Lyophilisation: its present state of development

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The objective of this presentation is, as the title implies, to review the general status of food preservation by lyophilisation or freeze-dehydration: the equipment and technique being used and in development, the products of interest and the product quality obtained, the cost and market picture as well as general trends of development. The basic principles of freeze-drying will also be discussed briefly.

The Indians of the Andes are said to have practised freeze-drying hundreds of years ago. Be that as it may, the fact remains that freeze-drying is a very young industrial method of food preservation, less than ten years old. For its age and for its humble size and importance it has certainly had its share of publicity, especially during the early stages of development. I need only remind you of the visions in Readers Digest of freeze-drying as the most significant break-through since Appert which should make all other preservation methods outmoded, combining the quality of fresh produce with low weight, unlimited storage life at room temperature, instant reconstitution and preparation and low costs. With the accumulation of practical experience and results of intensified research, this type of fanciful publicity has, fortunately, given way to a more modest and realistic outlook. Few people now believe in freeze-drying as a serious competitor to the established conventional preservation methods of canning, freezing etc. The quality is mostly not quite comparable to frozen products, and often not to canned products either. Storage life without refrigeration is definitely not unlimited, and costs are high and will probably remain so for a long time to come. On the other hand, it is also realized that the method can in many cases present such unique advantages, that its
future as an industrial method of food preservation should be guaranteed, even if the attained volume may never become particularly impressive, except, possibly, for a few applications, such as instant coffee. The actual growth of industrial freeze-drying achieved so far is difficult to ascertain, since no official statistics is yet available. Serious efforts have been made to estimate the size and predict the future growth of freeze-drying in the United States, but, unfortunately, no comparable effort has been made in regard to the rest of the world. However, the total production of freeze-dried foods in the world today counted on a wet weight basis is probably less than the production of canned foods in Sweden alone, which in 1964 amounted to 25,000 tons, a comparison which should stress that this is still a very small industry, in spite of annual growth figures in the order of 25 - 100%. In fact it could be said that what we have seen up to very recently has been nothing but large scale pilot plant operation and test marketing, and that the industrial phase has started first with the few plants of around 20 ton daily production capacity now in operation.

From this starting point we shall go over to discuss aspects of freeze-drying technique and equipment in operation and in development, after some words on basic principles for the benefit of those who possibly have not earlier had reason to give this drying method much thought.

Basic principles

In principle, freeze-drying means that the material or food is first frozen, and then the ice evaporated or sublimed in a vacuum chamber, while maintaining temperature and vacuum at such a level that there is no risk for melting of the ice until all of it has been removed. In practice, drying is carried still further to remove some of the bound, unfreezable water for improved stability of the dried product. During the sublimation (or evaporation) period the necessary heat of sublimation has to be supplied from some heat source.

The following two diagrams constructed by Roy (1) illustrate the general principles very well, one showing the amounts of various forms of water present during the different stages of freezing and subsequent freeze-drying, the other the product temperatures under ideal conditions of freezing and freeze-drying.
Freezing should be carried below the temperature where all free water is frozen out. During the sublimation stage, when the ice successively disappears and the front between dried material and remaining ice recedes into the sample, the temperature at this ice front has to be maintained low enough so that partial melting is avoided. When all ice has been sublimed away, the desorption phase starts when bound water is being removed, and temperature can be increased considerably, but below a level where heat damage to the dry product might occur. Some overlap between the two stages of drying will of course occur, since the product dries from outside in.

The basic components of a freeze-drier is a vacuum-drying chamber, a water vapor or ice condenser and a vacuum pumping system for removing air and other incondensable gases. Inside the drying chamber the frozen product is usually spread out in relatively thin layers or slabs on trays, placed between horizontal heating plates which supply the necessary heat of sublimation, usually as radiant heat. The water vapor is frozen out on a refrigerated cold trap or condenser, and the residual gas pumped out by vacuum pumps, or both water vapor and gas is taken care of by a multiple system of steam ejectors.
The rate at which freeze-drying can be achieved will primarily depend on the three basic product dependent temperatures already mentioned, and on the rate with which heat can be supplied to the retreating ice-front and vapor transported through the already dried layer and to the ice condenser. Except for the very initial phase of drying, heat transfer through the dried layer is generally believed to be the rate-limiting factor where radiant heat is used. The reason is that freeze-dried foods have a heat conductivity comparable to that of a good thermal insulating material. Consequently, drying cycles tend to be long and very dependent of sample thickness.

The heat of sublimation can also be supplied by conductive heating, where the product is frozen in direct contact with the heat source, and heat is conducted to the ice front through a diminishing thickness of frozen material with high thermal conductivity. Unfortunately, temperature of the heat source has to be maintained low enough to avoid partial melting of the ice, and the slab is dried from one side only, both factors which tend to increase drying time. It is also difficult to prevent the slab from coming loose and drying on the back side as well. I will come back later on to the possibilities of using microwave heating to drastically shorten drying cycles. At the present time, using radiant heat, a typical drying cycle for a slab of meat about 1 cm thick may be something in the order of 6 to 8 hours. The degree of vacuum necessary will depend on what ice front temperature has to be maintained for the particular product to avoid partial melting, and can be accomplished by the proper choice of ice condenser temperature and dimensioning of the vapor removal system.

Presently used equipment and processing technique

The freeze-drying units in use in the food industry today vary from small pharmaceutical type shelf dryers of batch type to very modern installations specifically designed for large scale freeze-drying, with a minimum of manual handling, supervision and cost, the latter type probably representing the main part of the volume produced. The plant components (the chamber, condenser and vacuum system) have been designed by a variety of principles and modifications by different equipment manufacturers. If the method of applying the heat of sublimation is considered only, dryers can be divided into contact dryers, radiant dryers, mixed contact-radiant and so-called accelerated dryers, of which the "accelerated" appear to be getting obsolete, even if there are still several such plants in operation. As a rule, cylindrical drying chambers predominate in Europe, whereas rectangular chambers with their higher product loading factor, are often the choice.
in the United States. In Europe there is also a tendency towards very large drying chambers, up to several tons loading capacity, while 1 ton seems to be the upper limit in the United States. Fixed, horizontal platens are generally used, heated by vacuum steam or by circulating oil, glycol, etc. The product trays (expanded metal mesh trays, or special whole-metal trays of finned or other design) are positioned interleaved between the heating platens in direct contact with these, or more usual at a distance for heat transfer by radiation. With high loading capacities and narrow spacing between platens and trays it is necessary to use special devices to simplify and speed up loading, unloading and handling. One way is to push the product trays in position from a special filling cart, another to place the trays on overhead rail carriers, which go right into the freeze-drying chamber. Still another method is to build the heating platens into a rail car on which the product trays are loaded outside of the freeze-drier, and the whole package run into the drying chamber after freezing and hooked to the heating system.

Loading and unloading is usually done through the same door, but systems are available and in use with separate wet end entry and dry end exit doors from the chamber, also of semicontinuous type with entrance and exit vacuum locks. Most dryers are of the batch type, although semicontinuous driers seem to represent a fair proportion of the drying capacity installed.

For vapor removal, modern plants are usually equipped with refrigerated condensers backed by vacuum pumps, while the use of steam ejectors seems to be on the return, partly because of the relatively low pressures required for some products. The refrigerated ice condenser, of tube or plate type, is either placed in a separate chamber, which can be disconnected from the drying chamber, or in the drying chamber itself, the advantages of the latter being shorter vapor path and considerably narrower vacuum tubing, and the possible disadvantages that defrosting of the condenser is more of a problem, and an effective heat radiation shielding required between heating plates and condenser.

For larger plant more elaborate control devices and labor saving handling systems are introduced such as overhead rail systems, special product filling and dumping devices, automatic tray cleaning etc. in combination with a systematic layout planning of the whole plant, with the combined purpose of cutting down costs and improving product quality. Much effort is being spent to improve on energy costs by using various heat pump adaptations, separate vacuum systems for pump down and drying, separate condensers for different
drying stages and by using time lags between different batch chambers to level out the load on refrigeration and vacuum systems. To cut on fixed costs there is also a clear effort to simplify design as much as possible.

In processing, freezing is done either by evaporation inside the drying chamber or, more often by prefreezing in a separate blast freezer before or after the product has been filled into the product trays. To prevent melting of prefrozen product the heating platens are cooled before and during pump-down of vacuum, or the product frozen in a blast freezer mounted inside the chamber or a vacuum system is used that can sufficiently fast pull down pressure to prevent incipient melting. During drying, vacuum is commonly maintained between 1 and 0.2 torr, depending on the type of product and size of load, and temperatures are measured for product surface and ice core, if the whole operation is not based on prior experience and a type of can- or chart-controlled programmer used, in combination with control devices and alarm systems. Drying cycles in batch driers often have to be adapted to the type of shift work that is practical, and may vary from 6-7 hrs up to 12 hours or more between different processors and products. A combination of a large chamber and fill factor and comparatively long drying cycle is preferred by some processors, while others are of the opinion that the shortest possible cycle time should be used.

After drying to final moistures in the order of 2 to 5%, vacuum is broken with inert gas, and products which are sensitive to oxygen are usually nitrogen packed in moisture and oxygen impermeable packaging, sometimes with the extra precaution of using an oxygen absorbent system. Sometimes, unfortunately, using packaging which permits only a very limited shelf life. For the consumer and institutional market cans are usual in the U.S., whereas flexible, laminated pouches in an outer carton are fairly common in Europe.

Processing variables such as pretreatment, product thickness, platen, product surface and ice front temperatures, actual drying time etc. are usually determined from pilot plant and trial run experience, even if basic food engineering data and more theoretical aspects are beginning to play a more important role in the initial phases of plant and process development. The actual equipment, such as vacuum, refrigeration, heating and handling equipment on the other hand, is often designed from strict engineering principles.

To clarify what has just been said about today's freeze-drying equipment let us take a quick look at some plants being offered by leading European and American plant manufacturers, without any endorsement or relative ratings intended:

The Leybold line of plant\(^{(2)}\) is probably the only one strictly based on the module principle and the only full scale semicontinuous system. It
consists of a cylindrical tunnel chamber, with several separate refrigerated condensers, and separate entrance and exit doors, with or without vacuum lookes, depending on whether the modules have been assembled into a batch or semicontinuous system. The product to be dried is filled into ribbed trays to increase the heating surface and load factor, and the product trays are transported on overhead rail carriers into and through the chamber, and at regular intervals deposited on the platens, which are heated by vacuum steam. The plants can be equipped with automatic unloading and packaging under inert gas.

The Atlas company who pioneered the so-called "accelerated" freeze-drying have come out with a new line of radiant heating plants. Like the Leybold they use a cylindrical drying chamber with built-in platens, separate entrance and exit doors and overhead rail carriers for the product trays. The refrigerated ice-condenser is located inside the chamber, underneath the product section and divided so that half of it at a time can be automatically shut off from the chamber and defrosted by vacuum steam, generated by waste heat from the refrigeration compressors.

The Sec company make a radiant heat batch drier on similar lines. Cylindrical chamber shape, fixed platens, separate entrance-exit doors, and internal refrigerated condenser are used. Differences are that the condenser unit is equipped with a turbo fan to double as a blast freezer. Product trays are entered on rail carts. Chambers up to loading capacities of 4 ton wet weight have been built. In these large plants diesel engines or steam turbines are being used for driving the refrigeration machines, and waste heat from these utilized for plate heat.

As examples of American plant I will limit myself to the Stokes and FMC designs as more or less typical. The Stokes design is similar in many respects to the two last mentioned, although chambers are usually rectangular in shape and the refrigerated condenser located outside the drying chamber. Overhead rail system is used for transportation of product tray carriers, and a ribbed tray, somewhat similar to that developed by Leybold but larger, has been designed.

The FMC company probably were the first to introduce a condenser located inside the drying chamber, positioned on the two opposite sides of a cylindrical chamber, with the heating platen - product tray assembly, which is movable on a rail system, located in between. Also the Vacudyne company have developed similar plant, but using rectangular chamber design. Of particular interest in regard to American plant is the major effort spent on developing completely integrated handling systems.
These were some examples of plant available and in operation today. There are of course also a number of variations in each make to satisfy individual customers requirements.

Recent equipment development

This is about where we stand technically at the present time as far as actual production equipment is concerned. Something should also be said about the intense development work going on to create more efficient and economic type of equipment. In Europe at least, this work seems to be concentrated towards bulk-freeze-drying of liquids or pastes, spurred by the possible success of freeze-dried coffee and whole egg. Two new such designs of bulk liquid driers have already reached to or near the industrial plant stage, both so-called tubular driers. The Sec system (7) has the following characteristics. Inside a vertical, cylindrical vacuum chamber a heat exchanger type tube bundle is mounted. The liquid to be dried is lifted into the tubes by a special filling device, and a 10 mm layer frozen on the inside tube walls by evaporating ammonia on the outside. Excess liquid is drained back, and heat of sublimation is supplied from pressurized ammonia being condensed on the outside of the tubes. It is claimed that very good contact between the tube wall and the ice can be maintained until nearly all ice is evaporated, so that very low temperature can be used while maintaining a reasonable drying rate. During finish drying the product shrinks from the walls and falls by gravity into a holding container.

The other tubular drier (8) designed by Mitchell-Edwards and available in pilot size, is similar in principles, one important difference being that the product is frozen on the outside of the tubes, and cooled respectively heated by circulating brine on the inside. Drying is made at higher temperatures than in the Sec design, with drying cycles in the order of 3-4 hrs for 7 mm layers. Both systems utilize the heat pump principle for low cost heating.

Another interesting development is spray freezing and spray freeze-drying. The PMC company have presented a semi-continuous spray-freeze-dryer in large pilot scale (9) where a liquid concentrate is sprayed directly into the vacuum chamber and frozen in small particles by evaporation, after which the powder is freeze-dried on a conveyor in a matter of minutes and discharged through a vacuum lock system on a semicontinuous basis. The Niro atomizer Co. (10) have developed a spray freezer, from which the frozen
particles are transferred into a small, rotating mesh wire drum inside a vacuum chamber, with radiant heating elements positioned around the drum. Through a combination of rotation and fluidization very good heat transfer should be obtained with drying times in the order of 3 hrs. Work on fluidized bed freeze-drying is also in progress at the Battelle Institute in the U.S. and in Grieve’s laboratories in Cambridge.

While these developments aim at accelerated freeze-drying of liquids, the USDA in Albany have developed pilot scale equipment for rapid freeze-drying of granulated or small particle size material of solid foods such as peas on a batch or semicontinuous basis \(^{(11)}\). In the semicontinuous plant the product is transferred through a slowly rotating hexagonal drum, set at an angle, the drum being heated on the outside by steam. They claim very good heat transfer without product damage and drying times in the order of 3 hours compared with 6-8 hrs for a conventional process.

Another possible means of achieving accelerated freeze-drying of particulate food seems to be by introducing rapid pressure fluctuations \(^{(12)}\) and full scale equipment based on that principle is being developed in Australia. Something should also be said about the efforts to use microwave heating for improved heat transfer and shortened drying time. Recently pilot equipment has been developed in the United States \(^{(13)}\) in which samples of thick food pieces such as hamburgers have successfully been freeze-dried in 2-3 hours, but the system is still in the early stages of development.

With increasing production of freeze-dried foods there is also mounting interest in truly continuous systems, where continuous entry and exit of the product and continuous vapor removal present difficult problems.

**Products and product quality**

The general properties of freeze-dried foods can briefly be summarized as follows: With the removal of practically all water follows low weight and low density, since the original volume of the food is very nearly maintained. With this follows a very porous structure with large total surface, leading to rapid water uptake in reconstitution, but also to high reactivity, particularly against oxidation. For the same reason, the material is also as a rule very brittle, all factors which combine to set stringent requirements on packaging for good storage life. Due to the mild form of processing with low temperature, especially while ice remains in the product, little damage to the original properties of the food is done, except for those inherent in freezing and water removal, and a quality is usually obtained which is markedly superior to that of other dehydration methods. The most common deteriorative changes in freeze-dried foods are caused by
oxidation of lipids, proteins and nutrients, by non-enzymatic browning and by enzyme reactions, due to exposure to too high levels of oxygen and moisture in storage. Protein denaturation by excessive heating and drying, impaired water uptake through partial melting during freeze-drying and loss of volatile flavour components may also be important. In storage, it seems a proper balance has to be maintained between moisture and oxygen, different for different products\(^{14}\), for which purpose it may be necessary to resort to moisture and oxygen scavenging systems in the package. In practice, levels of below 2% moisture and 1% oxygen can usually be achieved, but some products definitely require lower levels, while a few such as strawberries apparently show little effect from packaging without any oxygen protection at all. Moisture impermeable packaging is always required and, as a rule, also packaging in inert gas in a gas tight package, which should also provide protection against mechanical damage. As far as pretreatment and preparation for use are concerned, the same types of deterioration can of course take place as in any fresh food, only that during the process of reconstitution further damage may easily occur through leakage of juices, nutrients, pigments etc. if improper methods are used.

During the first years of commercial freeze-drying just about anything was freeze-dried, more or less to find out what could be freeze-dried and what could not. There was little time for any thorough investigations on the importance of different raw material, processing and storage variables, which was also evident from the poor quality of many of the products initially demonstrated and market tested, the enthusiasm over the newness of the method sometimes obscuring judgement. The result was of course disappointment and disinterest on the part of the consumer and disservice to the development of a freeze-drying industry. Unfortunately, you still occasionally find such products on the market, even if most of the food companies presently engaged in freeze-drying have long come to realize that comprehensive product and process research or development programs and detailed specifications and control procedures are a prerequisite for a good product. There has also been a steady improvement in product quality, even if the margin for improvement still may be considerable, as often evidenced when comparing samples produced in the laboratory with regular factory production.

What foods are being freeze-dried then, and what level of quality is being realized? The assortment is very large, even if quantities are not impressive for the majority of them, but certain foods dominate which seem particularly well suited from the viewpoint of quality and marketability, such as coffee, chicken, mushrooms, shrimp, beef, ham and certain fruits, vegetables and milk products.
The quality obtained will vary from product to product and from one manufacturer to the other. In general few freeze-dried products are fully comparable with the fresh or frozen equivalent, some will come rather close, while others are inferior both to frozen and canned foods but considerably better than any other dried foods. Storage life is generally limited to 1-2 years at room temperature, provided adequate packaging is used, and will decrease quite rapidly with increased storage temperature. While enumerating these limitations of freeze-dried products, it would be unfair not to point to their specific advantages of light weight, rapid reconstitution and preparation and their good retention at room temperature of many of the physical, chemical and nutritional characteristics of the fresh food, all facts which may combine into unique answers to many product problems.

An appraisal of the quality of commercially available freeze-dried foods was made by the USDA in 1962\(^{(15)}\) and has been given wide publicity, being for a long time the only well defined large scale palatability evaluation available by a neutral organization. The results are still of interest, but it should be kept in mind that the quality of freeze-dried products then available are probably not quite representative of what is being produced today. As reference products the panels used frozen products, and where an equivalent frozen product was not available canned foods were used. For most freeze-dried products a certain lack of flavour was noted, and for the meats decreased tenderness and juiciness. On the other hand a few products rated equal to or even better than the frozen, such as shrimp and crab meat. Stews and mixes rated well and also freeze-dried ingredients in soups. 18 out of 28 products compared quite well with frozen or canned references, and no product was rated unacceptable, even if quality defects of one type or another was noted in many. As examples, the results from comparisons between freeze-dried and canned diced beef and beef noodle soup are shown in the following table constructed from Bird's data (fig. 2).

**Palatability comparison between two freeze-dried and canned products.**

<table>
<thead>
<tr>
<th>Evaluated property</th>
<th>Diced Beef Freeze-dried</th>
<th>Canned</th>
<th>Beef Noodle soup Freeze-dried</th>
<th>Canned</th>
</tr>
</thead>
<tbody>
<tr>
<td>General acceptance</td>
<td>2.3</td>
<td>3.4</td>
<td>4.1</td>
<td>3.2</td>
</tr>
<tr>
<td>Appearance</td>
<td>2.9</td>
<td>3.5</td>
<td>4.2</td>
<td>3.7</td>
</tr>
<tr>
<td>Flavor</td>
<td>2.8</td>
<td>3.2</td>
<td>3.8</td>
<td>3.1</td>
</tr>
<tr>
<td>Juiciness</td>
<td>2.0</td>
<td>3.9</td>
<td>3.9</td>
<td>3.3</td>
</tr>
<tr>
<td>Texture</td>
<td>2.2</td>
<td>3.7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Tenderness</td>
<td>2.2</td>
<td>4.3</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Mean scores. \(1 = \) very poor, \(2 = \) poor, \(3 = \) fair, \(4 = \) good, \(5 = \) very good
Another much more recent study, combining sensory evaluation and objective analysis, was published only a year ago by the Bundesforschungsanstalt für Lebensmittelfrischhaltung in Karlsruhe (16). Their comprehensive study which included altogether a hundred samples of nuts, fruits, vegetables and composed meals from manufacturers in the United States, England, Germany and Holland, came to the conclusion, that overall quality of freeze-dried products was satisfactory, as judged by a taste panel trained on frozen products. The best products were considered quite comparable with frozen, such as crab, chicken, mushroom, cauliflower, meat soups and blueberries. Quite a few products were, however, of marginal quality in one or several respects, and an effort was made to assess the reasons for such quality defects. The conclusion was reached that the actual drying process was usually not to be blamed, but poor choice of raw material, poor pretreatment, after treatment and packaging. It is noteworthy that some products were found to be packed without proper protection either against moisture or oxygen.

There is also a recent investigation published in the U.S. on the microbial quality of a limited number of commercially freeze-dried foods, showing that in no case were the counts obtained excessive on a rehydrated basis. Total counts were low in products such as shrimp and much higher in chicken or pork. Salmonella or coliform bacteria were not found, but entero-cocci and coagulase-positive staphylococci were found in most samples.

**How can quality be improved?**

It is clear that for many freeze-dried products quality leaves something to be desired. What are the main reasons then for poor quality and how can quality and storage life be improved? The main factors important to product quality are: choice of raw material, pretreatment before freeze-drying, time-temperature history during freeze-drying, packaging and storage conditions, and method of reconstitution and preparation. Much research work has been made or undertaken to study the effects of such variables for different foods, and to ascertain what changes take place in the food, their cause and how to prevent them or take advantage of them, and much more work should be done.

A very good example of such work and its importance to freeze-drying development is the investigations made by Goldblith and coworkers at the M.I.T. on freeze-dried shrimp and salmon (14).

A good idea of the importance of raw material quality is given by the following figure, taken from the same paper, depicting initial quality and quality after storage for two different quality grades of raw material:
Fig. 3. Effect of initial raw material quality on the quality of the finished product.

As is seen, there is generally good correlation between raw material quality and quality after freeze-drying, and in storage the lower quality product tends to deteriorate at a faster rate, to reach sub-standard quality at a considerably earlier date. It deserves to be stressed at this point that quality damage initiated in the raw material, or during pretreatment and dehydration may often not become apparent until after prolonged storage.

Choice of raw material is just as important in freeze-drying as in freezing or in canning for that matter. Suffice it to point to the results obtained from proper selection of raw material in terms of variety, maturity, growing conditions etc. in the freezing of peas, strawberries, and more recently, in liquid nitrogen freezing of tomato slices. As an example of the importance of proper pretreatment can be mentioned Hoy’s method of "thermal treatment" for complete crystallization of freezable water in citrus juices, resulting in shortened drying cycles and considerably improved product quality due to absence of partial melting during drying. Own experience with raw meat has shown a deleterious effect on rehydration rate of very rapid freezing as well as from slicing the meat before freezing, whereas slicing in semifrozen state or sawing in the frozen condition gave good reconstitution after drying.

During the actual freeze-drying, partial melting or too high temperatures in the dried layer as well as too prolonged drying may seriously hurt quality of the finished product, just as too high residual moisture and oxygen can appreciably limit storage life. Own, unpublished work on raw meat has shown that to retain the red meat color, any exposure to oxygen after drying must be avoided, and preferably an oxygen scavenging system of palladium catalyst and hydrogen be used in the package.
Usually moisture and oxygen impermeable packaging should be used, which also gives some mechanical protection, and as low storage temperatures as practical conditions permit. Reconstitution and preparation finally offer many opportunities to ruin the results of the most painstaking efforts in production and storage, unless a real effort is spent in developing proper methods and instructions. Unfortunately much too little is known (like on many aspects of freeze-drying) regarding the possibility of reversing the dehydration step so that the original localization and binding of the water is restored.

Applicability of freeze-dried foods

Freeze-dried foods can be used and presented in a number of ways and shapes, but there will always be a limitation to fairly thin or small pieces of material of reasonably even size, such as slabs, balls, granules etc., even if the use of microwave heating may eventually permit reasonably rapid drying of thickness up to 1-2 inches. The practice closest at hand has been to dry foods in "whole" pieces for use after reconstitution like the fresh equivalent, for example steaks, hamburgers, fish cutlets, whole shrimp, mushroom or berries, or cut into slices or small pieces for use in stews, mixes, soups and cereals. Freeze-dried foods can also be used directly in the dried form as novel seasonings, aroma components, snacks or as base material in the baking and confectionery industries. Another and important application is as an alternative dehydration method for liquids such as coffee, tea, whole egg etc. in powdered or granulated form.

Only recently have people begun to realize the versatility of freeze-dried foods and their potential in creating new and entirely unique types of products such as freeze-dried ice cream (20) or foods compressed into bars which on reconstitution will rapidly regain their original volume and appearance and be highly palatable also in the dried condition. Unfortunately an effective deterrent to many a promising new product idea is cost and marketing approach.

Costs

The main factors determining freeze-drying processing costs are the type of product and amount of handling and pretreatment required, the size of the plant, the product loading and the length of the drying cycle, the degree of utilization of the plant and the local costs of labor and energy. There are bound to be great variations between available cost estimates, partly because there is no one agreed upon basis for making them, partly because variations with locations, company etc., may be considerable, and partly because subjective interests may be involved so that certain cost factors tend to be underestimated or neglected entirely. Estimates by equipment
manufacturers sometimes include only the investment for the freeze-dryer itself and not refrigeration, handling, building, supervision etc.

It is also typical that freeze-drying plants are assumed to run continuously 24 hrs a day 300 days a year, when most processors in the world would no doubt be very happy to achieve half of this utilization.

True costs realized are well guarded secrets of the processors, but available literature data should nevertheless give a reasonable, general idea on the subject. The USDA have, also on this phase of freeze-drying, made an impressive and detailed contribution with the "Cost Projections" of Kermit Bird (22). More recently, objective cost analysis have also been presented by the Association Francaise de Chimurgie in their recommendable survey on "La Lyophilisation des produits Agricoles" (23) and by the French Ministry of Agriculture in their technical and economical study of freeze-drying (24).

The costs of actual freeze-drying equipment represents a very high investment as can be seen from the following table based on Bird's data:
(Fig. 4)

<table>
<thead>
<tr>
<th>Plant size (tons of water evaporated per day)</th>
<th>Investment in dollars</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>300 000</td>
</tr>
<tr>
<td>8</td>
<td>500 000</td>
</tr>
<tr>
<td>16</td>
<td>1 040 000</td>
</tr>
<tr>
<td>32</td>
<td>1 640 000</td>
</tr>
</tbody>
</table>

The corresponding costs calculated for European conditions are about the same at lower capacities but show a more favourable cost relationship with increasing plant size (23). According to that study the investments necessary for buildings, offices, laboratory and equipment for pretreatment, freezing, handling, packaging etc. may very well be of comparable magnitude.

Compared to other processing methods, a British journal (25) cites a Unilever statement that for equivalent tonnage the relative investment for a canning plant, a freezing plant, an air-drying plant and a freeze-drying plant should be approximately 1:1.5 : 1.5:5.

For the actual processing costs the corresponding relationships should be about 1:1.5 : 1.5:3.

For a plant of conventional batch type and a capacity of approximately 4 ton evaporated water/24 hrs the processing costs should, according to Bird, distribute themselves as in the fig. below:
Fig. 5  Synthesized costs of freeze-drying chicken in a small plant  
(cited from Bird)

Conditions:  
3 shifts, 250 days/year  
200 m² shelf area, shelf load 10 kg/m²  
Diced chicken 1500 tons/year (frozen)

Processing costs:  
Fixed costs  
Variable costs: labor 50 000 dollars  
utility + maintenance 34 000 "  
Total 158 590 dollars

Total cost per kg of: 
water removed 17.7 cents

Total costs per kg of: 
frozen food 9.5 cents

For the same plant processing mushrooms instead, with a considerably higher water content, the cost per kg of frozen product would be about 30 % higher.

The costs calculated in the French estimate \(^{(23)}\) is about 58 centimes per kg water, which is of the same magnitude.

The relative importance of the various cost factors in the USDA estimate for chicken are seen in the following table:

Fig. 6  Freeze-drying costs of 4-ton model plant processing chicken

<table>
<thead>
<tr>
<th>Fixed costs</th>
<th>Variable costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depreciation</td>
<td>Labor</td>
</tr>
<tr>
<td>27 %</td>
<td>31 %</td>
</tr>
<tr>
<td>Buildings &amp; equipment</td>
<td>Utilities</td>
</tr>
<tr>
<td>16 %</td>
<td>21 %</td>
</tr>
<tr>
<td>Salaries</td>
<td>Repairs</td>
</tr>
<tr>
<td>4 %</td>
<td>1 %</td>
</tr>
<tr>
<td>47 %</td>
<td>53 %</td>
</tr>
</tbody>
</table>

The large items are depreciation, labor and utilities at this capacity of plant. With increasing plant size, the role of depreciation or amortization tends to grow and that of labor to diminish.

The calculated effect of plant capacity and degree of utilization for a chicken processing plant is illustrated by another figure from Bird:
With increasing plant capacity and degree of utilization there is a steady decrease in cost, approaching about 9 cents/kg at 30 ton capacity. The positive effect of running at full capacity is particularly apparent for the smaller plants.

Length of drying cycle will of course have about the same influence as degree of utilization, as long as the same size of product load is concerned.

The French estimate earlier referred to\(^{(23)}\) arrives at comparable figures, but summarizes the results in a graph (below) which is perhaps more self-explanatory, always in terms of a plant processing mushrooms.
Cost

P/kg water removed

Plant size tons/day

Number of operating hours/year

Fig. 8

At the present time plant size in the range 4-10 tons/day seems to be the average size, and cost estimates referred to here and from many other sources seem to agree reasonably well on a cost range between 10 and 20 cents per kg evaporated water for well utilized plant, the spread depending on factors just mentioned. To this will then come costs of freezing and pretreatment, packaging, HMD, quality control, advertising and marketing etc. Another cost, which usually tends to be overlooked in cost estimates, concerns the special requirements and standards for raw material that may be necessary for freeze-drying in terms of variety, maturity, grade etc.

Means of cutting down costs are of course, as already shown, to increase plant size and degree of utilization and decrease cycle time as far as possible without impairing product quality. Another possibility is to combine freeze-drying with other methods of processing, particularly with pre-concentration, which is of course primarily applicable for liquids such as coffee, tea, milk products etc. An estimate published by the German Dairy Research Institute in Niof (26) claims that, in this manner, freeze-drying costs for milk products can compare favourably even with regular milk in half liter Parga packs, a result which certainly appears surprising.
The relative processing costs earlier referred to for freeze-drying, freezing, air-drying and canning in large capacity plant were approximately 3 : 1.5 : 1.5 : 1. Compared with frozen products, freeze-dried might be expected to be as much more expensive as the actual drying costs, since freezing is part of the pre-treatment. The freeze-dried products will require more expensive packaging and are as a rule more bulky. On the plus side will come considerably lower weight, meaning somewhat lower transportation costs, and no need for freezer storage, even if some refrigeration may be required for reasonable storage life in tropical countries. For countries where a well-developed cold chain is available, such as the U.S. or Sweden, the saving may be immaterial, but where no such cold chain exists, or where products have to be transported large distances overseas, freeze-drying may become more attractive relative to freezing, especially if compression techniques can be developed commercially.

Comparing instead the processing costs for freeze-drying with those of other methods of dehydration, data given by Goldblith (27) show the following approximate relationships: (Fig. 9)

<table>
<thead>
<tr>
<th>Drying method</th>
<th>Products to which applicable</th>
<th>Approx. cost (£/lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>Prunes, apples, pears,</td>
<td>1.0 - 1.5</td>
</tr>
<tr>
<td></td>
<td>raisins, etc.</td>
<td></td>
</tr>
<tr>
<td>Drum</td>
<td>Cereals, potato products</td>
<td>0.9 - 1.0</td>
</tr>
<tr>
<td>Spray</td>
<td>Eggs, milk</td>
<td>0.7 - 1.5</td>
</tr>
<tr>
<td>Foam mat</td>
<td>Juice and purees</td>
<td>2.0 - 3.0</td>
</tr>
<tr>
<td>Puff or vacuum</td>
<td>Fruit and vegetables</td>
<td>3.0 - 4.0</td>
</tr>
<tr>
<td></td>
<td>juices and purees</td>
<td></td>
</tr>
<tr>
<td>Freeze</td>
<td>Probably all</td>
<td>5.0 - 10.0</td>
</tr>
<tr>
<td>Sun</td>
<td>Fruit and raisins</td>
<td>0.5</td>
</tr>
</tbody>
</table>

The plant utilization being of extreme importance to the economy will pose particular difficulties in the present early stage of market development, particularly when seasonal products are involved. The processor may be forced to handle a very large variety of products, which of course complicates production planning, quality control and R&D and may not permit the use of streamlined handling and processing techniques or the most economical size and number of units, making continuous or semicontinuous processing rather impractical.

This all goes to show that, in general, freeze-drying is an expensive processing method, yielding an expensive product.
The high costs associated with small plant size will necessitate a concentration on products from expensive raw material or for special usage, where cost will be of less importance, whereas the lower costs obtainable in truly large-scale operation may permit production also of relatively low cost bulk products, such as liquid egg.

On the other hand, production costs should not be overemphasized since they often represent only a relatively small proportion of final cost on the market after cost for packaging, advertising, marketing, profits etc. have been added on. According to the recent estimates of the French Dept. of Agriculture\(^{(24)}\), freeze-drying processing represents a cost increase of 20-50% on a technical basis but only 10-20% on a commercial basis.

Actual market prices vary a great deal depending on quantities, type of market and a variety of other factors, and it is difficult to estimate how meaningful they are, since at this early stage of market development many processors may not be operating at a profit, or there may be government or other forms of subsidies involved. Mushrooms are claimed to be sold at equivalent prices to the canned product in Europe and crabfish is presumably sold on the institutional market in the U.S. at an equivalent price to the frozen. In Britain freeze-dried liquid egg on a bulk basis appears to compete directly with the frozen product with no price advantage. Freeze-dried instant coffee sells at about 30% higher cost than spray-dried on the European consumer market. At least the two last mentioned products are apparently giving a reasonable profit. Where the consumer market is concerned, prices are sometimes very high indeed, especially in outlets for campers etc., where the price for meat may be equivalent to four times the market price for the same quantity of fresh material. Hopefully this will represent a sizeable profit. It certainly illustrates that one reason for slow development of a consumer market is cost.

Market aspects

Size of market

How big is then the present freeze-drying market? How does it compare for size with the conventional processing methods and what kind of a market development can be visualized over the more immediate future?

It has already been mentioned at the beginning of this presentation that the total volume of freeze-dried products in the world today, counted on a fresh product basis, is probably less than the production of canned foods in a small country like Sweden alone. In other words a very small industry, which can in fact still be considered a world-wide test market.
Actual production and market figures are equally difficult to extract from the industry as processing costs or profits. Estimates of market size and expected growth up to 1970 for the U.S. were made some years ago independently by Bird (28) and by Goldblith (27), arriving at similar results, which are still considered reasonably valid by most experts. Naturally, it has been considerably more difficult to predict relative growth of individual products.

According to a table given by Goldblith, freeze-dried volume in the U.S. should in 1963 amount to about 50,000 tons and in 1970 to 115,000 tons on a fresh weight basis, representing a total dollar value in 1970 of 450 million dollars, whereas frozen products should at the same date amount to about 50 times that volume. In 1964 the volume of freeze-dried should have been only about 9,000 tons. The estimates by USDA (Bird) are more detailed, but arrive at comparable if somewhat higher figures, as seen from the following graph, recalculated into units of 1,000 tons:

![Graph of anticipated growth of the U.S. freeze-drying industry](image)

According to this graph the total volumes of freeze-dried products should have been 20,000 tons and 40,000 tons fresh weight respectively for the years 1965 and 66, with predictions for this year of about 70,000 tons and for 1970 around 150,000 tons. The constructed curve has been arrived at in comparison with the pattern actually obtained in the past for a number of successful products such as frozen specialties and frozen poultry, assuming then a similar growth pattern for freeze-dried products. A present volume of about 70,000 tons should then be produced by the roughly 25 freeze-drying plants in operation in the States, of which only 5 or 6 can be considered really big (capacities around 20 tons/day). This would roughly correspond to a consumption of about 100 grams of freeze-dried products per person in the United States.
As far as European conditions are concerned, there has been no similar
effort made by any central agency to estimate the volume of the freeze-drying
market and its growth, and the variation in guess estimates is quite
disconcerting, covering the whole field from less than one tenth of the
American market to about the same volume. There are about the same number
of processing plants in Europe and nearly as many really large plants as in
the U.S., but the average plant size seems to be smaller and the degree of
utilization lower in Europe in my personal point of view. Based on information
from leading equipment manufacturers, food processors and research institutes,
the following guesstimates of our own has been arrived at, which is given for
what worth it may have, together with the lowest and highest other estimates
we have come across. We have also attempted to make breakdowns for individual
countries, again knowing that this is very uncertain ground where you try to
go by the few facts available and steer a course somewhere between the dis-
couraged pessimists and the rosy enthusiasts. (Fig. 11).

<table>
<thead>
<tr>
<th>Guesstimate of production rate for freeze-dried foods in Europe in tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>frozen input per year</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Britain</td>
</tr>
<tr>
<td>Germany</td>
</tr>
<tr>
<td>France</td>
</tr>
<tr>
<td>Holland</td>
</tr>
<tr>
<td>Others</td>
</tr>
<tr>
<td>Total:</td>
</tr>
</tbody>
</table>

Estimates by others

<table>
<thead>
<tr>
<th>end 1965</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lowest found</td>
</tr>
<tr>
<td>Highest found</td>
</tr>
</tbody>
</table>

The nominal capacity of erected plants is considerably higher,
but for various reasons these appear not to have been possible to
realize in practice. If the above figures are reasonably correct, it
would mean that Europe would be about two years behind the U.S. in freeze-
dried volume. As far as the rest of the world is concerned, there are some
20 plants scattered all around the globe, in Australia, Canada, New Zealand,
Japan, Brazil, Peru, Taiwan, India, Pakistan etc. but in total volume they
are as yet rather insignificant compared to the development in the United States and Europe. On the other hand it is interesting to note that plants are erected in developing nations at the sources of cheap raw materials, evidently directed towards export to Europe and the United States.

Outlets and products

Who actually buys the freeze-dried food produced and what proportion is absorbed by the different outlets? Again, there are very little actual data available, possibly with the exception of the United States. It has been reported(23) that in 1965 the relative importance of the various market outlets should have been the following:

<table>
<thead>
<tr>
<th>Outlet</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial use</td>
<td>63</td>
</tr>
<tr>
<td>Defense</td>
<td>20</td>
</tr>
<tr>
<td>Institutional use</td>
<td>6</td>
</tr>
<tr>
<td>Consumer</td>
<td>8</td>
</tr>
<tr>
<td>Campers</td>
<td>3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>100</td>
</tr>
</tbody>
</table>

However, these figures seem somewhat doubtful, judging from statements by several experts, expecting defense spending on freeze-dried foods in the U.S. to have been considerably less at that time and the institutional use higher than consumer use. Since then, purchase for the military seems to have increased considerably, especially of precooked meals. It is likely, also, that institutional use has increased in proportion to consumer use. For the institutional market products like shrimp, chicken, and, lately, salad mixes and sandwich spreads appear to be promising, while for the consumer market hopes have been high for mix-ins of freeze-dried ingredients in breakfast cereals and, currently, for freeze-dried coffee. Complete dinners based on freeze-dried and conventionally dried ingredients have, in spite of much effort, failed to enthuse the consumer, probably because of too high price level for the food value contained. Possibly, the freeze-dried meals for the military, (freeze-dried after formulation) which are now produced in large volume, may stand a better chance on the civilian market.

As in the States, industrial use is predominant also in the European countries, and to a large extent involving the same type of foods. There is, however, considerable interest in bulk freeze-dried whole egg in Britain and in freeze-dried milk products in Germany, the latter evidently also for the consumer market. Freeze-dried coffee appears to offer a real opportunity for instant coffee to make inroads into the European coffee market, with a cup quality approaching that of regular brewed coffee, and freeze-dried
coffee is now marketed in most western European countries. At least five plants are producing coffee only, and many are doing it part time, while several new large size plants for coffee processing are planned to go into production in the reasonably near future. According to a leading food processor, instant coffee has in a few years risen from 9 to 12.5% of the total coffee consumption in western Europe, which they believe to be largely caused by the advent of freeze-dried coffee.

At least in Britain and Sweden freeze-dried meals seem to be doing reasonably well, in contrast to the situation in the U.S. Actually it is no particular wonder that such meals have not been a great success, since the food in the dry condition will not have a particularly attractive appearance to the "uneducated" consumer, especially to those having a lingering bias against dehydrated foods from the war time rations. The convenience may not always be so apparent either with several small packages to open inside a large one, and several different methods and times of reconstitution and preparation to take care of.

A "military" market exists also in Europe but, for evident reasons, to a much lesser extent than in the U.S. It is doubtful if an institutional market for freeze-dried foods even exists in West European countries as yet. Naturally, Europe can hardly be considered a homogenous market and like in other contexts, there will certainly be great individuality in market patterns, habits etc. from one country to the other. It would for example be hard to visualise any great success for freeze-dried gourmet meals or whole milk in France while they may very well succeed in Britain or Sweden. On the other hand you hardly know what to expect, when freeze-dried tea is claimed to be a promising prospect and not an outrage in England. As for the production of freeze-dried foods in the rest of the world, much of this appears to be keyed to export to the United States or Europe, although there is also some interest in developing countries in the possible potentials of freeze-dried foods for their own markets, possibly as an alternative to fresh or frozen foods where a cold chain would be impossible to develop within a reasonable time. Unfortunately it is difficult to see how the economics of freeze-drying would be reconciled with such a scheme.

In the marketing of freeze-dried foods the word "freeze-dried" does not appear to have any particular appeal to the consumer's mind and little advertising value by itself, and people have to be persuaded by other means such as convenience, quality and novelty. An important factor will be consumer education to overcome bias and learn how to use the products properly, whether you talk in terms of the industrial, institutional or retail customer markets.
The future of freeze-drying

I am not going to attempt to look into a crystal ball and predict the future of freeze-drying, but will limit myself to point out a few trends while briefly summarizing my presentation.

Freeze-drying has not turned out the indisputable success hoped for by many 10 years ago, but neither has it turned out a failure. In fact, growth figures so far look quite promising and the recent developments in freeze-drying of liquids point to a growth potential for coffee, tea, egg, milk products etc. that could be very great. On the other hand, the development of market volume for solid foods appears to be slowing down, in spite of the fact that some of the unique properties of freeze-drying are primarily associated with solid piece food material. Should a market develop which is loop-sided in favor of liquids, involving the construction of highly specialized plant equipment like tubular or spray freeze-driers, there might be a danger, a food processor points out, of a set-back caused by continuing improvements in competing, lower cost liquid drying methods, in which case the specialized freeze-driers could not be put to any good use. Some promising future uses for freeze-dried solid foods have already been pointed out, another might be use of freeze-dried base materials for actual food preparation, with minimum waste, both in the industry and in home and mass-feeding kitchens.

Processing costs have to and will continue to go down, by simplified and improved plant construction, larger and more automated plants, increased utilization, efficiency and shorter cycles. Of great importance may be the savings possible by streamlined material selection, pretreatment and packaging which may help bring costs down near the level of conventional dehydration methods and quality up nearer that of frozen foods.

One factor which will be of very great importance is the continued contribution from food science and technology. A thorough understanding of the process itself and the changes taking place in the food material, as well as painstaking determinations of the effects of important raw material and processing variables, material constants etc. is necessary for the development of improved equipment and processing conditions as well as minimum costs. Much work has been done already, but very much more remains to be done.

In conclusion, it seems that freeze-drying is definitely here to stay, whether you call it an industry in itself or a section of the dehydration industry. It is quite small, but growing at a very respectable pace, and the several unique qualities of freeze-dried foods may possibly provide us with pleasant surprises in the future, to upset our present outlook on freeze-drying as a volume-wise small industry or dehydration method, which is not likely to compete with our conventional processing methods, but limit itself to special applications.
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