C.2

SUSTAINABILITY
SURVIVABILITY SUPPORTABILITY

TECHNICAL REPORT
NATICK/TR-94/014

AD A 277 411

NOVEL ULTRASONIC METHOD FOR FOOD DEHYDRATION

By
S.R. Taylor
J.C. Hansen

S. R. Taylor and Associates
Bartlesville, OK 74003

March 1994

FINAL REPORT
March 1993 - October 1993

Approved for Public Release; Distribution Unlimited

Prepared for
UNITED STATES ARMY NATICK
RESEARCH, DEVELOPMENT AND ENGINEERING CENTER
NATICK, MASSACHUSETTS 01760-5000

SUSTAINABILITY DIRECTORATE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
MARCH 1994

3. REPORT TYPE AND DATES COVERED
FINAL Mar 1993 - Oct 1993

4. TITLE AND SUBTITLE
Novel Ultrasonic Method for Food ~~Hydration~~ DEHYDRATION

5. FUNDING NUMBERS
2132040 36T-6T06
P665502 S19129
C DAAK60-93-C-0020

6. AUTHOR(S)
S.R.Taylor and J.C. Hansen

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
S.R. Taylor and Associates
121 N. Adeline Ave.
Bartlesville, OK 74003

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Natick Research, Development
and Engineering Center
Kansas St. ATTN: SATNC-WAA
Natick, MA 01760

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NATICK/TR-94/014

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release;
distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report summarizes the work accomplished in the succesful completion of Phase I of this SBIR Project. The overall conclusion is that the ultrasonic activation during aerosol dehydration results in significant increases in evaporation/dehydration rates. These improvements in dehydration rates allow for much more rapid and energy-efficient processing, thus reducing dehydration costs.

14. SUBJECT TERMS
FOOD DEHYDRATION
ATOMIZATION
LIQUID FOODS
DENTAL PATIENTS
FREEZE DRYING
WATER REMOVAL
LIQUID DIET
ULTRASONIC TRANSDUCERS
DEHYDRATED FOODS
DENTAL LIQUID ENTREES
DEHYDRATION

15. NUMBER OF PAGES
34

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
UNCLASSIFIED

18. SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

19. SECURITY CLASSIFICATION OF ABSTRACT
UNCLASSIFIED

20. LIMITATION OF ABSTRACT
SAR

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

PREFACE

This is the final report for Phase I of "Ultrasonic Dehydration for Liquid Dental Meals" which was performed by S.R. Taylor and Associates under contract #DAAK60-93-C-0020, with the U.S. Army, Natick RD&E Center. This technical data and information are in accordance with the requirements, quintets and schedules as set forth in the Contract Data Requirements list, DD Form 1423 and Data Item Description DI-MISC-80711.

S.R. Taylor and Associates has utilized MIL-STD-1472, Human Engineering Design Guidance for Military Systems, Equipment and Facilities as guidance in developing the optimized drying procedure. MANPRINT (manpower, personnel, training, human factors engineering and system safety) consideration was integrated into the ultrasonic drying procedures.

Under System Safety, S.R. Taylor applied Safety Engineering and Safety management principles, criteria and techniques as a Formal System Safety Program effort that stressed early hazard identification, evaluation, elimination, or subsequent control to preclude injury or death to the user of material developed for the U.S. Army. All hazards identified during initial contract research are described in the final report. All solutions for identified hazards are also described.

The project office4 for this project was originally Dr. Tom Yang. The current project officer is Joseph Cohen, of Natick's Sustainability Directorate.

Citation of trade names in this paper does not constitute an official endorsement or approval of the use of a product.

Research reported in this paper was accomplished under US Army Contract #DAAK60-93-C-0023.

1. Summary

Foods are dehydrated to make them easier to package and store at room temperature. The removal of water reduces the opportunity for harmful chemical reactions. Dehydrated food powders and particles are also used in "liquid meals" for dental patients. However, dehydrated foods traditionally have been difficult to rehydrate and are of relatively poor quality. These difficulties occur because of thermal damage due to the high temperatures that are necessary to dehydrate the foods.

S.R. Taylor and Associates (SRTA) proposed the alternative method of ultrasonic drying for food dehydration for the US Army. Ultrasonic drying has been effective for certain types of heat-sensitive materials such as many fresh foods. A Small Business Innovation Rersearch (SBIR) contract was awarded to SRTA. For Phase I, SRTA proposed to determine which types of food could be appropriately dried ultrasonically and to study the processing variables.

Based on the results of the study, the overall conclusion is that ultrasonic activation during aerosol dehydration results in significant increases in evaporation/ dehydration rates. These improvements in dehydration rate allow for much more rapid and energy-efficient processing, thus reducing dehydration costs. Specifically, the following conclusions can be made.

1. Ultrasonic atomization, either with an American Petroleum Institute (API) - style or Screen-style atomizer is effective for liquids or soluble foodstuffs, but not for pastes or slurries.
2. Liquid atomizers do not efficiently atomize food slurries.
3. *An aspirator, similar to those designed for solids aspiration,* is effective for atomizing food slurries and/or pastes.
4. Ultrasonic vibrations that are transmitted through a fluidizing air stream greatly increase evaporation/dehydration rates, even at room temperature.
5. Oily, fatty foods do not "dry" effectively in an aerosol; the stickiness of the oily particles also leads to sticking of the material to the walls of the chamber.

These conclusions show that all of the Phase I objectives were met. The ultrasonic dehydration process is best suited to non-oily or fatty materials since these materials tend to coat the walls of the chamber rather than to become aerosolized. The process is affected by residence time, airflow rate, and ultrasonic power input.

Air temperature was not varied or investigated as a variable during Phase I testing. Since large improvements in dehydration were observed even without heating the air, slight increases in air temperature should lead to further increases in dehydration. Finally, the process appears to be very cost effective, since the heat required for evaporation can be obtained from the surroundings.

As a result of the Phase I testing, Phase II development efforts can focus on further testing and optimization of the process. A larger dehydration array should be fabricated and testing should be conducted with a variety of foods in order to verify the relationship between operating variables and drying rates, and to develop accurate cost estimates for full-scale production. The dehydrated product should be characterized for nutritional value retention and for ease of rehydration. Finally, the product should be used to prepare a complete ration that includes other ingredients.

2. INTRODUCTION

Problem

Foods are dehydrated to make them more easily packaged and stored at room temperature. Thijssen, 1974, showed that the removal of water reduces the opportunity for harmful chemical reactions (1). Dehydrated food powders and particles are also used in "liquid meals" for dental patients. However, dehydrated foods traditionally have been difficult to rehydrate and are of relatively poor quality. Holdsworth, 1985, demonstrated that these difficulties occur because of thermal damage due to the high temperatures that are necessary to dehydrate the foods (2).

Many processes have been developed to overcome these problems by lowering the thermal requirements for water removal. Osmotic dehydration involves placing the food in a sugar or salt solution. This causes the water to leave the food by osmosis. However, it is a very slow process.

Holdsworth, 1985, wrote that vacuum drying is also useful for heat-sensitive foods, but it is also very slow and expensive (2). Thijssen, 1974, wrote that reverse osmosis and ultrafiltration are low temperature and energy efficient membrane processes, but they do not achieve high levels of of moisture removal (1).

Another process useful for heat-sensitive foods, and is presently being used by the US Army for their dehydration needs, is freeze-drying. The process is described by Rey, 1978 (3). Freeze-drying is a multistage process of lowering the temperature to the freezing point, thereby crystallizing the water in the substance. The ice is then removed by sublimation under a vacuum.

Freeze-drying, although effective, has its drawbacks. Van Pelt and Jansen, 1988, showed that freeze-drying is a very expensive process that involves high capital costs and high energy costs (4). Van Pelt, 1983, (6) and Van Pelt and Swinkels, 1985 (7) , as well as Kessler 1985 (5) have shown that the energy necessary for freeze-drying is in the range of 594 to 745 kJ per kg of water removed.

Opportunity

SRTA proposed an alternative method to food dehydration for the Army. Ultrasonic drying has been proven effective for certain types of heat-sensitive materials, such as many fresh foods. For Phase I, SRTA proposed to determine which food types could be appropriately dried ultrasonically and to study the processing variables. Phase II will involve process optimization for the highest quality dried and rehydrated product at the lowest cost.

Table 1, from Soloff, 1964 (8) shows the effectiveness of sonic dehydration when compared to air drying. Note the minimal times that are required to reach the desired final moisture content.

Table 1 - Comparison of Drying Rates

Material	Initial Percent Moisture	Desired Final Percent	Retention Time Minutes	Sonics Feed Rate kg/min	Sonics Feed Rate lb/hr	No Sonic Feed Rate kg/min	No Sonic Feed Rate lb/hr
Wood Flour	5.5	1.53	3.0	0.012	90	0.005	37
Orange Crystals	3.5	1.8	15.0	0.005	38	0.001	8
Grated Cheese	16.8	5.9	16.2	0.005	35	0.003	25
Powdered Coal	19.2	2.0	5.0	0.015	110	0.006	48
Antacid Powder	15.1	6.0	15.0	0.004	27	0.002	15
Gelatin Beads	12.9	3.7	20.0	0.003	22	0.002	12
Enzyme Crystals	9.8	6.4	120.0	0.0007	5	0.0003	2
Rubber Crumb	44.0	6.0	90.0	0.0009	7	0.0005	4
Carbon-Black Pellets	48.7	1.0	25.0	0.002	18	0.002	12
Polystyrene powder	0.5	0.1	30.0	0.002	14	0.0008	6
Aluminum Oxide	0.5	0.2	5.0	0.007	56	0.004	32
Metallic Soap of Fatty Acid	27.0	0.4	60.0	0.001	10	0.0005	4
Rice Grains	27.6	14.5	11.0	0.005	40	0.002	18

In another study,Palme, 1957, (9), found that fresh wood was dried by the application of sound in 5 minutes, as compared to 3 weeks by conventional methods.

Ultrasonic dehydration is also very energy efficient. It involves the use of a standing wave to rapidly change the pressure that surrounds the food particles. This enhances evaporation of water from the particles. Such a sound wave can be easily produced from a circular flexural plate wave guide.

SRTA has been actively involved in the development of a novel ultrasonic flexural plate design to deliver a highly asymmetric sound beam into gaseous and liquid media. This plate has been used by SRTA, Thomas, et al., 1988, (10) for the development of a barrierless ultrasonic air cleaner (10); for zero gravity phase separation, (Rouse, et al., 1992 (11), Thomas, et al., 1988, (12)); for cleanup of enhanced oil recovery process waters, (Taylor, et al., 1987 (13)); for cleanup of metal working wastewaters, (Taylor and Farmer, 1991 (14)); and olive processing wastewaters, (Taylor and Thomas, 1989 (15)). In general, the novel plate design allows very efficient generation of the necessary standing wave field for the active coalescence of suspended particulate.

This unique flexural plate will produce the desired sound wave pattern to enhance food dehydration at unharmful temperatures and conditions. As stated by Thijssen, et al., 1988 (16):

> "Unlike the concentration of most "chemicals," the dewatering of foods is a delicate affair. Even at moderate temperatures many of their constituent prove to be chemically unstable. At temperatures between 30 and 70^{o}C, enzymatically catalyzed reactions can alter food properties within a few minutes."

Boucher, 1959 (17) showed that the mechanism behind ultrasonically enhanced drying involves sound waves' ability to produce areas of increased and decreased pressure. Frederick, 1965,(18) showed that these waves surround the particles through a process of "echoing," thus allowing all surfaces to be affected by the changing pressures. Boucher, 1959, (19) showed that by alternating the pressure around a particle, small vacuums are created and destroyed, but at the rate of thousands of cycles per second. The gas pressure at the surface is decreased by the vacuum, thus causing enhanced evaporation of the surface moisture, and subsequent drying of the particle.

However, Gréguss, 1963, (20) writes that if only the surface moisture was affected by ultrasonic drying, then the low moisture contents achieved by ultrasonic drying would not be possible.

Likov, 1950, (21) described a theory to explain this phenomenum with the following relationship:

$$k_W = \frac{\sigma k}{4\eta}$$

where k_W = concentration diffusion current

σ = surface tension

η = viscosity, and

k is the pore distribution dependent

Altenberg, 1953, (22) wrote that ultrasonic irradiation affects the viscosity of water which is related to the diffusion current. This enhances the capillary action of the internal moisture, thus allowing more complete drying of the particles.

This information demonstrates the importance of the processing parameters on the effectiveness of ultrasonic drying. To achieve the most efficient drying, the material must be positioned at a nodal point. To accurately do this, the ultrasonics must be in a consistent standing wave pattern. SRTA has developed a novel flexural plate waveguide design which produces a very consistent, controlled standing wave. Otsuka, et al., 1982, (23) described the design. This flexural plate is a type of circular stepped plate, which can easily produce a higher sound pressure than a standard circular plate, without producing heat form the plate itself.

Sonic drying results, such as those seen in Table 1, required sound pressure levels of 169 dB from a propagating wave. Soloff (8). Previous work by SRTA, (Thijssen (1)), that involved the flexural plate design at a sound pressure of 120 dB, mimicked results of Reethof and Tiwary, 1987 (24), Reethof and George, 1986 (25) and Reethof and Tiwary, 1986 (26) that used 140 to 160 dB. This demonstrates the efficiency of the standing wave and flexural plate design. It is reasonable, then, to expect efficient drying results with a lower sound pressure, and therefore lower energy requirement, when using a standing wave instead of a travelling or propagating wave.

A process which would allow dehydration of foods at ambient temperatures and atmospheric pressure would not only be more energy efficient, but would allow a higher quality product that can be easily rehydrated.

Phase I Technical Objectives

The overall objective of this proposed program was to determine the technical feasibility of using a novel ultrasonic drying system to provide a highly efficient and economic dehydration process. The specific objectives addressed in this Phase I program were to:

- Assess the potential of various ingredients for successful and economic ultrasonic dehydration.
- Fabricate and characterize the novel ultrasonic drying system in terms of air flow rate capacity, solids capacity and energy requirement.
- Measure the effective dehydration rate as a function of the flow rate, relative humidity, feed water content, and ultrasonic power input.
- Evaluate the cost effectiveness of various ultrasonic dehydration system configurations.

3. EXPERIMENTAL

Food Materials and Preparation

In order to produce material suitable for ultrasonic dehydration, the food must first be prepared into slurry form so that it can be atomized. Experience with several forms of ultrasonic atomization, effective for pure liquids or solutions, suggested potential for use with slurries. It was felt that if one of these methods would work with a slurry, it could greatly assist the dehydration process since the slurry could be atomized into very fine-sized droplets. Of course, the finer the droplet size, the more rapid the evaporation. This should increase the surface area of the resulting solid particle and improve the rate of mass transfer for dehydration.

The proper slurry should be produced from particulates that can be atomized, but should not take excessive amounts of additional water or time to produce. Several procedures were attempted and these procedures are listed in Table 2. The basic method involved taking a measured amount of raw carrot, placing it in a Waring^{TM} Blender and blending it under high shear for a specified length of time. The condition of the resulting slurry was noted and its ability to be atomized was observed during the feeding of the material through the API-style atomizer.

Table 2 - Carrot Slurry Preparation Procedures

Carrot Mass grams	Water Mass grams	Blend Time minutes	Description
84	168	2	No atomization, too chunky
84	168	4	No atomization, slurpy texture
84	84	2	No atomization, chunky
84	84	5	Slight atomization
112	196	6	Slight atomization

The final method listed was tried with all of the atomizers. In addition, carrots in baby food form was also tried with the atomizers. As will be discussed below, all of these method were ineffective. Additionally, the moisture content in the feed material was increased so that most of the atomization and ultrasonic energy was expended to atomize the water.

Feed for the aspirator was provided by grinding raw carrot in a Waring™ Blender in the following manner:

Carrot (250 g, average of 6 carrots) was chopped into 1.2 cm chunks and blended for 2 minutes at medium speed. The ground material was pushed down off the wall of the container and blended for 3 minutes at high speed. The ground material was again pushed down off the wall of the container, 28 g of water was added, and the material was reblended for 3 minutes at high speed. The resulting paste was pressed to filter out excess water and to leave a paste with approximately 88% moisture content that could be fed through the aspirator.

Dinty Moore Beef Stew™ and Chef Boyardee Spaghetti and Meatballs™ were also ground using the described procedure. Both produced a paste that could be aspirated.

The moisture content was measured by weighing the food collected on the filter in the array, drying the material for 2 hours at 82°C, and weighing the dried product.

Equipment

The entire dehydration array is described in detail below. The ultrasonic power generator used for all testing was an ENI EGR-800B[1] model with an ENI EVB-1[1] impedance match box. The transducers were piezoelectric and fabricated by SRTA. The air flow rates were measured by determining the pressure drop across a calibrated orifice.

4. RESULTS AND DISCUSSION

Potential Ingredients Selection

In order to select materials for dehydration, a survey of current military specifications under the Federal Supply Class 89GP - subsistence, was done. These classes are shown in Table 3.

Table 3 - Federal Supply Classes Covering Dehydrated Foods

Supply Class No.	Title
8905	Meat, Poultry & Fish
8910	Dairy Food & Eggs
8915	Fruits & Vegetables
8935	Soups & Boullions
8940	Special Diet Foods & Food Spec Prep

These classes were surveyed and Mil Specs describing dehydrated products were identified. Virtually all of the specifications for solid foods specify freeze-drying as the dehydration method. In all the cases examined so far, there are specific limits on time/temperature histories for such dehydration. This would seem to make these products suitable candidates for ultrasonic drying enhancement, but not for the proposed ultrasonic pneumatic drying system.

Since the proposed system relies on atomized droplets as the material source to be dehydrated, the method will, at least initially, be best suited to materials that are already in a fine powder form. A large group of such products are those specified for oral liquid feeding. As can be seen, the materials specified for oral liquid feeding primarilly include vegetables, fruits and some starches. There are no meats (not including gravies) specified.

Representative copies of several of the specifications were procured and reviewed prior to experimental work. Based on this preliminary analysis, carrots were selected as a baseline material since they are specified for standard dehydration as well as oral liquid rations. Two preprocessed foods were also selected for preliminary dehydration studies: spaghetti and meatballs and beef stew. These were purchased at a local food market and used directly from the can. The oil and fat content of both of these was high. This significantly inhibited dehydration processing.

Original System Design

The basic dehydration array design took advantage of our prior ultrasonic coalescence studies. The proposed design met the following requirements.

- Simple, easy to clean dehydration chamber
- Ultrasonic activation independent of material feed and flow direction
- Variable air flow capability, ultrasonic power capability, and feed rate capability
- Variable temperature operation

Prior studies showed that relatively low frequency operation is suitable for work in systems in which the bulk fluid is a gas. Additionally, the observed ultrasonic effects are independent of frequency in as the range of 15 to 50 kHz. The dehydration chamber was fabricated from acrylic tubing to allow visual observation during actual test runs. The ultrasonic components including the flexural plate, were designed to handle variable power levels. Since ultrasonic coalescence in gaseous fluids is usually directly dependent upon the power input, i.e., sound intensity within the chamber, the components were fabricated to allow generation of sound pressure levels up to 170 dB.

The system was designed to allow feed material input from several ports with material flow against or with the drying air flow. Although most work was done with room temperature air, the system was designed to allow heating of the inlet drying air as well. Figure 1 is a schematic drawing of the original array.

The sound pressure within the chamber was mapped with a sound level meter at several different locations, in order to verify the axisymmetric quality of the sound beam. Figure 2 show a map of the sound pressure distribution. The

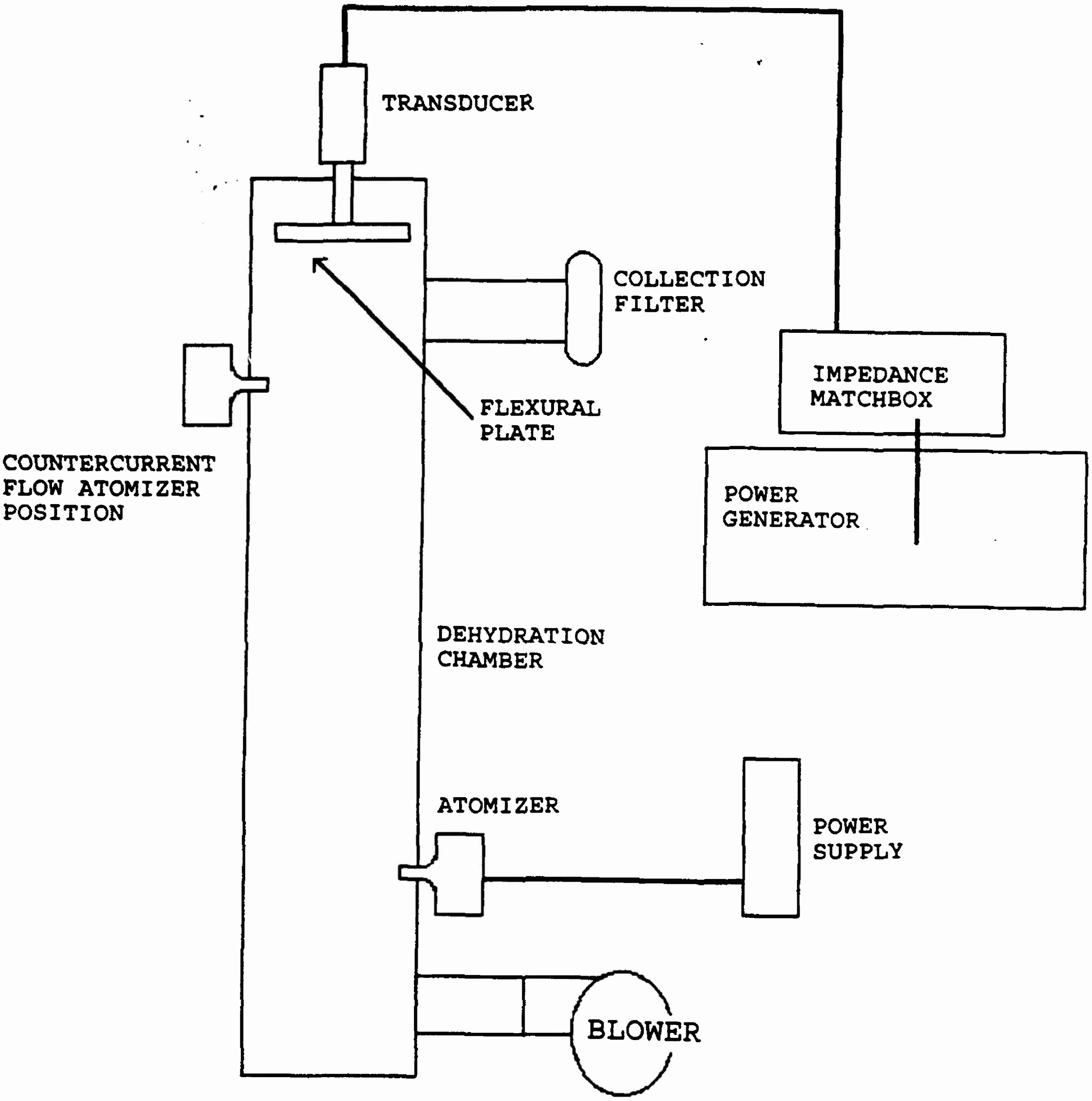

Figure 1. Detailed Schematic Drawing of Dehydration Array

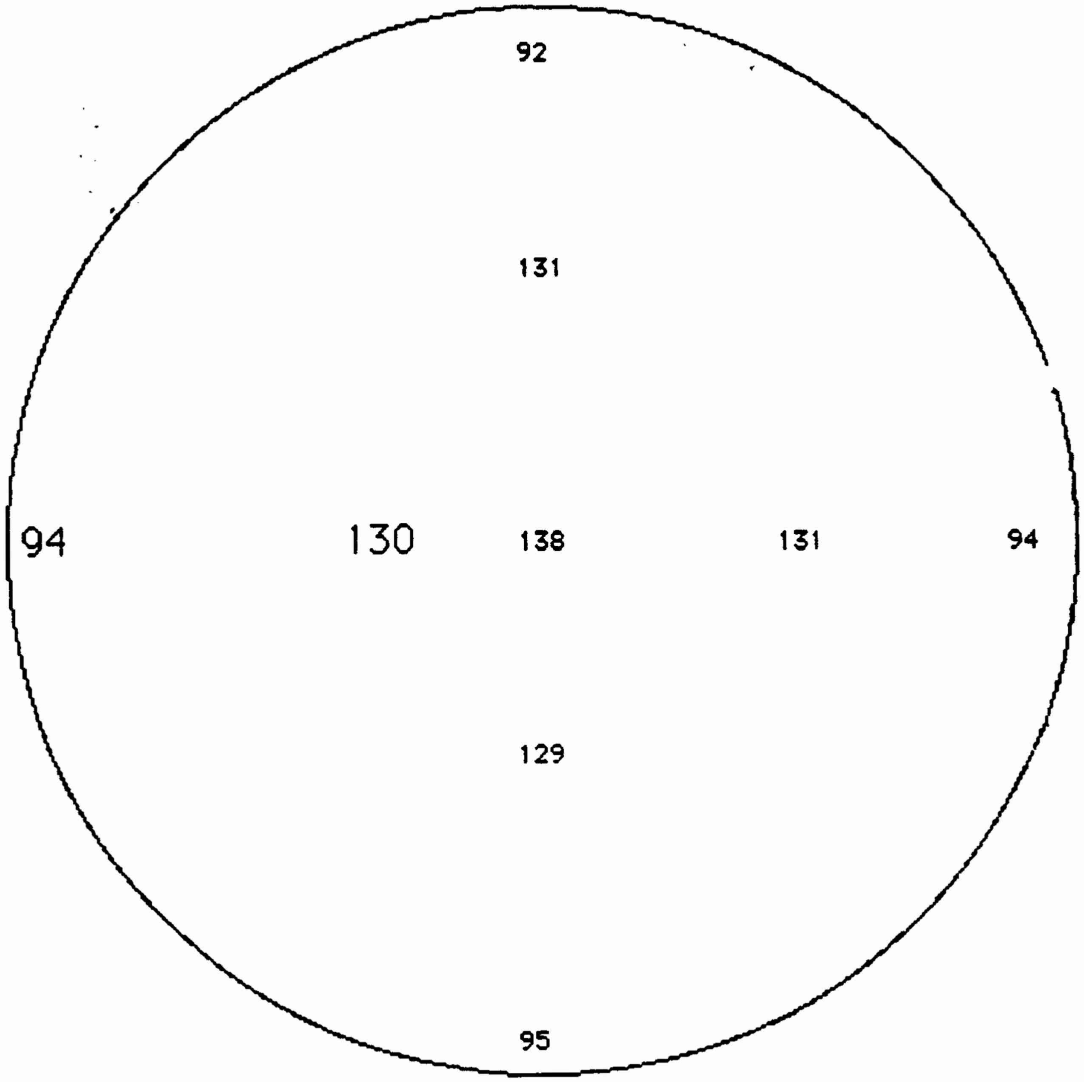

Figure 2. Map of Sound Pressure Dehydration

axisymmetric quality is readily apparent. The array is shown during assembly in Figures 3 and 4.

Atomizer Testing

API-style Ultrasonic Atomizer*

In addition to assembling the dehydration chamber, an ultrasonic atomizer was constructed and tested with water to verify atomization. Figure 5 shows a photograph of the atomizer and power supply. The atomizer was a standard API design with fluid passageways of 0.229 cm (0.090 in) diameter. Although the actual droplet size is a function of the frequency, the large diameter allowed a rather coarse slurry to be fed. The goal of initial atomization development was to determine the minimum blending time required to provide a slurry that could be continuously atomized.

Initial water tests indicated that most of the water droplets evaporated by the time the top of the chamber is reached. In other words, the atomizer produced droplets fine enough to promote rapid evaporation. If the atomizer produced similar sized droplets with the carrot slurry, excess water evaporation should also occur very rapidly so that the ultrasonic standing wave field energy can be utilized for dehydrating the remaining carrot particulate efficiently.

The carrot slurry, either from fresh carrots or baby food, was thin enough to get through passageways in the atomizer. Indeed, atomization was done in the dehydration chamber and a small amount of product was collected at the filter. However, the atomization was very inefficient.

It was observed that the carrot slurry flooded the tip of the atomizer very easily and it appeared that the water was atomizing, but most of the carrot solids were left behind. Apparently, the particles of carrot are generally larger than the droplet size, hence they do not get atomized. The atomizer was operated at a frequency of approximately 40 kHz which resulted in droplets of approximately 30 to 40 microns. If the carrot particulate was larger than 20 microns, it was unlikely that an atomized droplet would contain any carrot.

Although there was some carrot material fine enough to be collected on the filter, this method may require too much grinding and shearing of the foodstuff, in addition to producing a slurry with a very high initial moisture content. Alternatives that were tried included another API-style atomizer that operated at a lower frequency to produce larger droplets, a Screen-style ultrasonic atomizer, and a pressurized liquid atomizer.

Low-Frequency Atomizer

A new API-style atomizer was fabricated for use at approximately 18 kHz. With water, this lower frequency produces droplets with an average diameter of 90 microns. The new atomizer, operating at 18kHz, clearly provided much larger droplets. Atomization of the carrot slurry produced an orange aerosol, although not all of the slurry was atomized. Apparently, it was very easy to flood the atomizer so that the liquid layer did not form adequate surface waves. Although this atomizer

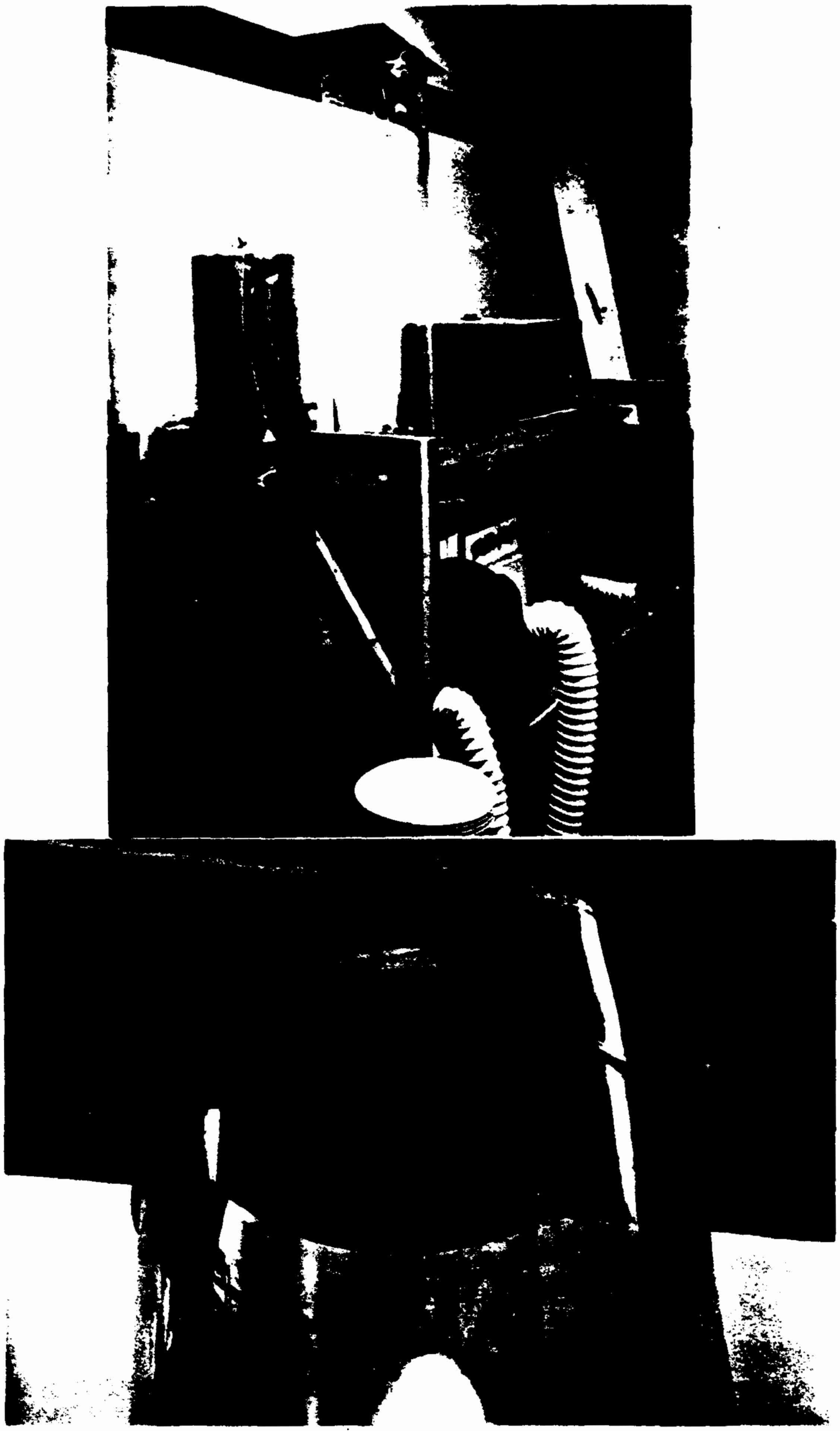

Figure 3. Dehydration Chamber During Assembly
Overall View of Chamber and Detail View of Flexural Plate

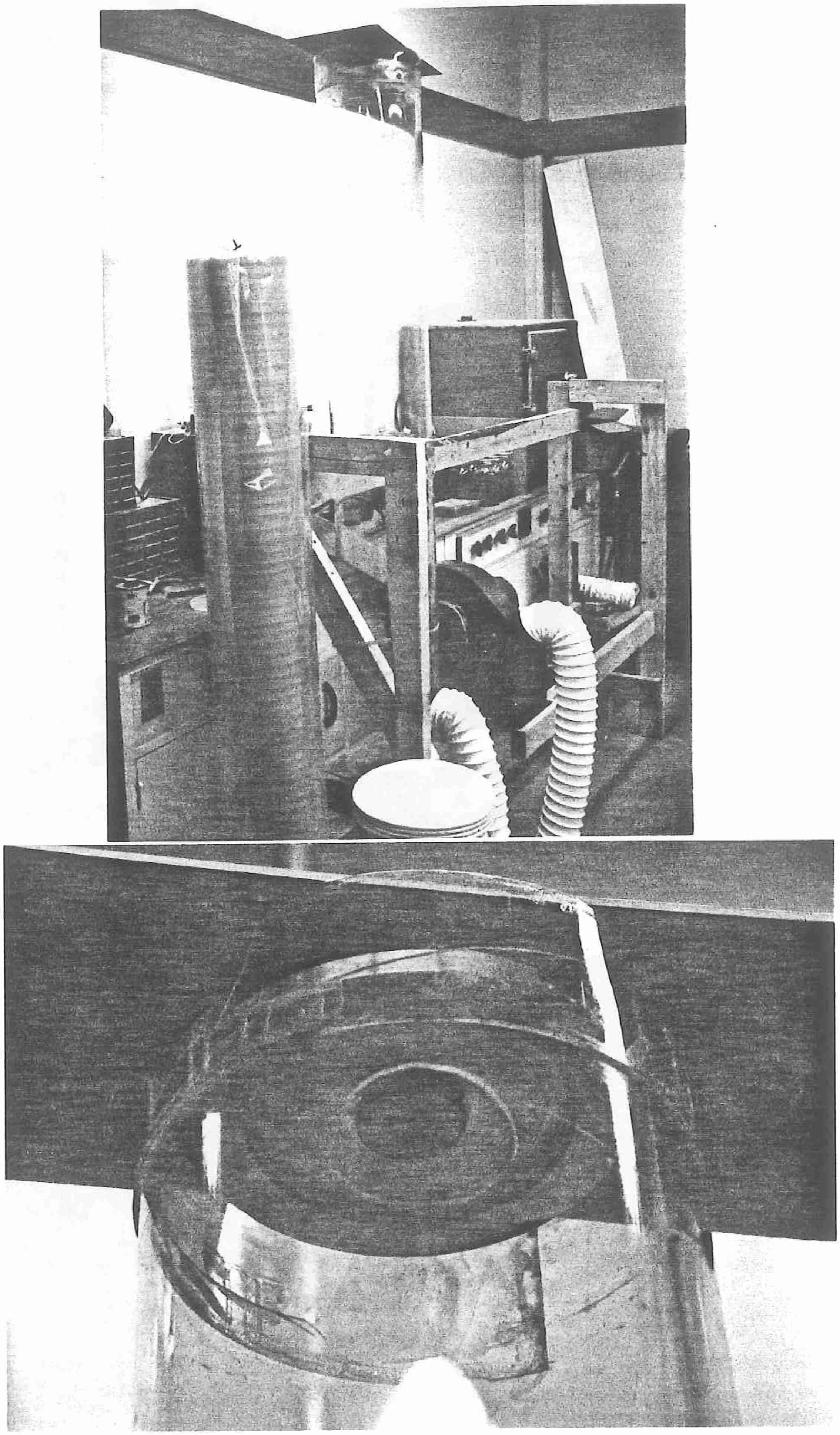

Figure 3. Dehydration Chamber During Assembly
Overall View of Chamber and Detail View of Flexural Plate

Figure 4. Dehydration Array Components
View of 15 kHz Cu-Be Flexural Plate and Transducer and
View of Power Generator and Impedance Match Box

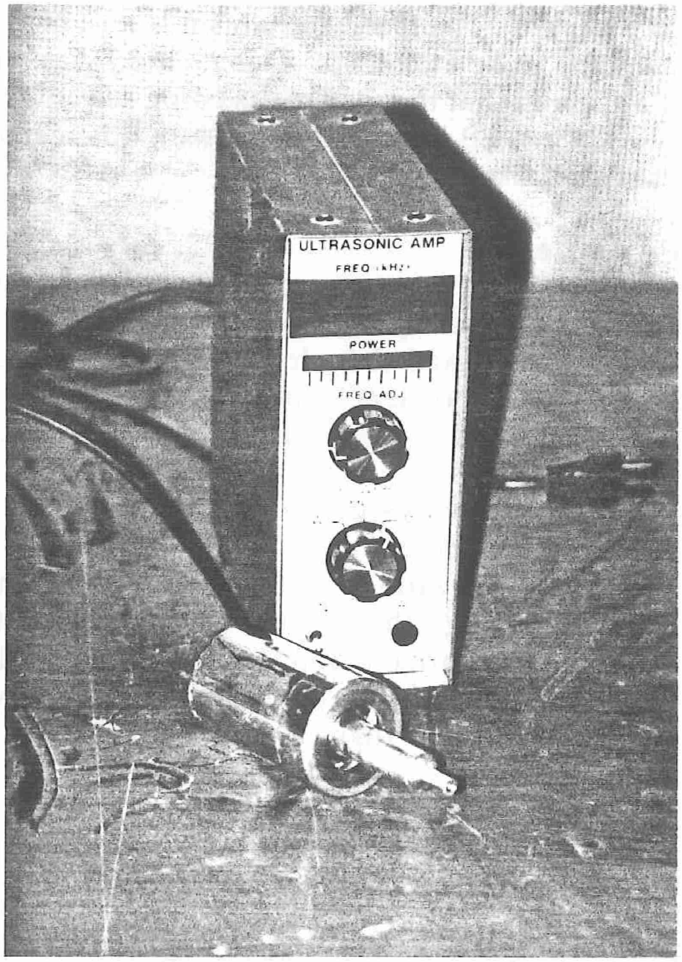

Figure 5. Ultrasonic Atomizer and Power Supply

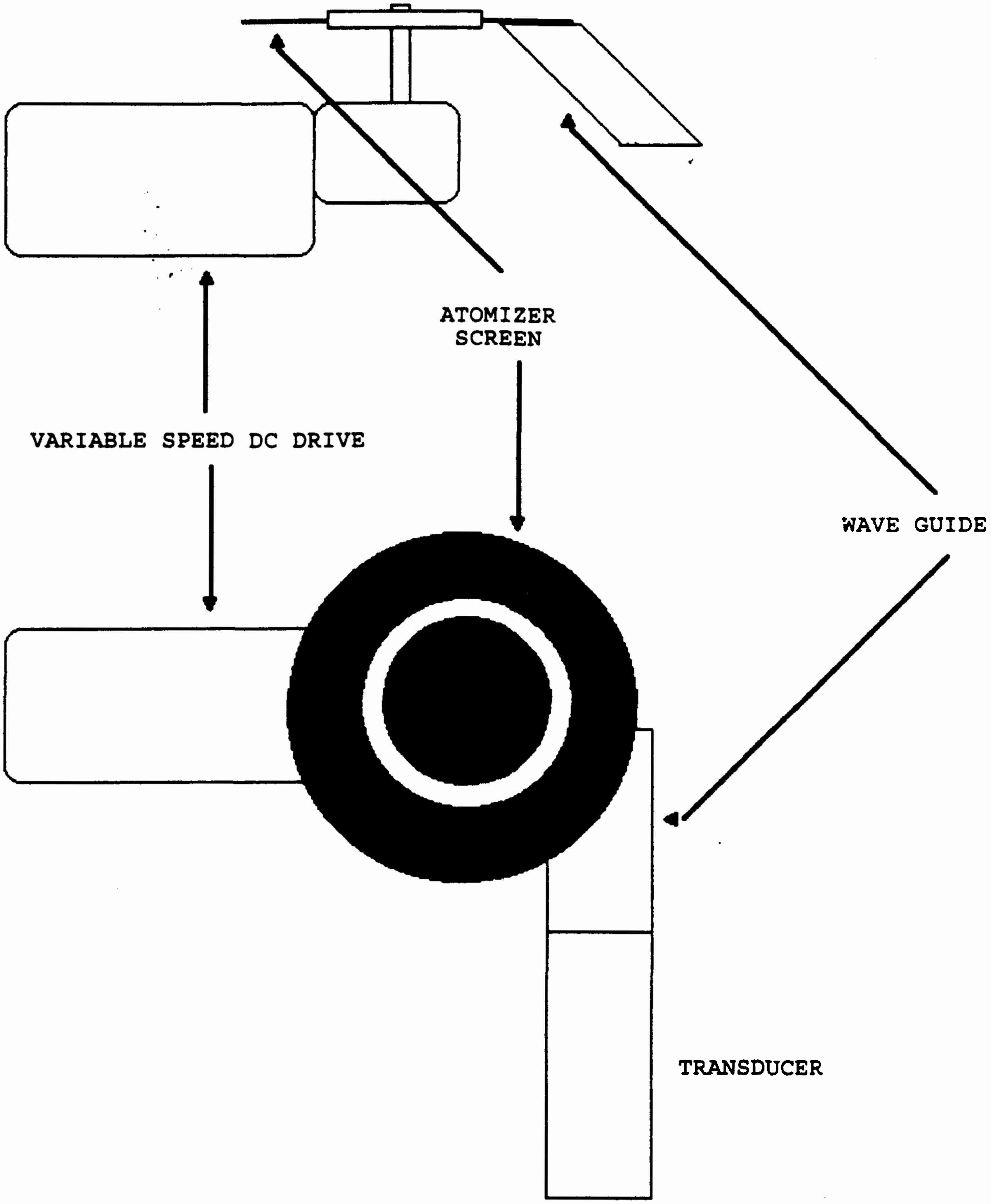

Figure 6. Schematic Drawing of Screen-Style Atomizer

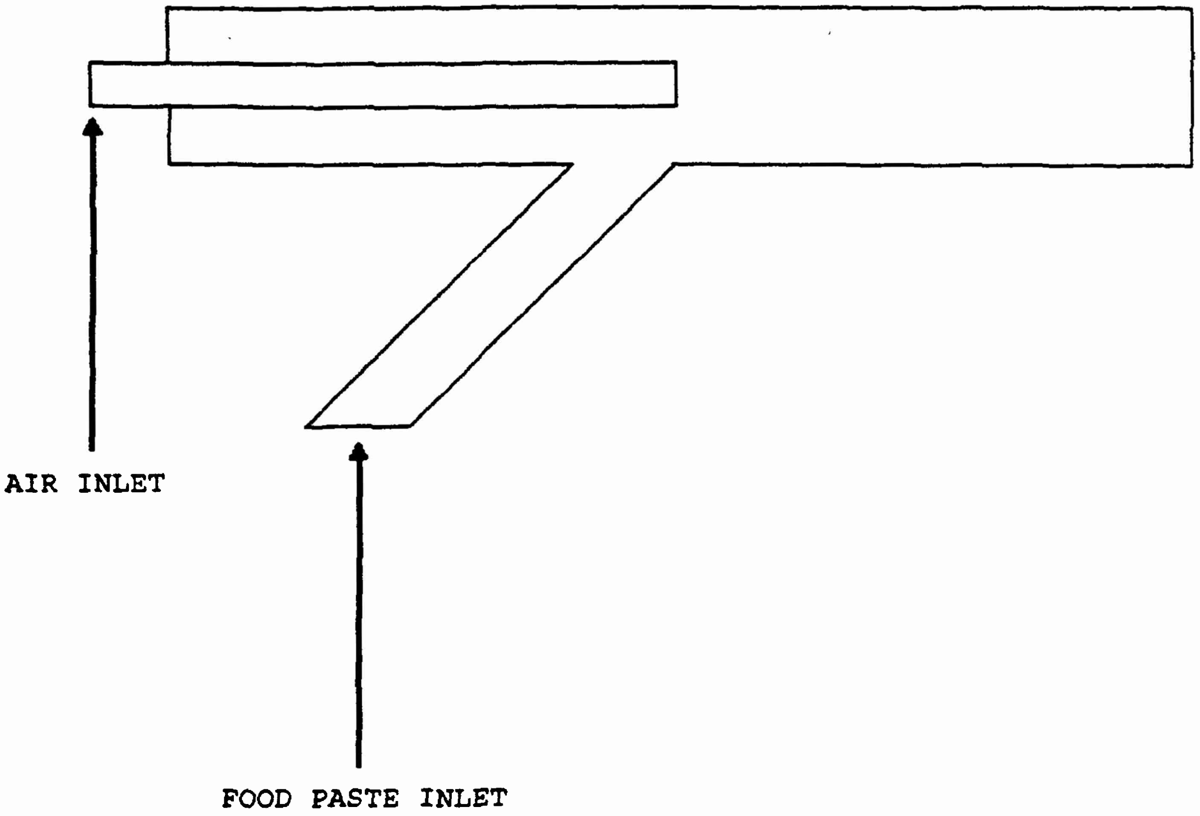

Figure 7. Schematic Drawing of Aspirator

and an ultrasonically activated flexural plate mounted in the top. This is shown as a schematic diagram in Figure 8. Essentially, the system can be operated as a very low density fluidized bed. Hence, material does not leave the bed until it is dry enough (e.g., light enough) to be pneumatically carried out of the chamber.

The original chamber had a length of 1.5 m (5 ft). The modified chamber was set up to have a total length adjustable between 1.5 and 2.4 m (5 and 8 ft). This allowed comparison of the effect of increased residence time without reducing the air flow rate. Figures 9 and 10 are photographs of the final, modified array.

Dehydration Tests

Original System

Once a suitable carrot slurry was produced and it was possible to achieve some atomization, the carrot slurry was atomized in the chamber to produce an aerosol which was then collected on the filter. Table 4 presents initial data on collection and dehydration of the atomized carrot slurry.

Table 4 - Initial Carrot Slurry Atomization and Dehydration

	Flow		U/S Power	Moisture Content
Test	ft^3/min	m^3/min	Watts	%
1	75	2.12	--	56
2	75	2.12	50	32
3	75	2.12	100	20
4	75	2.12	200	18

Since the airflow rates controls both the residence time and the amount of transfer medium (air) that the material "sees", control tests were conducted and the results are shown in Figure 11. As expected, increasing airflow rate does improve dehydration although, even at the highest flow rate, the product material is still very wet.

The ultrasonic activation did affect the moisture content of the collected carrot solids, however, the amount collected was still very small. Typical captured solids were 0.03 to 0.07 grams. This low collection means that there is a large potential for error in the measurement of moisture content. Finally, since the slurry used for atomization was relatively low in solids content, the moisture content of the recovered material was still too high.

Figure 12 shows a graph of the data. It is clear that increasing ultrasonic power input led to increased dehydration as expected,

As noted above, tests with either the Screen-style ultrasonic atomizer or the pressurized liquid atomizer did not produce sufficient aerosol to recover material on the filter. As a result, no dehydration data were obtained with those atomizers.

Modified System

The addition of the aspirator to the system and the modifications to improve air flow through the chamber led to a dramatic increase in throughput. It was possible

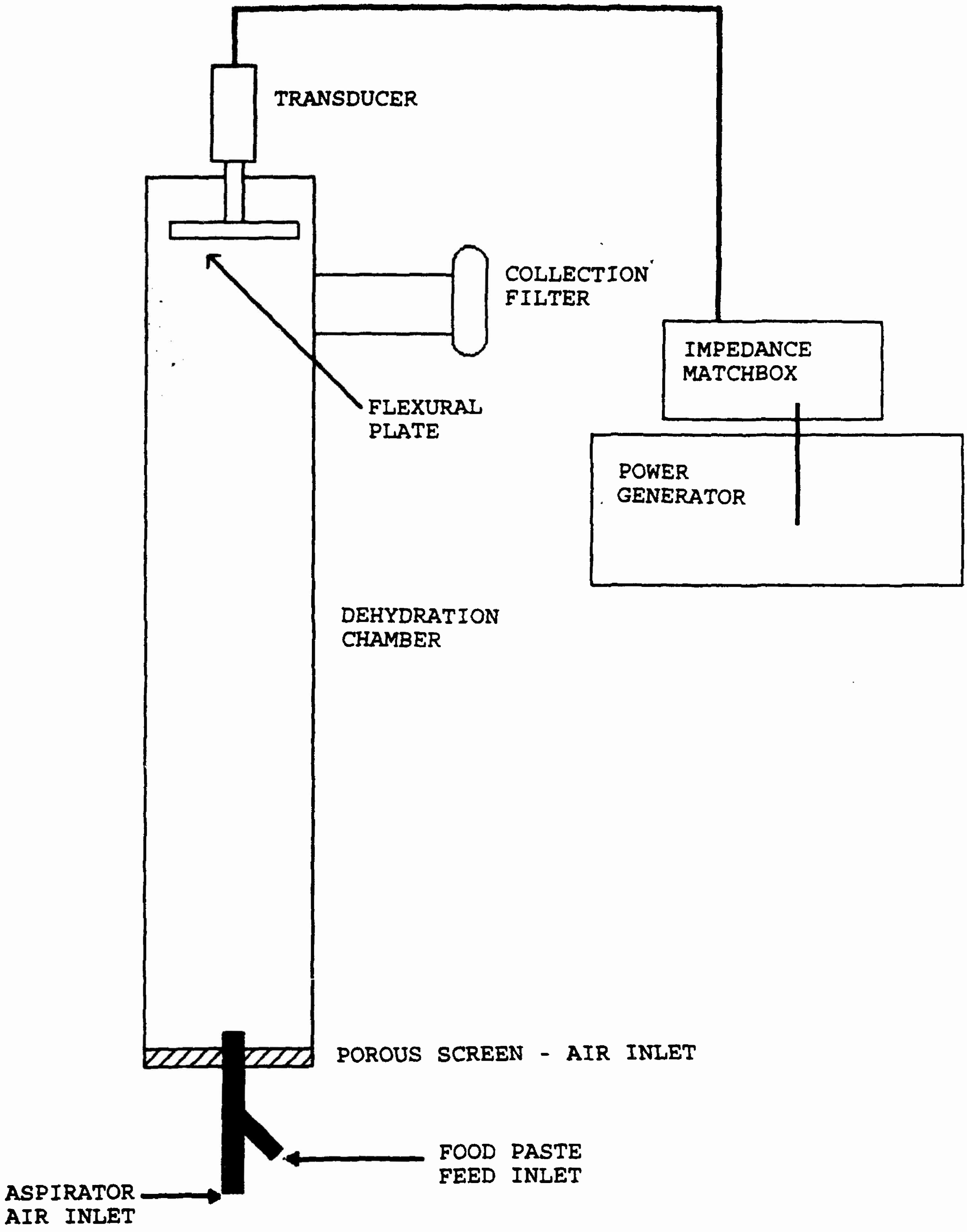

Figure 8. Schematic Drawing of Modified Array

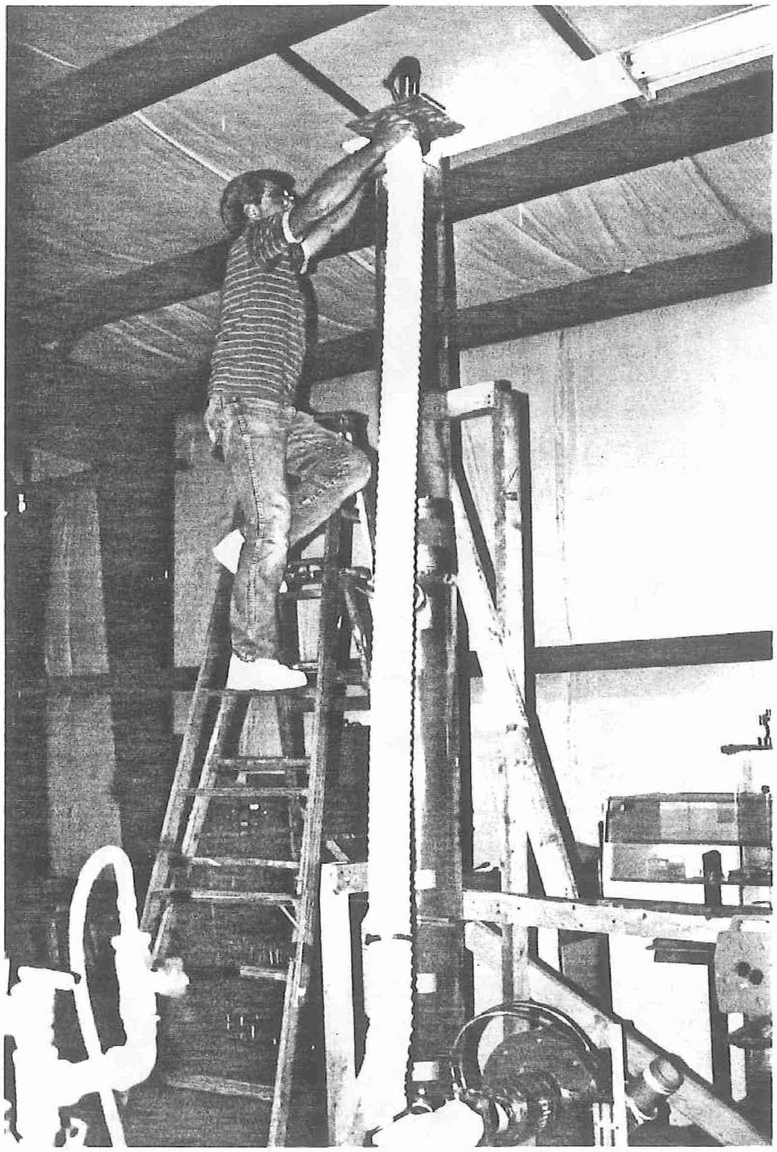

Figure 9. Modified Array

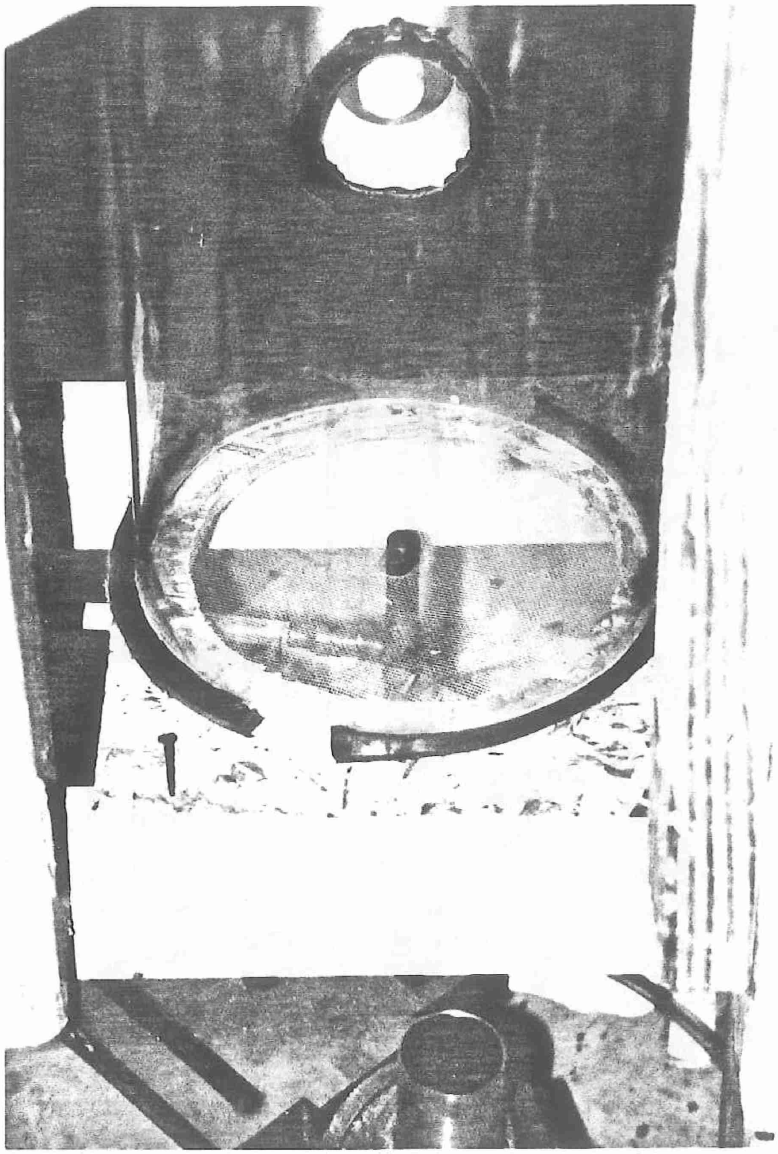

Figure 10. Modified Array

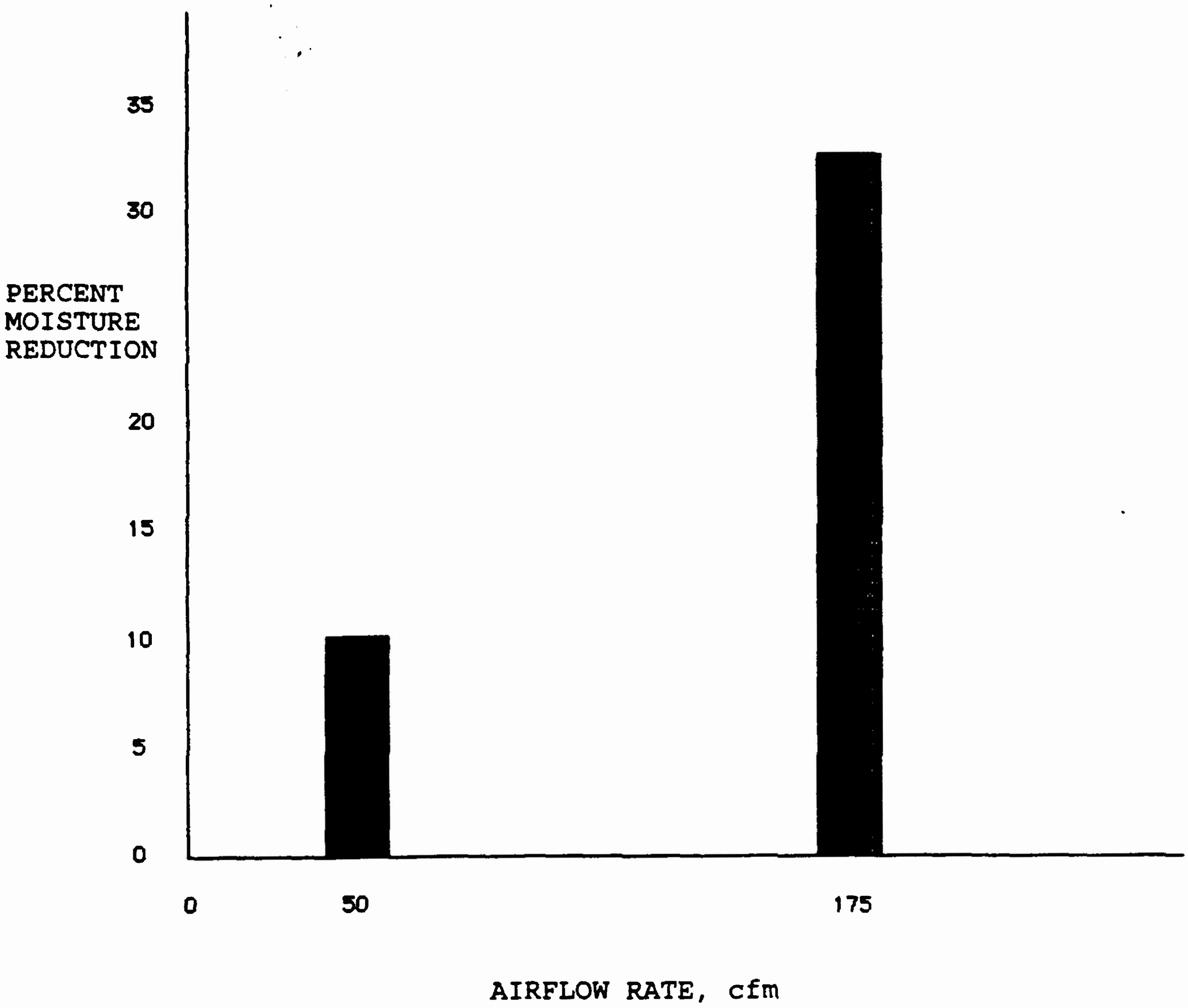

Figure 11. Effect of Air Flow Rate on Dehydration

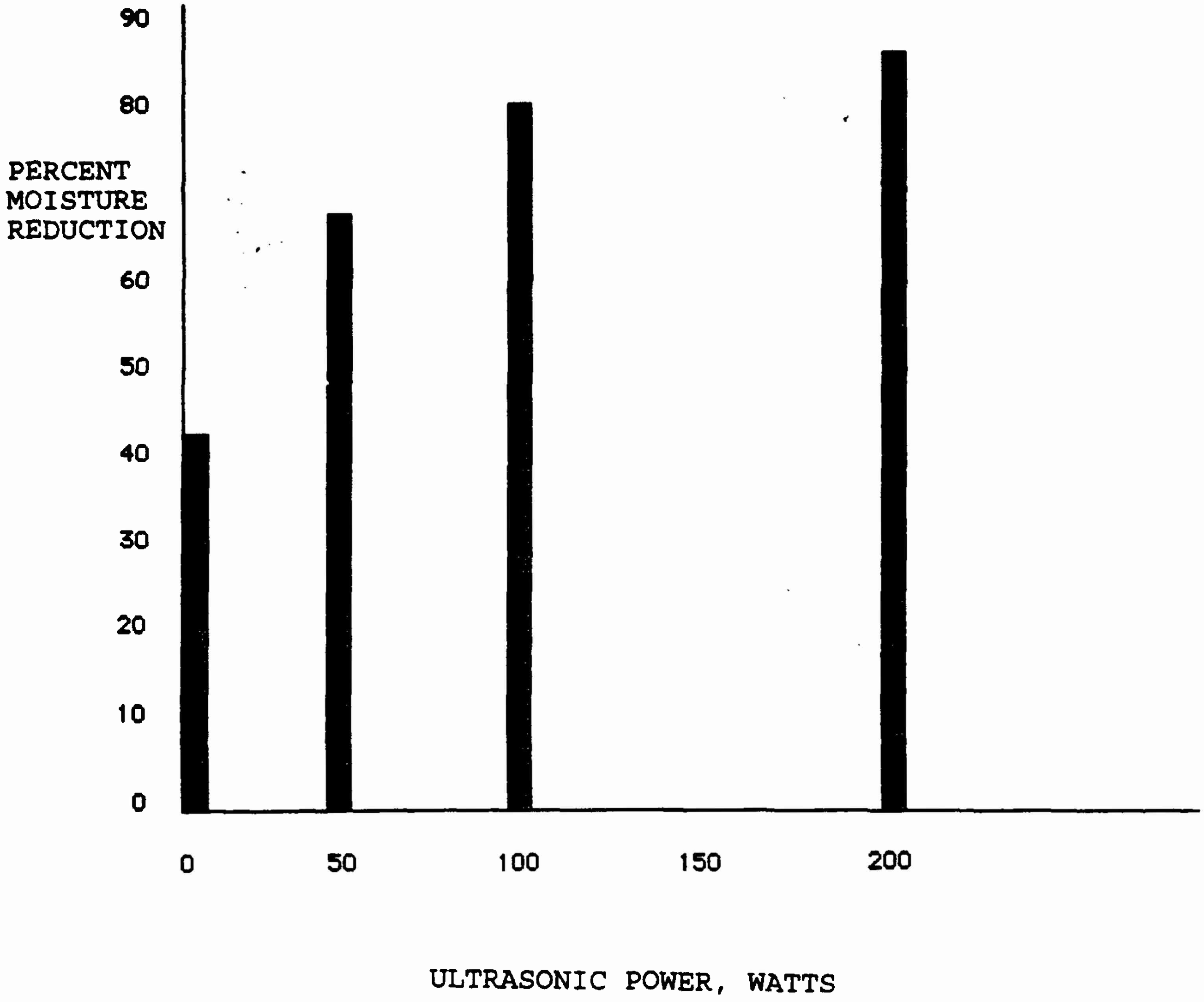

Figure 12. Effect of Ultrasonic Power on Dehydration

to feed the carrot paste at rates of 1.4 to 2.7 kg (2.5 to 5.0 lb) per hour through the aspirator. This allowed collection of much more material on the filter. Test were conducted with varying air flow rates and/or varying residence times. The data are shown in Table 5.

Table 5 - Dehydration Test Data With The Modified Array

Flow		Chamber Length		Residence Time	Ultrasonic Power	Average Moisture Reduction
m^3/min	ft^3/min	m	ft	sec	Watts	%
1.4	50	1.52	5	2.9	--	10
5.0	175	1.52	5	0.8	--	32
1.4	50	1.52	5	2.9	150	64 (86 max.)
5.0	175	1.52	5	0.8	150	61 (95 max.)
5.0	175	1.52	8	1.3	150	82

Figure 13 shows the effect of residence time on the dehydration. It is apparent that increasing residence time leads to better dehydration without sacrificing throughput.

Rehydration Tests

Samples of the dehydrated carrots, both before and after final drying to determine moisture contents, were placed in a beaker. Water was added to produce the same moisture content as the original material (approximately 90%) The effort and time required to rehydrate the material were determined. Very little mixing was needed as the dry material literally sucked the water right up. Gentle swirling of the beaker contents provided sufficient mixing to reabsorb all of the water.

Preliminary Cost Estimate

Table 6 shows this information.

Table 6 - Preliminary Cost Estimate

Cost Element	kWh/hour	Cost, $/hour
Aspiration, 1 HP	0.750	0.0750
Blower, 1.5 HP	1.125	0.1125
Ultrasonic Plate	0.250	0.0250
Total		0.2125

These numbers are based on the Phase I lab scale array that processed a maximum of 2.3 kg (5 lb) per hour wet to produce approximately 0.34 kg (0.75 lb) per hour dry. This leads to an estimated cost of $0.62 per kg ($0.28 per lb).

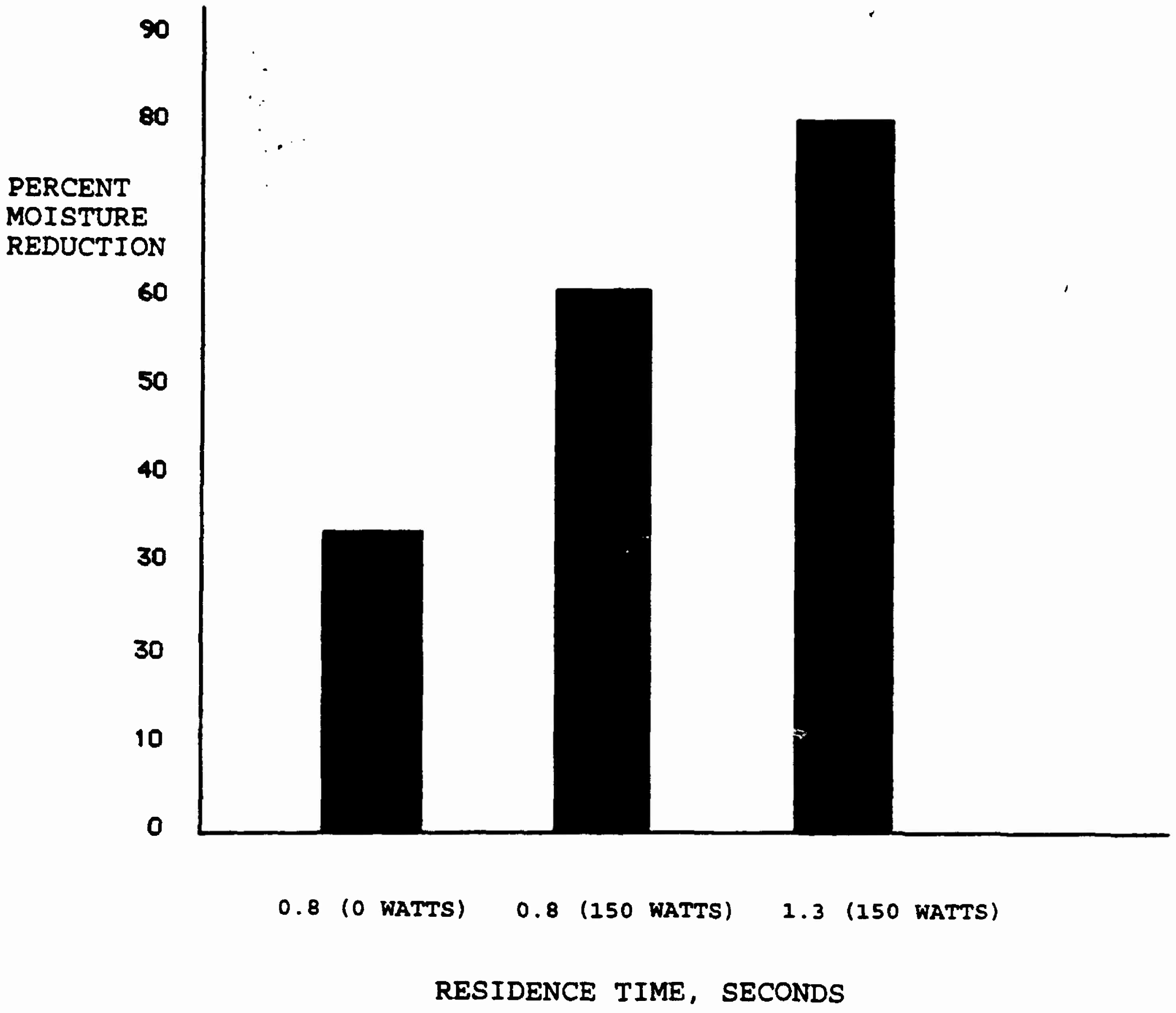

Figure 13. Effect of Residence Time on Dehydration

5. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH AND DEVELOPMENT

Based on the results discussed above, the overall conclusion is that ultrasonic activation during aerosol dehydration results in significant increases in evaporation/dehydration rates. These improvements in dehydration rate allow much more rapid and energy-efficient processing, thus reducing dehydration cost. Specifically, the following conclusions can be made:

- Ultrasonic atomization, either with an API-style or Screen-style atomizer, is effective for liquids, or soluble foodstuffs.
- Liquid atomizers do not efficiently atomize food slurries.
- An aspirator, similar to those designed for solids aspiration, is effective for atomizing food slurries and/or pastes.
- Ultrasonic vibrations, transmitted through a fluidizing air stream, greatly increase evaporation/dehydration rates, even at room temperature.
- Oily, fatty foods do not "dry" effectively in an aerosol; the stickiness of the oily particles also leads to sticking of the material to the walls of the chamber.

The conclusions show that all of the Phase I objectives were met. The ultrasonic dehydration process is best suited to non-oily or fatty materials, since these types of materials tend to coat the walls of the chamber rather than becoming aerosolized. The process is affected by the residence time, airflow rate, and ultrasonic power input. Air temperature was not varied or investigated as a variable during Phase I testing. Since large improvements in dehydration were observed even without heating the air, slight increases in air temperature should lead to further increases in dehydration. Finally, the process appears to be very cost effective.

As a result of the Phase I testing, Phase II development efforts can focus on further testing and optimization of the process. A larger dehydration array should be fabricated, and testing should be conducted with a variety of foods in order to verify the relationship of the operating variables to drying rates and to develop accurate estimates for full scale production. The dehydrated product should be characterized for nutritional value retention and for ease of rehydration. Finally, the product should be used to prepare a complete ration that includes other ingredients.

This document reports research undertaken at the
US Army Natick Research, Development and Engineering
Center and has been assigned No. NATICK/TR-91/014
in the series of reports approved for publication.

6. REFERENCES

1. Thijssen, H.A.C., Fundamentals of Concentration Process, Chapter in Advances in Preconcentration and Dehydration of Foods. Ed., Arnold Spicer, John Wiley & Sons, New York, 1974
2. Holdsworth, S.D., Advances in the Dehydration of Fruits and Vegetables, Chapter in Concentration and Drying of Foods. Ed., Diarmuid MacCarthy, Elsevier Applied Science Publishers, London, 1985
3. Rey, L.R., Glimpses into the Fundamental Aspects of Freeze-Drying, Proceedings of the International Symposium on Freeze-drying of Biological Products, Ed., V.J. Cabasso and R.H. Regamey, Washington DC, 1978
4. Van Pelt, W.H.J.M., and Jansen, H.A., Freeze Concentration Economics and Applications, Chapter in Preconcentration and Drying of food Materials, Ed. S. Bruin, Elsevier, Amsterdam, 1988
5. Kessler, H.G., Energy Spects of Food Preconcentration, Chapter in Concentration and Drying of Foods, Ed. Diarmuid MacCarthy, Elsevier Applied Science Publishers, London, 1985
6. Van Pelt, W.H.J.M. in Grenco Special Applications, B.V. Holland, May, 1983
7. Van Pelt, W.H.J.M and Swinkels, W.J., Fourth International Congress of Engineering and Food, Edmonton, Alberta, July 7-10, 1985
8. Soloff, Robert S., Sonic Drying, J. of Acoustical Soc. of America, Vol. 36, no. 5, May 1964
9. Palme, J. Soc. Ing. Civ., Jan. 1957
10. Thomas, B.J., Desai, P.M., Treuhaft, M.B. and S.R. Taylor, Barrierless Ultrasonic Air Cleaner, U.S. Army Contract No. DAAE07-87-C-R065, Final Technical Report, February, 1988
11. Rouse, C.M. Thomas, B.J., Farmer, E.E. and S.R. Taylor, Zero Gravity Phase Separation - Phase II, Final Technical Report, NASA Contact No. NAS 9-18173m March, 1992
12. Thomas, B.J., Butcher, C.W., Treuhaft, M.B. and S.R. Taylor, Zero Gravity Phase Separation via Ultrasonic Coalescence, Final Technical Report, NASA Contract No. NAS 9-17950, July, 1988
13. Taylor, C.M., Desai, P.M., Thomas, B.J. and S.R. Taylor, EOR Process Water Cleanup via Ultrasonic Coalescence, U.S. Dept. of Energy Contract No. DE-AC01-86ER80346, Final Technical Report, March, 1987
14. Taylor, S.R. and E.E. Farmer, Novel Cleanup of Metal Working Wastewaters, Final Technical Report, EPA Contract No. 68D00030, March, 1991
15. Taylor, S.R. and B.J. Thomas, Olive Oil Process Water Cleanup via Ultrasonic Coalescence, Final Letter Report, for Lindsay Olive Co., Lindsay, CA, March, 1989
16. Bruin, Dr. S., Thijssen Lecture: Introduction to the Symposium Topic: Preconcentration and Drying of Food Materials, Ed., S. Bruin, Elsevier, Amsterdam, 1988
17. Boucher, R.M.G., Ultrasonics in Processing, Chemical Eng., Oct. 2, 1961
18. Frederick, Julian R., Ultrasonic Engineering, John Wiley & Sons, New York, 1965

REFERENCES (CONTINUED)

19. Boucher, R.M.G., Ultrasonics Boost Heatless Drying, Chemical Eng., Sept. 21, 1959
20. Greguss, P., The Mechanism and Possible Applications of Drying by Ultrasonic Irradiation, Ultrasonics, April-June, 1963
21 Likov, A.V., Theory of Drying, 1950
22. Altenberg, K., Naturwissenshaften, 1953
23. Otsuka, Tetsuro, Kamishima, Yoshiyuki, and Seya, Koichiro, Aerial Ultrasound Source by Stepped Circular Vibrating Plate, Proc. of 3rd Symposium on Ultrasonics Electronics, Tokyo, 1982
24. Reethof, G. and Tiwary, R., Numerical Simulation of Acoustic Agglomeration and Experimental Verification, J. of Vibration, Stress and Reliability inDesign, 1987
25. Reethof, G. and George, W., On the Fragility of Acoustically Agglomerated Submicron Fly Ash Particles. J. of Vibration, Stress and Reliability in Design, 1986
26. Reethof, G. and Tiwary, R., Hydrodynamic Interaction of Spherical Aerosol Particles in a High Intensity Acoustic Field, J. of Sound and Vibration, 1986