	--

b. Flow Rate (m<sup>3</sup>/s) As A Function Of The Adjustable Opening

<u>Temp. °C</u>	<u>Opening (cm)</u>				
	<u>2.5</u>	<u>5.0</u>	<u>7.5</u>	<u>10.0</u>	<u>12.5</u>
40	1.27	1.05	0.79	0.40	--
50	1.10	0.99	0.61	0.49	0.30
65	0.90	0.80	0.36	0.22	--
70	0.95	0.72	0.41	0.22	--
75	0.87	0.74	0.38	0.20	--
80	0.81	0.72	0.32	0.19	--
85	0.67	0.60	0.21	0.20	--
90	0.73	0.66	0.57	--	--

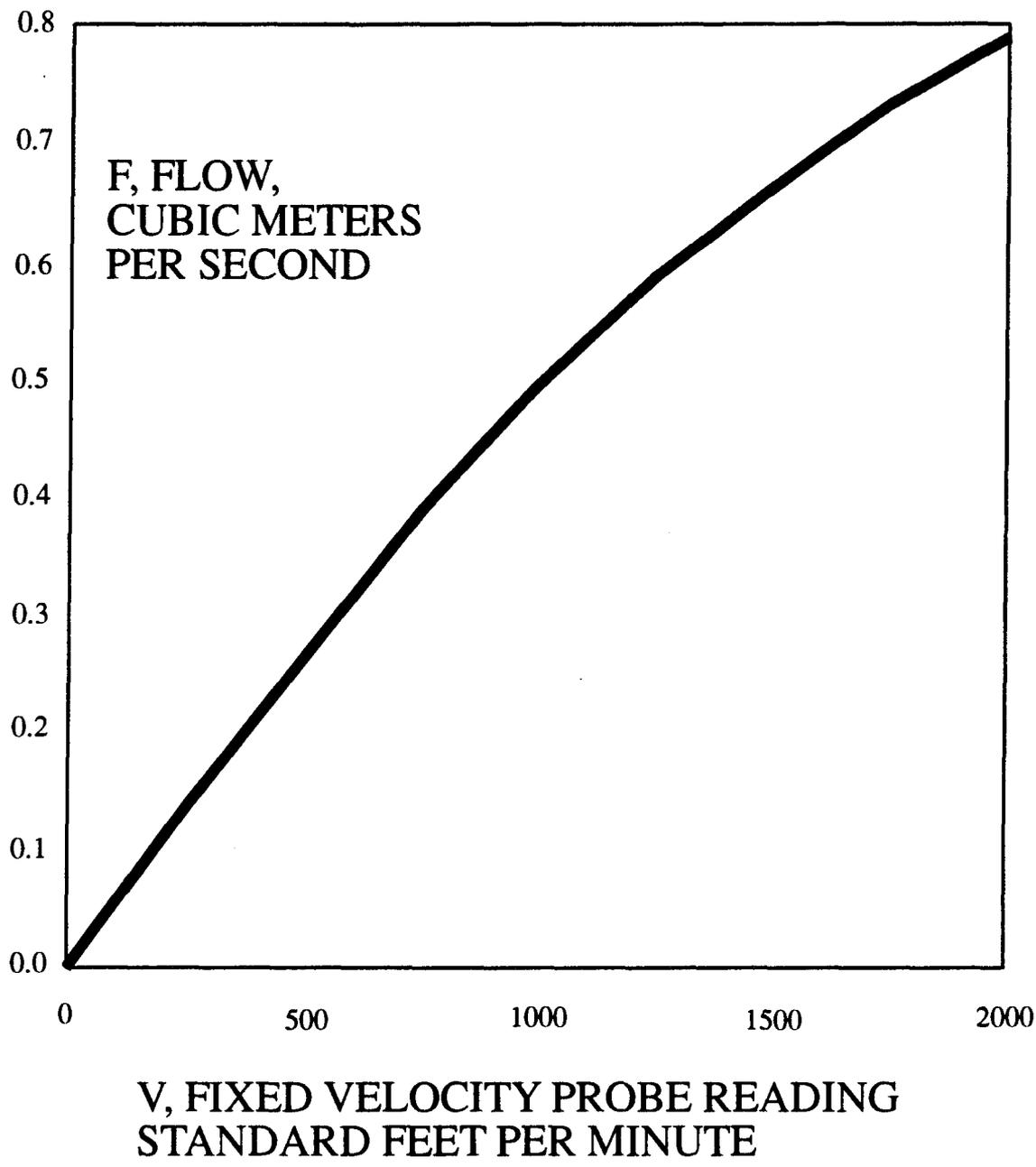


Figure A-3 - Flow Rate as a Function of Fixed Velocity Probe Reading