CONTROL OF THE DEHYDRATION PROCESS IN PRODUCTION OF INTERMEDIATE-MOISTURE MEAT PRODUCTS: A REVIEW

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I. INTRODUCTION

Intermediate-moisture (IM) meats are temperature stable products with a moisture content around the equilibrium moisture content of the meat mixture at ambient temperature and humidity. The products can be consumed as they are without rehydration, having a desirable texture without brittleness or overdryness.

Most of the traditional IM meat products have evolved from natural drying of the meat mixture. In the drying process, the ultimate water activity (a_w) of IM meat approaches 0.60 to 0.90, which is equivalent to a relative humidity (RH) of 60–90% at ambient temperature (Leistner, 1987). The products do not require either strict moisture impermeable packaging or refrigeration during storage. Indeed the products are processed and dried to a stable state and can be kept at ambient temperatures without spoiling.

There are many traditional IM meats in all parts of the world. Their production varies with the climatic conditions and the economic and technological status in each country. Man observed naturally sun-dried grains and fruits before learning to dry fish and thin slices of meat by hanging them in the air and sun. Drying of these animal products usually took a long time, so that bacterial spoilage during the time-consuming operation often occurred (Shin and Leistner, 1983). Thus, the use of salt, sugar, and smoke as further preservative agents gradually evolved in combination with drying. Sun-drying is still in use in many parts of the world including the United States. While sun-drying in some parts of the world and for certain products is the most economical method of drying, it has several obvious disadvantages according to Leistner (1987):

1. Sun-drying is dependent upon the elements;

2. It is slow and not suitable for many high quality products;
3. It generally will not lower the moisture content below about 15%, which is too high for storage of numerous food products;
4. It requires considerable space; and,
5. The food is subject to contamination and loss from dust, mold, insects, rodents, and the like.

There has been a renewal of interest in IM meat products as costs of refrigeration have increased and with the development of new technologies. It is the purpose of this review to update and consolidate the latest information on drying procedures that have been used or show promise for producing IM meat products.

II. TRADITIONAL PRODUCTION OF IM MEAT PRODUCTS

Processing equipment used in traditional meat drying is simplistic, and in some cases primitive, making process control difficult, if not impossible. The processor is at the mercy of the weather for sun or smoke–fire drying. Product quality is uncertain and variable, so standards are met only by luck and sheer artistry. Yet, nearly every country in the world produces its own characteristic IM meat product. A few products from different countries are used here as examples of successful IM meat products. However, limitations in manufacturing are frequently encountered making their production difficult or self-limiting. Generally these products are safe, although they may have an abundant microflora (Gibbs, 1986).

A. IM MEAT PRODUCTS OF TURKEY

Production of pastirma or basturma, which is an IM meat product of Turkey, has been described by Leistner (1987). It is preferably produced from September to November, since flies are not prevalent during this season. The air temperature is not as high as in the summer, and the relative humidity is moderate due to scanty rainfall.

According to Leistner (1987) pastirma is produced by dry curing thin strips (50–60 cm long by 5 cm in diameter) of meat at ambient temperature. The strips of meat are dry-cured followed by pressure treatment and air drying. After salting, drying, and application of pressure, the meat is covered with 3–5 mm of a paste containing garlic and other spices and dried for 1 day in a pile and hung for 5–12 days in a room with good ventilation. The product is then ready for distribution and consumption. The final product has an a_w of 0.85–0.90.

Berkman (1960) investigated the survival of salmonellae, anthrax bacilli, pathogenic clostridia, rinderpest virus, and tapeworm larvae in pastirma and found this product was virtually absent of these organisms. Krause *et al.* (1972) recovered micrococci and lactobacilli, but rarely any Enterobacteriaceae. The lactic acid producing organisms appear to play an important role in assuring the safety of this product. Nevertheless, the problems encountered in producing pastirma and the labor intensive operation limit its production. Genigeorgis and Lindroth (1984) have investigated the safety of basturma from salmonella and found it is generally safe.

B. CHINESE AND MALAYSIAN IM MEATS

1. *Slice-Cured Chinese and Indonesian (Dending) Products*

Slice-cured meat (pork or beef) is produced for the Chinese and Malaysian markets (Leistner, 1987; Chuah *et al.,* 1988; Wang and Chen, 1989) and utilizes essentially the same process as Indonesian dending (Buckle *et al.,* 1988). The sliced-cured Chinese product has been described by Leistner (1987) and can be produced by one of two methods. The first procedure utilizes paper-thin (0.2 cm) slices of lean meat (pork or beef) cut parallel to the grain. The meat is cured with a mixture of sugar, salt, soy sauce, monosodium glutamate, and spices. The traditional cure does not use nitrite or nitrate. The meat is cured for 24–36 hr at 4°C and then the thin strips are placed side by side (slightly overlapping) on an oiled bamboo basket or wire rack and dried at 50–60°C, until they lose approximately 50% of their original weight. The meat is removed from the containers and further dried by cooking over charcoal or deep fat fried to give a final a_w of about 0.69. The product is then ready for distribution. Dending of Indonesia is produced by essentially the same process, although procedures and formulation may vary slightly as described by Buckle *et al.* (1988).

2. *Cooked and Dried Meat Cubes*

In another process described by Leistner (1987) and Buckle *et al.* (1988), the whole muscle is boiled for 40–45 min, after which it is cut into cubes or pieces (5 × 5 × 10 cm). Although beef is preferred because of its fibrous nature, pork and chicken are sometimes used (Lo, 1980). The cubes are added to the cure in a steam kettle and cooked until nearly all of the cure has evaporated. The meat is removed from the steam kettle and dried in a hot air dehydrator. The final a_w is about 0.69. Leistner (1987) concluded that an $a_w < 0.69$ is critical for Chinese dried meats, although Ho and Koh (1984) suggested that an $a_w < 0.61$ is needed to prevent mold growth.

3. *Zousoon and Dried Pork Floss*

Two other Chinese products are produced. One is a semidry product called Zousoon and the other a dry product known as dried pork floss. The composition and water activity of these products are shown in Table I. Production of these two products has been described briefly by Chang *et al.* (1991). Both products traditionally are prepared from prerigor pork, which is boned, cut into pieces parallel to the muscle fibers, added to a gas-fired scraping frypan along with a small amount of water, sugar, and salt, and cooked to the desired degree of dryness. Zousoon has an a_w of about 0.65 and dried pork floss of about 0.45. Zousoon is more desirable because of its fibrous texture, lighter color, better flavor, and higher yield (Chang *et al.*, 1991).

4. *Lup Cheong (La Zang)*

Lup Cheong (Cantonese) or La Zang (Mandarin) is the most typical Chinese sausage according to Leistner (1987), with some variation being produced in different areas (Lo, 1980; Ho and Koh, 1984). Leistner (1987) described production of Lup Cheong, which is a raw nonfermented sausage made from coarsely ground pork (preferably ham) and pork fat mixed with sugar, salt, soy sauce, Chinese wine, potassium nitrate, five-spice powder (anise, clove, fennel, and watchau), and monosodium glutamate. Up to 25% water is sometimes added to give a wrinkled appearance to the sausage after drying. The mixture is stuffed into small hog casing tied at 15-cm intervals. The casings are punctured regularly to allow the escape of entrapped air and water during drying. It is dried by heating over charcoal at

TABLE I

PROXIMATE COMPOSITION AND WATER ACTIVITY OF ZOUSOON (SEMI DRY CHINESE LONG-FIBER PRODUCT) AND DRIED PORK FLOSS (DRY ROASTED SHORT-FIBERED CHINESE PRODUCT)[a,b]

	Zousoon (semi dry)	Dried pork Floss (dry)
Protein content (above) (%)	47	32
Carbohydrate content (below) (%)	16	15
Fat content (below) (%)	12	43[b]
Ash content (below) (%)	9	7
Moisture content (below) (%)	13	4
a_w (range)	0.60–0.65	0.40 or below

[a] Source: Chang *et al.* (1991). Reproduced with kind permission from Elsevier Science Ltd.
[b] After adding lard during finishing process.

45–50°C for 1–2 days and then held at room temperature for 2–3 days to allow for moisture equilibration.

Lup Cheong can be stored for 1–3 months without refrigeration if mold growth is controlled. It has a reddish–brown color and has a fat speckled appearance. It is always heated before consumption and is consumed sliced and steamed with rice. It has an intense aroma and a few slices are sufficient to season an entire dish.

Leistner (1987) concluded that the microbiological stability of Lup Cheong mainly is due to rapid reduction in a_w, which is aided by its salt (2.8–3.5%) and sugar (1–10%) contents, the thin casings (26–28 mm), the high ripening temperature (45–50°C), and a low relative humidity (65–75%). The pH is not important since it is relatively high (5.7–5.9) and the lactic acid bacteria count is low ($<10^6$/g). Leistner (1987) reported an average a_w of 0.75 and a pH of 5.9 for 24 samples imported from China and analyzed. Ho and Koh (1984) reported an a_w of 0.6–0.7 for Lup Cheong samples produced in Singapore, which was probably due to the higher sugar content (15–20%).

Leistner (1987) stated that the number of Gram-positive bacteria in the raw meat should be moderate. The a_w must be decreased to <0.92 within 12 hr and to <0.90 by 36 hr. This can be achieved by drying for 36 hr at 48°C and 65% relative humidity. If drying is not carried out over charcoal, it should be lightly smoked at 48°C and 65% relative humidity. The product should be held at 20–25°C and 75% relative humidity for 3 days to allow for moisture equilibration or until an a_w of <0.80 is achieved. The sausage should then be vacuum-packaged, since this improves the flavor and inhibits mold growth.

C. IM MEAT PRODUCTS OF EUROPEAN ORIGIN

Fermented meat products have been produced in Europe for centuries, with the bacteria being indigenous to each processing plant and producing a characteristic product. Natural fermentation was later controlled to some extent by using small amounts of product from a previous batch to give the same bacterial flora, which is called backslopping (Romans *et al.,* 1985). Salami is an example of a semidry (IM) sausage. Today most semidry sausages are produced adding pure or mixed bacterial cultures, which gives better control of the fermentation process as explained by Bacus (1986). These fermented products are preserved by a combination of low pH and drying.

1. *Salami and Other Fermented Products*

Pearson and Gillett (1995) have described the processing of salami. The meat is first ground or chopped and the cure is added during the process.

The cure is composed of salt, sugar, and nitrite or nitrate. The culture is also added during the chopping process. Seasonings are added as desired and the product is stuffed into synthetic or natural casings. Fermentation takes place in a fermentation or "greening room" held at 24°C and 75% RH for 36 hr. The sausage is then dried for 9–10 weeks in a drying room at 10°C and 75% RH. Salamis and other fermented European-type sausages have an a_w of 0.62–0.80 and are now widely produced in other countries.

The use of nitrite and salt helps to inhibit the growth of the food-poisoning bacteria during ripening (Leistner, 1978, 1987, 1990a). However, the production of lactic acid during fermentation lowers the pH and provides further safety as the a_w is lowered during drying (Bacus, 1986; Leistner, 1987).

2. *Other Fermented European Sausages*

Although many fermented semidry and dry sausages originated in Southern Europe (Romans *et al.,* 1985; Bacus, 1986), they are now widely produced in other developed countries. Cervelat or summer sausage originated in Germany, but it is now the most popular semidry sausage according to Romans *et al.* (1985). Cervelat is made from a mixture of beef and pork and usually utilizes a culture. It contains salt, sugar, and nitrite and characteristically contains whole black peppers. After fermentation it is smoked and dried to give an a_w of about <0.85.

Pepperoni is also a common IM sausage that is now widely produced, although it originated in Italy as explained by Romans *et al.* (1985). It typically contains pork, beef, salt, sugar, nitrite, and spices and is fermented while holding in a greening room, followed by smoking and drying. Pepperoni may reach an a_w of about 0.65 and shrinks by about 35% (Pearson and Gillett, 1995). Typical Italian pepperoni is dried but not smoked (Romans *et al.,* 1985).

Farmer sausage originally was produced by farmers in northern Europe and commonly is made of 65% beef and 35% pork, which is chopped medium fine, seasoned, stuffed in beef middles, and heavily smoked (Romans *et al.,* 1985). The smoking and drying of quite small pieces produces a relatively stable product with an a_w of 0.85. Holsteiner is a similar product, but the ends are fastened together (Romans *et al.,* 1985).

Mortadella originated in Bologna, Italy, according to Romans *et al.* (1985). It is typically made of 75% pork and 25% beef with garlic in the seasonings. It can also be manufactured using turkey, chicken, goat, or mutton and often contains green pistachio nuts and/or olives. Traditionally it is fermented and dried or cooked as described by Pearson and Gillett (1995). It normally has an a_w of >0.85 and is popular with Italian and Spanish populations. It is a large volume product in the world market.

Rosselló *et al.* (1995) have described the production process of Sobrasada, which is typically produced in the Balearic Island off the coast of Spain. It usually contains approximately 50% fresh raw lean pork, 40% fresh pork fat, 5% paprika, 2% salt, and 5% white pepper. The lean and fat are finely ground and kneaded together until the mixture has a paste-like texture, after which the paprika, salt, and white pepper are mixed with the meat and stuffed into natural casings. The mixture is held at about 4°C for 24 hr and ripened at ambient winter temperature of about 8–15%°C and a relative humidity of 60–85% for about 4 months.

The pH falls rapidly to about 5.3 during the first few days. The initial a_w falls from about 0.93 to 0.88 to 0.83, which coincides with the loss of about 15% of the initial water content. The lactic acid bacteria become the predominant microflora and by the end of about 30 hr enterobacteriaceae organisms are virtually absent.

3. Low Acid IM Meats

Some IM meat products from Europe are dried without fermentation and have a final pH of about 6.0 and a_w values in the range of 0.87–0.90 as outlined by Incze (1991, 1992). Drying is initiated at low temperatures to prevent spoilage and only later during processing is the temperature increased to accelerate drying. Long-cured hams are cured with a mixture of salt, sugar, and nitrate at temperatures below 5°C until they are placed in the smokehouse after being partially preserved by salt and then smoked until the a_w reaches >0.90.

Low acid sausages are first refrigerated 6°C and then when cured are smoked to further reduce the a_w to about 0.88. The heat is added gradually as explained by Incze (1991, 1992). Although sugar may be added to both long-cured hams and low-acid sausages, it is not necessary. The final pH is unimportant, but usually is about 6.0. Thus, low-acid IM meat products are produced by salting and low temperatures during the early stages of preservation and by salt and drying in the latter stage of processing. Nitrite may also provide an additional hurdle as explained by Leistner (1978). Prosciutti and capacola are examples of low-acid IM meats originating in Europe.

D. SOME IM MEAT PRODUCTS FROM AFRICA

1. Biltong

An IM meat product produced in South Africa is known as biltong. Its production is described by Ledward (1981, 1985), Leistner (1987), Obanu

(1988), and Van der Riet (1982). It is usually made from long strips of beef muscle, which is commonly cured by dry salt, although sugar and spices are often added. Nitrite or nitrate may be used to stabilize the color of biltong. South African regulations allow addition of 0.1% potassium sorbate to prevent mold growth. The original procedure as described by Obanu (1988) points out that sun-drying is common and is carried out by hanging the salted strips on barbed wire or galvanized wire fences.

Van den Heever (1970) analyzed 70 samples of biltong and found an average of 25% moisture, 6.6% salt, an a_w of 0.74, and a pH of 5.9, which can be compared to 23% moisture, 5.6% salt, an a_w of 0.70, and a pH of 5.7 for 20 samples analyzed by Van der Riet (1976a,b). Shin and Leistner (1983) and Shin (1984) found 25 biltong samples had a_w values ranging from 0.36 to 0.93, with most samples falling within a range of 0.65–0.85. The pH varied from 4.8 to 5.8, with most being around 5.5. Salt levels ranged from 5 to 15%, with an average of 7%. Some 32% of the samples were spoiled by yeasts, molds, and *Micrococcaceae* during transport and storage.

Several salmonella species have been reported to be present in biltong by a number of investigators (Bokkenheuser, 1963; Van den Heever, 1965, 1970; Prior and Badenhorst, 1974). Salmonellosis in humans has been traced to biltong by Bokkenheuser (1963) and Botes (1966), which emphasizes the importance of good hygiene and sound manufacturing practices. Although *Aspergillus flavus* is frequently isolated from biltong, aflatoxins are not normally found in biltong (Prior and Badenhorst, 1974; Leistner *et al.*, 1981).

2. *Kilishi and Bande*

Okonkwo (1984) and Obanu (1988) have discussed production of kilishi and bande, which are made by sun-drying and hot smoking–cooking, respectively, in Africa. Igene *et al.* (1992) have described the traditional production of kilishi as produced in Nigeria. Typically these products are made from lean beef or goat meat, which is cut into thin strips and dried in the sun or smoked–cooked over a low fire until they are preserved. Salt may be added to hasten drying, but often is not added. Smoking may also aid in preservation. Flies are normally a problem, so smoking–cooking is preferred.

E. NORTH AND LATIN AMERICAN IM MEATS

Four IM meat products that are indigenous to North America include pemmican, jerky, country hams, and Lebanon bologna.

1. Pemmican

Pemmican is a product originally made by American Indians and its production is described by Ashbrook (1955) and Binkerd *et al.* (1976). It was made from lean buffalo meat or venison. Processing is carried out by either sun-drying or smoking at low temperatures followed by pounding the dried meat into a shredded mass. It then had dried fruit pounded into the dried meat and was embedded in melted fat. It was sewed in rawhide bags and used by Indians on the warpath or in times of scarcity and later by mountain men and Arctic and Antarctic explorers (Stefansson, 1956). Although interest in pemmican was revived during World War II, it is no longer produced.

2. Jerky and Dried Beef

Ashbrook (1955) also has described production of jerky (beef or venison), which was cured in a hot brine and smoked over a low burning fire. Production of dried beef was also described by Ashbrook (1955), which is cured in a brine with a high-sugar content, followed by draining and smoking. A similar product was produced from dried salted mutton by Zapata *et al.* (1990).

Today jerky is a popular product in the United States with a number of companies specializing in its production. Modern processing in temperature and humidity controlled smokehouses produces jerky in 10–24 hr. During the early phases of drying–smoking, humidity must not be lowered too fast or case hardening will occur. The final a_w is between 0.70 and 0.75.

3. Country-Cured Hams

Country-cured hams are made by dry curing hams so as to be stable at ambient temperatures and are produced in a similar form in many countries (Kemp *et al.*, 1983; Pearson and Tauber, 1984; Romans *et al.*, 1985). These products have a high-salt content, which lowers their a_w and makes them stable. During storage, the indigenous enzymes, particularly the cathepsins, play a role in flavor development (Toldra and Etherington, 1988; Lopez *et al.*, 1992). Country-cured hams have an a_w of about 0.80–0.85 and are in demand in the southern United States.

4. Lebanon Bologna

Production of Lebanon bologna originated in Lebanon Pennsylvania. Typically, it is made from lean whole carcass cow beef, to which is added

2% salt and it then is held for 8–10 days at 2–4°C to permit fermentation by the natural microflora as described by Pearson and Gillett (1995). Today most Lebanon bologna is produced by using starter cultures, which permits production while smoking. The cow meat is ground and mixed with salt, sugar, sodium nitrite seasonings, and the starter culture and smoked until the pH reaches less than 5.0. The finished product has a pH of 4.7 to 5.0, a salt content of 4.5 to 5.0%, a moisture content of 52–56%, and an a_w of about 0.85. The final product has a tangy acid and salty taste. It is often called Lebanon style bologna when made in areas other than Lebanon, Pennsylvania.

Recently, 275 tons of Lebanon bologna were recalled by a Pennsylvania processor due to possible salmonella contamination (Anonymous, 1995b). This emphasizes the importance of good manufacturing practices and careful control of microbial contamination in processing of IM meat products.

5. *Charqui*

Torres *et al.* (1989) have described the production of the popular Brazilian IM meat product, charqui, which is cured in dry salt, washed, and sun dried. Heating–smoking can be utilized instead of sun drying. Pardi (1961) concluded that charqui is stable for periods exceeding 6 months at ambient Brazilian temperatures. The same principles apply to the production of charqui as to other IM meats that were discussed earlier herein.

6. *Cecina*

Reyes-Cano *et al.* (1995) have described the process utilized in production of cecina—an IM meat product that is widely produced and consumed in Mexico. Fresh lean beef from the hindquarter is sliced parallel to the direction of the muscle fibers in long strips at a thickness of about 5 mm and immersed in a 15% salt solution at a ratio of 1:2 meat to solution for 4 hr. The meat then can be dried by oven drying at 50°C for 1 hr or sun dried for several days. Still another procedure adds salt to the thinly sliced meat and folds the meat over the salt until curing is complete. The final product has an a_w of about 0.85 and is similar in composition to beef jerky (Reyes-Cano *et al.*, 1994). The final pH is about 5.4 to 5.5 (Reyes-Cano *et al.*, 1995).

Production and processing of cecina is highly variable in different states of Mexico, with some products having added oil or vinegar (Reyes-Cano *et al.*, 1994), whereas other use salt only. The only constants in production are the use of salt and drying of the thin strips of lean beef, which may be aided by application of heating in an oven or sun drying. The addition of vinegar or oil also aids in the drying process.

7. *Salchichon*

Salchichon is a popular Spanish style sausage with the Spanish name meaning large sausage. Serrano-Moreno (1979) reviewed the literature on production of salchichon and stated it can be made from lean beef, lean pork, or a combination of the two. Pork backfat is added along with seasoning (1–4% salt, nitrate and nitrite, and white pepper) and sugar (1% of a 1 : 1 mixture of sucrose and dextrose). It is normally held at a temperature of 25–30°C and a relative humidity of 80–90% for 5 days, after which it is held for an additional 60 days at 30–37°C and 70–80% relative humidity for maturation. This reduces the moisture content of about 50–60 to 26–35%. The final a_w is 0.80–0.87, and the final pH is 4.6–4.8.

Serrano-Moreno (1979) has described the production and physicochemical characteristics of salchichon, which was made from lean ground cow beef (40%), lean pork (30%), and pork fat (30%). It contains about 3% NaCl, sucrose (1%), dextrose (1%), white wine (0.5%), ground pepper (0.25%), whole pepper, potassium nitrate, and sodium nitrite, which were ground and mixed together. Incubated at 20°C and a relative humidity of 80% for 5 days after stuffing in large casings (natural or artificial), salchichon then undergoes maturation at about 12°C at 70% relative humidity for an additional 60 days.

Salchichon made in this way has a final chemical composition of about 25% protein, 27% moisture, 43% fat, and 5% ash. It has a final pH 5.90 and an a_w of 0.85 (Serrano-Moreno, 1979). Micrococci and lactobacilli are the predominant microorganisms, with the former being the most important by the end of maturation. The salt content rose from 2.69 initially to 4.03% in the final product.

III. TECHNOLOGY OF PRODUCING IM PET FOODS

Development of IM pet foods has proceeded that of IM foods for humans and many problems can be prevented by applying principles and techniques learned in the commercial manufacture of IM pet foods. Some of the principles and techniques used in their production will be described.

A. PRINCIPLES INVOLVED IN PRODUCTION OF IM PET FOODS

Development of IM semimoist pet foods was discussed by Karel (1976), since it was considered to be sufficiently important to have application in producing IM foods for humans (Davies *et al.*, 1976). Burrows and Barker (1976) pointed out that two techniques have been utilized in production of IM pet foods, namely, (1) making a slurry of the ingredients, heating them to a pasteurizing temperature and extruding them to produce a semimoist product; and (2) infusing whole chunks of meat or meat analogs with humectants to lower their water activity in order to produce a stable semimoist pet food.

Burrows and Barker (1976) stated that raw meat products utilized in producing pet foods have an a_w of about 0.97 and a moisture content of about 60–70%. They concluded that the a_w must be lowered to about 0.80 by adding of humectants and drying. At this a_w the product is palatable and shelf stable, except for mold growth. However, mold growth can be prevented by addition of a mycostat, such as potassium sorbate. Products produced in this way were both palatable and shelf stable.

The humectants that have been used to lower the a_w of pet foods include sugar, salt, and polyhydric alcohols (Burrows and Barker, 1976). Addition of these humectants results in products containing about 35–45% moisture.

The salt content is limited due to its effect upon acceptability so the polyhydric alcohols and sugars are normally utilized at higher levels (Davies *et al.*, 1976) in order to lower the a_w. Propylene glycol is the polyhydric alcohol of choice, although others, such as glycerol, have also been utilized (Burrows and Barker, 1976).

Table II, which was taken from Karel (1976), gives the range of the most common ingredients used in pet food formulations. Salt may also be utilized but is limited to about 2–4%. The wide range of other components in the products means that they must also be balanced, i.e., adjusted up or down according to the amount of other constituents in the formulations.

TABLE II

RANGE OF TYPICAL INGREDIENTS UTILIZED IN IM PET FOODS[a]

	%
Meat or meat by-products	30–70
Sodium caseinate	7.5–25
Sugar	15–30
Propylene glycol	2–10
Starch	0.5–10
Nutritional supplements	1–5
Flavor and color additives	As desired

[a] Source: Karel (1976).

B. HUMECTANTS USED IN IM PET FOODS

Table II shows that sugar and propylene glycol are the main humectants utilized in producing IM pet foods. However, since sodium caseinate and starch also are added in the dry form, they also assist in lowering the water activity of the final products and acts as humectants.

Although glycerol also acts as a humectant, propylene glycol is commonly preferred because of a desirable effect upon the flavor (Burroughs and Barker, 1976). The high-sugar content in some formulations may lead to the Maillard reaction and produce melanoidins, thus having a deleterious effect upon both color and flavor (Davies *et al.*, 1976).

C. MYCOSTATS

Federal meat inspection regulations permit soaking of sausage casings in 2.5% potassium sorbate or 3.5% polyparaben solution to inhibit mold growth (Rust, 1988). The same fungicides also are used in semimoist pet foods to prevent mold growth during storage at ambient conditions.

IV. PRESERVATION PRINCIPLES AND THEIR APPLICATION TO IM MEATS

A. STABILIZATION DURING PROCESSING

Stabilization of meat and meat products is achieved during processing as well as in storage. The stability achieved is due to the cumulative effects of the processing operations, treatment, and final storage condition for each product (Gould, 1989a,b), although mechanical failure may occur in biological systems (Atkins, 1987).

B. COMPARISON OF HEATED AND RAW PRODUCTS

Certain meat products are preserved by heating. Heating is used to destroy some of the pathogenic bacteria and to make the product more palatable (Pearson and Tauber, 1984). However, some raw IM meats are consumed without any prior heat treatment, such as is the case with salami (Romans *et al.*, 1985). For some processed (heated) products, heating is applied during processing, where its major function is to achieve stability rather than the effects on palatability. Most heated meat products still require preconsumption reheating, except for some IM meats (Leistner, 1987). Currently, there is a trend to heat more of the formerly uncooked raw meats to improve their safety and stability (Leistner and Rödel, 1976; Leistner *et al.*, 1981).

1. The Simple Stabilization Operation

High temperature transient heating of meat produces in closed containers makes sterilized canned meat items stable when stored at ambient temperature at $a_w = 1$ (Potter, 1986). The product is heat processed and does not require further heating before consumption. Chilling and subsequent storage at −20°C also renders frozen meat items stable at $a_w = 1$ (Potter, 1986).

The high degree of moisture removal and subsequent holding of the products at an $a_w < 0.6$ renders dehydrated meat items stable at ambient temperature (Leistner, 1987). However, the products normally do require rehydration before consumption.

2. Preservation by Complex Stabilization Treatments

Many of the same principles apply to all IM foods as explained by Gee *et al.* (1977). Refrigerated meat items are subjected to mild chilling in combination with other stabilization treatments and then stored at <4°C at $a_w = 1$ (Romans *et al.*, 1985). Shelf stable meat items are subjected to a moderate degree of transient heating (less than canned meat items) to achieve an a_w of 0.90–0.97 along with other stabilization treatments (salt and pH) and stored at ambient temperatures (Leistner, 1987). For IM meats, several optional stabilization treatments usually are involved. The only required operation is dehydration, with some IM meats being produced without involving heating (Okonkwo, 1984; Leistner, 1987; Obanu, 1988). However, dehydration is applied only to remove the moisture to a certain level, which is designed to be about in equilibrium with ambient relative humidity at ambient temperature. The products are finally stored at the achieved a_w, which is equivalent to the ambient relative humidity (Ledward, 1981, 1985; Leistner, 1987; Obanu, 1988; Okonkwo *et al.*, 1992a,b). Indeed, the products are dehydrated in combination with other optional stabilization operations and/or treatments to produce a stable moisture state. Stable storage conditions for each product are defined in relation to their storage surroundings in terms of temperature and relative humidity.

The sequence of the applied stabilization operations and/or treatments is variable among available IM meats as explained by Obanu (1988). For example, heating can be applied either in a high-moisture or in a low-moisture atmosphere. In the latter case, the heating may be a complete process or may not be complete until heating before consumption. The water activity and storage temperature of IM meats also varies with the prevailing climatic conditions to which each product is exposed (Ledward, 1985; Obanu *et al.,* 1975a,b, 1976). In tropical areas, water activity and storage temperatures of products will be higher than those of the same products in a temperate area (Leistner, 1987). The stability of various meat products depends on the whole series of stabilization factors, which must be achieved in the preservation procedure as shown in Tables III and IV. The final water activity, in itself, is simply a physical index of product stability in terms of chemical and microbial deterioration (Troller, 1980; Gould, 1989b).

IM meats can be preserved at ambient temperature without any stabilization treatment other than dehydration according to Leistner (1987). The commonly associated soluble solids (sugar and salt) in most IM meats are added to achieve stability during the early stages of dehydration. However, when a meat mixture has an a_w between 0.90 and <0.97, it is subjected to a certain degree of in package heating, so that the processed mixture is classified as a shelf stable product (Table IV). When a meat mixture is

TABLE III

EFFECTS OF TREATMENTS ON VARIOUS PARAMETERS INFLUENCING SPOILAGE AND/OR GROWTH OF FOOD POISONING MICROORGANISMS

Treatment	Effects on stability characteristics
Drying	Lowering a_w to 0.90 or less. Prevents bacterial growth and spoilage.
Salting	Preserves by lowering a_w by accelerating drying.
Sugar	Lowers a_w and inhibits bacterial growth. Counteracts water loss due to salt.
Fermentation	Lowers pH and inhibits growth of spoilage and food poisoning organisms. Assists in removal of water.
Acidification	Lowers pH and aids in removal of unbound water. Aids in drying.
Removal of O_2	Prevents growth of aerobic microorganisms.
Smoking	Adds organic acids and other preservative substances.
Addition of CO_2	Inhibits growth of aerobic bacteria. Lowers surface pH.
Irradiation	Low level radiation reduces number of viable bacteria. High level inactivates.
Freezing	Stops bacterial growth and delays deterioration of meat.
Cooling	Slows down rate of bacterial growth and spoilage onset.
Preservatives	Inhibits growth of microorganisms.
Bacteriocins	Bactericidal and bacteriostatic agents (nisin). Destroys or inhibits microorganisms.
High pressurization	3000–4000 atm. Destroys vegetative cells and inactivates enzymes.
Electrical current	Application of high levels of electrical current destroys bacteria without heat.
Addition of spices	Some spices have bactericidal and bacteriostatic effects.

TABLE IV

TARGET ORGANISMS CONTROLLED IN VARIOUS PRODUCTS BY DIFFERENT STABILIZATION TREATMENTS

Type of product	Target organisms[a]
Fermented meats	*Staphylococcus aureus* and *Escherichia coli* O157:H7
Canned meats (sterilized)	*Clostridium botulinum*
Modified atmosphere packaged meats	Pseudomonads, *C. botulinum* (vacuum packaging)
Frozen meats	Pseudomonads
Cured meats (salt and nitrite)	*S. aureus* and *C. botulinum, Enterococceae*
Irradiation—pasteurization dosage	*E. coli* O157-H7, Salmonella, Listeria, Pseudomonads *C. perfringens*
Irradiation—sterilization dosage	*C. botulinum*
Chilled meats (raw) (0 to −4°C)	Pseudomonads, *Yersinia* (pork), *Aeromonas,* Salmonella, Listeria, *E. coli, Campylobactor,* Pseudomonads, *C. perfringens*
Dry and semidry meats (a_w = 0.90 to 0.40)	*S. aureus, E coli* O157:H7
Cooked uncured meats	Salmonella, Listeria, *C. botulinum* (Modified atmosphere packaging)
Freeze-dried meats	*C. botulinum,* Salmonella, Listeria and *S. aureus*

[a] Microorganisms which are generally targeted for control of their growth. This list may not be complete.

subject to a high degree of in package heating at $a_w = 1$, the processed mixture becomes a sterilized product, which in concert with other treatments, such as nitrite can greatly increase the stability of the product as explained by Sebranek (1988).

Preservation of IM meat is complex in nature. The identified stabilization operations/treatments in processing, water activity, and storage temperature of IM meat are never greater than those for other preserved meats (Leistner, 1987). The specific preservation procedure or step for each empirical product cannot be taken for granted, but must be determined by experimentation. The possible involved consequence and/or synergistic stabilization factors developed in the preservation procedure should be subjected to more scientific scrutiny.

V. PROBLEMS IN PRODUCTION OF DIFFERENT IM MEATS

Production of IM meats can be divided into different steps. The manufacture of dry and semidry sausages is steeped in art according to Pearson and Tauber (1984) and Romans *et al.* (1985). However, the art is slowly being replaced by scientific principles. In modern practice, dry and semidry sausages are the most difficult and time-consuming to produce. Ironically, these types of sausages are thought to have been the first produced in early history, dating back to the Babylonian culture around 1500 BC, approximately 3500 years ago.

A. PROCESSING EQUIPMENT AND RAW MATERIALS

Processing equipment used in traditional meat drying is simplistic and in some cases primitive, making process control difficult, if not impossible as outlined by Leistner (1987) and Obanu (1988). The processor is often at the mercy of the weather for sun-drying or smoke-drying. Product quality is uncertain and variable so stability is achieved only by luck or sheer artistry. Quality of both the raw materials and the finished products are variable and often inferior. Dried meat production in tropical Africa has remained shrouded in secrecy as explained by Obanu (1988). Salmonellae are often troublesome, the recovery of salmonella spp. from biltong has been reported by Bokkenheuser (1963) and Van den Heever (1965). Biltong with such indigenous infection has also caused salmonellosis in humans (Bokkenheuser, 1963; Botes, 1966). The introduction of biltong for general use in developing countries is obviously hampered by health-related requirements.

Production of dending in Indonesia generally is limited in scale to that which can be made in the home or in butcher shops, with there being relatively few large scale processors according to Buckle *et al.* (1988). Production statistics for dending in Indonesia are not available, but substantial quantities are produced. High storage temperatures and humidities and high initial levels of microbial contamination can lead to significant problems by spoilage from chemical, physical, and microbiological changes unless production and storage conditions are controlled. Studies on Malaysian IM meats by Chuah *et al.* (1988) led them to conclude that the quality of different batches differs widely due to poor quality control and the lack of proper equipment. However, these production problems are slowly being overcome with the introduction of more modern equipment, which not only speeds up the rate of production but also results in more consistent quality products due to more precise control (Buckle *et al.*, 1988). For example, product particle size, temperature, air speed, and other processing parameters can be standardized and improve the end products.

B. IMPROVEMENT OF PROCESSES AND PRODUCTS

Since production of Zousoon is rather an empirical process and suffers from lack of control of time and temperature, a study was undertaken by

Chang *et al.* (1991) to investigate the design and operating parameters for better controlled heating–drying equipment in producing this Chinese product. The process is described in greater detail later in the present review. Similarly preliminary results in producing pork slices by Lin (1981), and I. M. Lin *et al.* (1981), and S. L. Lin *et al.* (1983a,b) showed that an improved process was superior to the conventional process in respect to labor cost, quality of product, and rate of production. The new process can be summarized as follows: Pork (sliced)–seasoning–molding–freezing–slicing–drying–roasting–final product. The product produced by the conventional process requires a great deal of labor and time, in addition to being unsanitary and depending upon atmospheric air drying, according to Lin *et al.* (1981).

For industrialized countries, traditional IM foods in developing countries are of considerable interest. In cooperation with scientists from developing countries, the principles behind these IM meats have been studied (Chang *et al.*, 1991; Lin *et al.*, 1981; Chuah *et al.*, 1988; Buckle *et al.*, 1988). Results suggest that processing and shelf life can be improved without impairment of their sensory and nutritive properties. The improved formulas should be made widely available, because they could be of great benefit in many parts of the world, if the products are acceptable to local tastes. In addition to traditional meat-based intermediate-moisture foods, new and promising ideas for product development in industrialized countries could emerge, although these meat items are based upon centuries-old trial-and-error processes.

There is a trend toward food preservation methods that simultaneously provide extended shelf life and minimum changes in food quality. Nowhere in the world is this need more urgent than in less developed countries where the lack of refrigeration makes perishable foods unavailable for widespread consumption.

With these facts at hand, the remainder of this review will focus upon: (1) The effects of predrying upon muscle structure and the moisture compartment as affected by slaughter and handling operations and by manufacturing, including heating and osmotic treatments; (2) Mechanisms involved in the dehydration process; (3) The influence of storage stability on the quality attributes as affected by dehydration and the associated processes, and finally (4) Process optimization and appropriate technology.

VI. EFFECTS OF SLAUGHTERING, HANDLING, CHILLING, FREEZING, STORAGE, AND THAWING ON MUSCLE PROPERTIES

A. CHANGES IN MUSCLE STRUCTURE AND THE MOISTURE COMPONENT

Schmidt *et al.* (1981) have demonstrated that the protein matrix in muscle has a marked effect upon its functionality and properties. Every process involved in the conversion of muscle to meat alters the characteristics of the structural elements (Stanley, 1983). The most obvious physical postmortem change in muscle is the stiffening and the loss of extensibility as a result of rigor mortis as explained by Lawrie (1979). During rigor, multiple attachments are formed between actin and myosin filaments, which lock the interdigitating mechanism into a rigid, inextensible structure (Pearson and Young, 1989). After a period of time muscle begins to undergo a tenderizing process. In terms of the physical properties, a decrease is noted in the modulus of elasticity as rigor mortis becomes complete, but extensibility does not return (Bendall, 1969).

B. EFFECTS OF RIGOR MORTIS

The tensile and adhesive properties and the structure of selected beef muscle strips undergoing rigor mortis have been followed at various times postmortem by Currie and Wolfe (1980). They found that changes in the mechanical properties of the muscles correlate well with final pH and the rate of pH fall. Additionally, and perhaps most importantly, the shapes of the curves generated over the postmortem aging times were correlated with the changes in the extracellular spaces. Thus, the authors concluded that intrafiber water must be considered as an important factor in meat tenderness, in addition to the effects of myofibrillar contraction and connective tissue orientation. One factor that may influence the extracellular spaces may be cooking which was studied by Locker and Carse (1976). Another factor that also may alter extracellular space is cold shortening, which has been described by Voyle (1969) and Marsh *et al.* (1974).

1. Structural Alteration

Greaser (1986) has discussed the physical and biochemical changes that take place during the conversion of muscle to meat. According to Offer and Knight (1988a) the fibers in beef sternomandibularis muscle almost touch and the fiber bundles fill the perimysial network after 2 hr postmortem at 10°C. Between about 4 and 6 hr postmortem, however, a significant change can be seen. The fiber bundles shrink away from each other and gaps of about 5–50 μm develop between the fiber bundles and the perimysial network. Nevertheless, at this stage the fibers still seem to fill the endomysial network. The results imply that up to this stage both the cell membrane and the endomysium shrink with the fibers. At about 24 hr postmortem, roughly at the time the fibers enter rigor, another structural change is apparent. In addition to the gaps between fiber bundles, gaps develop between the fibers and the endomysial network. It, thus, appears that the gaps at the endomysial–perimysial junction do not act as a sink for all the fluid expelled from the myofibrils as explained by Offer and Knight (1988b), which is responsible for drip losses. A possible reason for this is that the endomysial network may resist shrinkage beyond a certain point. Alternatively, at the point of rigor onset in a fiber, the shrinking force may rise so fast that ruptures occur before much of the fluid can flow through the endomysial network. Thus, the histological results demonstrate that in muscle at rigor there are two extracellular spaces: first, the gaps between fibers and the enclosing endomysial sheaths, and second the gaps between the fiber bundles and the perimysial network.

Stanley (1983) concluded that postmortem events influence the physical properties of meat, not only through rigor mortis, but also as a result of the action of numerous endogenous enzymes on myofibrillar structure, and perhaps, connective tissue as well. A major structural alteration that has been observed in postmortem muscle is Z-disc degradation. The unreactive chemical nature of collagen may preclude any major attack by endogenous muscle enzymes on this fibrous protein (Offer *et al.*, 1988).

2. *Fragmentation of Muscle Fibers*

According to Cia and Marsh (1976) electrical stimulation results in contracture bands that cause tearing and fragmentation of myofibers/myofibrils. McLoughlin (1971) and Van der Wal (1971) suggested that death caused by electrical stunning and CO_2 gas brings about marked changes in the turnover rate of ATP in the muscle and is responsible for fragmentation of the myofibers. Brief electrical stimulation directly or via the motor nerve depletes creatine phosphate, accelerates the breakdown of ATP, and increases the formation of lactate. McLoughlin (1971) suggested that it is necessary to maintain the intracellular environment as close as possible to the *in vivo* state after death in order to reduce postmortem glycolysis and concluded that commercial methods of stunning and slaughter presently used do not meet this requirement.

3. *Other Structural Alterations*

Other structural alterations observed during electrical stimulation to the contractive bands include intracellular edema, swollen membranous organelles, myofibrillar fragmentation, and other changes consistent with accelerated autolysis of muscle resulting from tissue disruption (McLoughlin, 1971). Stanley (1983) has shown that several other abnormalities in texture (structure) also may result as a consequence of failure to properly cool prerigor meat immediately following slaughter. Jones (1977) has followed the ultrastructural changes occurring in meat postslaughter.

4. *Densely Stained Cross-Bands*

Bendall and Wismer-Pedersen (1962) have observed irregular wavy, densely staining cross-bands in the muscle fibers of pale, soft, and exudative (PSE) pork. They observed that muscle filaments ran through the dense bands and concluded that the change was not of myofibrillar origin. They theorized that myofibrillar material from a number of sarcomeres accumulated to form the dense bands. On either side of the dense bands, they observed recognizable but short sarcomeres. Bendall and Wismer-Pedersen (1962) further pointed out that the dense bands were similar to the contracture bands or zone of supercontraction that can be induced in muscle by other treatments, such as electrical stimulation. Zones of supercontraction alternating with zones of stretched sarcomeres also have been observed in muscle exposed to an elevated temperature prior to the onset of rigor, after thaw rigor, after cold-shortening, or in electrically stimulated muscle according to Bendall nd Wismer-Pedersen (1962). All this suggests that some of the muscle fibers undergo excessive shortening prior to rigor, leading to a heterogeneity of sarcomere length and irregular zones of supercontraction. However, supercontracted fibers are not always present at rigor, and it is possible that zones of supercontraction persist only in the more extreme forms of PSE muscle (Bendall *et al.,* 1963). The reason, although not clear, is most probably a result of contraction still being in a reversible state.

C. FREEZING AND STORAGE

Freezing of meat is a common preservation technique which has been discussed by Stanley (1983). It has been demonstrated that when whole muscle tissue is frozen and stored under accepted processing and packaging conditions, little if any alteration in structure or physical properties is produced during a normal storage period (Pearson and Miller, 1950).

D. RAW PRERIGOR MUSCLE

Raw muscle in a specific postmortem physiological stage and/or stored under proper temperature conditions has been strictly selected and used as the raw material for some specific IM meat products due to the eventual physical properties of the finished items (Chang *et al.,* 1991). Examples include Zousoon and cooked-dried pork pieces or cubes (Leistner, 1987;

Chang *et al.,* 1991). The idea of boning the carcass prior to chilling has been examined because the procedure has many economic advantages, not the least of which is a large energy savings in terms of refrigeration (Henrickson and Asghar, 1985).

Some IM meat products require hot-boned prerigor or warm meat as a source of raw material, not because of the concern for energy savings, but rather because of their specific structural and/or physical properties (Chang *et al.*, 1991; Chang and Pearson, 1992). For developing countries, hot boning is a general practice for postmortem handling of meat (Obanu, 1988). For the domestic pork market in Taiwan, people still prefer pork from hot-boned meat (S. F. Chang, unpublished observations).

VII. EFFECTS OF PREDRYING TREATMENT AND HANDLING OF MUSCLE

A. CHOPPING OR GRINDING

Romans *et al.* (1985) stated that to achieve the best particle definition, the raw meat should be ground or chopped at very low temperatures (−4 to −6°C). Mixing and unnecessary handling of the meat should be avoided as much as possible. The cold meat temperature reduces protein extraction and helps to eliminate unnecessary particle deformation. Mixing should be only enough to allow uniform distribution of the curing ingredients and/or other additives (Pearson and Tauber, 1984).

B. ROLE OF MYOFIBRILLAR PROTEINS IN WATER BINDING

The myofibrillar proteins, especially the myosin molecule, are extracted at low-ionic strength (0.1–0.3 *M* KCl at pH 6.0–8.0) and spontaneously form aggregates as explained by Katsaras and Budras (1992). Some of the aggregates are long and spindle-shaped and are called synthetic filaments. The synthetic filaments thus become building components in a three-dimensional network. Some of the reactive aggregates are bound to each other by hydrogen bonds and electrostatic charges to form a continuous but reversible coagulated structure (Offer and Trinick, 1983). Within the three-dimensional protein network a large amount of free water is absorbed, as described by Wismer-Pedersen (1971) and by Offer *et al.* (1988). The water has two functions: (1) as a hydration layer it separates the protein aggregates; and (2) via the hydrogen bonds it constitutes a link between the protein network. If there is a sufficient amount of water available the protein remains in a colloidal "sol-state". The coagulation bonds are still rather unstable and, in addition, are weakened by the intermediate layer of water molecules.

C. FERMENTATION

All phases of meat fermentation were reviewed in a recent book edited by Campbell-Platt and Cook (1995). The discussion covers the safety aspects of fermentation in meat products as well as its use world wide and the techniques that are utilized.

During the process of sausage fermentation and after a certain period of adaptation, bacterial populations increase in number as outlined by Katsaras and Budras (1992). The growth of lactic acid bacteria is dominant because these bacteria enjoy the advantage of selection in the milieu of fermented sausages. The lactic acid bacteria break down sugar and produce lactic acid. As soon as the sausage has reached the isoelectric point of about pH 5.3, the negative and positive charges compensate for each other and the bound water is released, i.e., the water binding capacity in the fermented sausage has reached its minimum. Consequently, the amount of immobilized water between the protein threads is reduced and its function as a "spacer" becomes increasingly ineffective so that the protein aggregates and the meat particles gradually approach each other. The spindle-shaped protein aggregates are subjected to a series of changes, and the intermolecular interactions successively create new bonds, until an extended, dense, three-dimensional network of protein threads are built as explained by Katsaras and Budras (1992). The process, which is accompanied by water loss and shrinkage of the sausage in a drying atmosphere, is called syneresis. Fermentation results in proteolysis and an increase in the amount of insoluble protein as reported by Astiasaran *et al.* (1990), which may assist in dehydration.

Ibanez *et al.* (1995) compared dry-fermented sausages formulated so that part of the NaCl was replaced with KCl from the standpoint of their effects on carbohydrate fermentation and nitrosation. Both sausages attained similar final pH and a_w values, at pH 5.06 and 4.99 and a_w 0.85 and 0.88 for the control NaCl and the KCl-containing sausage. Final a_w values were achieved in less than 20 days and were well below the a_w value of <0.90, which is required for stability of IM meats.

D. EFFECTS OF HEATING

According to Sebranek (1988) heating is believed to cause the denaturation of the muscle proteins even below 60°C, but not enough to greatly affect shear resistance. The decrease in shear observed at 60°C was attributed to collagen shrinkage. Hardening at 70–75°C was believed to be due to increased crosslinking and water loss by the myofibrillar proteins, while decreasing shear at higher temperatures may indicate solubilization of collagen.

Heating produces major changes in muscle structure. Voyle (1981) has reviewed modifications in cooked tissue observable with the scanning electron microscope. Several authors (Hsieh *et al.,* 1980b; Voyle, 1981) have reported alteration in muscle structure due to heating, which include coagulation of the perimysial and endomysial connective tissue, sarcomere shortening, myofibrillar fragmentation and coagulation of the sarcoplasmic proteins. Heating and/or drying intensifies the detachment of the myofibrils from the muscle fiber bundles, which is caused mainly by electrical stunning or stimulation and improper conditioning following slaughter (Chang and Pearson, 1992).

The bovine sarcolemma with its associated endomysium has been shown to maintain its postrigor integrity except for the occurrence of some small perforations in the sarcolemma (Rowe, 1989a,b). The close structural association of the three component parts, i.e., the plasmalemma, basement membrane, and endomysium, persists even during physical disruption of the muscle, such that when a tear occurs all three parts are involved according to Rowe (1989a,b). After 1 hr at 50°C, the collagen fibrils of the endomysium appear beaded, which is brought about by their close association with the heat-denatured noncollagenous proteins in the extracellular spaces. Heat denaturation of the lipoprotein plasmalemma results at a temperature of 60°C for 1 hr. The breakdown products of the plasmalemma are large granules and are often associated with the basement lamina, which appears to survive intact even after heating at 100°C for 1 hr (Rowe, 1989a,b).

When an animal or plant is killed, its cells become more permeable to moisture as pointed out by Potter (1986). When the tissue is blanched or cooked, the cells may become still more permeable to moisture. Generally, cooked vegetable, meat, or fish will dry more easily than their fresh counterparts, provided cooking does not cause excessive shrinkage or toughening (Potter, 1986). Cooking also results in a decrease in WHC (Stanley, 1983). Liquid components, such as water and lipids, are removed. Shrinkage in fiber diameter and length occurs and the apparent density increases (Stanley, 1983). Other changes, such as denaturation of the sarcoplasmic proteins, are also observed (Bendall and Wismer-Pedersen, 1962).

E. INFLUENCE ON OSMOTIC TREATMENT

Osmotic concentration can be considered a simultaneous water and solute diffusion process. As explained by Lerici *et al.* (1988) the membrane is only partially selective, thus, there is always some leakage of solute from the solution into the food and from the food into the solution. By means of a suitable choice of osmotic solutions and of the processing conditions, the solute diffusion can be minimized or enhanced, depending on the desired characteristics of the food. It is this duplicity of action in respect to the food, (partial dehydration and controlled chemical composition) which makes direct osmosis so interesting in food processing (Ponting *et al.* 1966). Guilbert (1988) demonstrated that an edible layer of material could be utilized to protect from moisture during storage of tropical fruits dried by osmosis.

Muguruma *et al.* (1987) demonstrated that low-temperature osmotic dehydration improved the quality of IM meat products. They utilized a so-called "dehydrating sheet" to develop osmotic pressure and improve the rate of water removal at relatively low temperatures, which resulted in better quality IM meat products.

On immersing either a whole muscle or single isolated fibers in a hypertonic medium, the single fibers behave as osmometers and shrink substantially as explained by Offer and Trinick (1983). In contrast, the whole muscle shrinks only slightly, because the fibers within it shrink substantially, which is almost matched by an increase in the extracellular space. This would be expected, since connective tissue sheaths are presumably not permselective (selective semipermeable membranes), and therefore, neither the perimysial nor the endomysial networks should alter in volume in the presence of an osmotic agent. Shrinkage of myofibrils (or fibers) leads to a greater proportion of loosely held water, which has the potential of being lost from the meat. The greater the amount of shrinkage, the greater is the potential for water loss (Offer and Knight, 1988a). The loss, however, will only occur under appropriate conditions, such as pressure.

VIII. FACTORS INFLUENCING ABSORPTION PHENOMENA IN MEATS/MEAT MIXTURES

A. BOUND AND UNBOUND WATER IN MEAT PRODUCTS

Moisture may be bound to the solids so that full vapor pressure is no longer exerted according to Watson and Harper (1987). They pointed out that the terms unbound (free) and bound are commonly used to distinguish moisture in the relatively large spaces from that held more tightly by other forces. They further stated that there is a continuous transition from unbound to bound moisture, and it is not possible to make a precise dividing line. Unbound moisture is frequently defined as that which exerts the normal vapor pressure, while bound moisture has a lower vapor pressure (Watson and Harper, 1987).

Offer and Knight (1988b) concluded that muscle protein molecules in an aqueous solution interact with water, and when it moves through the solvent it carries some water with it. Part of this bound water is believed to be hydrogen-bonded to the surface of the protein molecule, while part may be present in clefts or pockets. Both are in dynamic exchange with "free" water. These authors stated that the amount of water associated with proteins in this way can be measured by a variety of techniques. However, it amounts to only about 0.5 g of water per gram protein. The total concentration of protein in muscle is about 200 mg/ml, so that as emphasized by Hamm (1960, 1986), only about a 10th of the water in muscle can be considered to be closely bound with the proteins.

Measurement of water vapor pressure of a food as a function of moisture content provides information on the vaporization potential at a given moisture content with respect to the specific solids in a food (Watson and Harper, 1987). Thus, water vapor pressure is a useful measure of moisture content in food products.

B. RELATIONSHIP OF WATER VAPOR PRESSURE TO WATER ACTIVITY

Water activity was defined by Scott (1957) using the equation $a_w = P/\text{po}$, where P is the water vapor pressure of food and po is the water vapor pressure of pure water at the same temperature. Water activity is, thus, an index of degree of freeness (the potential to be vaporized) of the solid bound moisture relative to pure water.

Relative humidity has been defined by Aguilera and Stanley (1990) using the equation RH (%) = $P/\text{po} \times 100\%$, where P is the partial water vapor pressure in an atmosphere and po equals the water vapor pressure of pure water at the same temperature. Thus, the water activity of a food can be determined by the prevalent relative humidity in the atmosphere surrounding the food when in an equilibrium state. It can be expressed by the equation $a_w = P/\text{po} = \text{RH\%} \times 1/100$ (in equilibrium state) $= \text{ERH\%} \times 1/100$, where ERH is an expression of equilibrium relative humidity (Watson and Harper, 1987).

Water activity is, thus, an index of water vapor pressure of food or its moisture state (in our case meat) and is a function of: (1) the moisture content/solid content of a meat or meat mixture, (2) the components in and composition of a meat or meat mixture, (3) the microstructure of a meat or meat mixture, (4) the temperature, and (5) the state of some component solids (i.e., sugar).

C. SORPTION PHENOMENA IN MULTICOMPONENT FOOD SYSTEMS

When food components differing in a_w are put into the same system, the components of higher a_w give up moisture to those with a lower a_w until the mixture reaches equilibrium as described by Potter (1986). A practical consequence of this is that each component of a mixture can be prepared separately under specific conditions of formulation and/or infusion. When these components are subsequently blended and reach the equilibrium a_w of the mixture, they will retain different amounts of water in keeping with their individual water sorption isotherms and texture. This principal is employed in producing complex mixtures.

Rockland and Nishi (1980) stated that isotherms appear to be related to different modes of water binding. Their statistical study suggests that local isotherms do not always give a precise and unequivocal definition of the state of water in heterogeneous mixed-component systems. Linko *et al.* (1981) have discussed the additive model of water absorption by calculating the adsorption isotherm of skim milk powder and its components. They obtained good agreement between adsorption isotherms of skim milk powder and those of various binary and ternary mixtures. Casein appeared to be the main adsorber of water at $a_w < 0.2$. In the range of 0.2 to 0.6, the sorption behavior of dried milk products was dominated by the physical state of lactose. At $a_w > 0.6$, the salts present in the milk powder had the major influence on water adsorption. Van der Riet (1976b) utilized sorption isotherms to predict the critical moisture content for storage of biltong.

Aguilera and Stanley (1990) concluded that at high-moisture contents an aqueous environment prevails and many components, in particular salts and low molecular weight sugars, exist in solution. The undissolved components are high molecular weight materials, such as proteins, and form the structural matrix of the food, which contains the aqueous phase. Liquid water itself has a stable structure due to hydrogen bonding that is perturbed every time a solute is introduced. The same authors stated that water activity for actual solutes in a high-moisture range can be estimated by Raoult's law. They further concluded that high molecular weight polymers, such as proteins, may immobilize large quantities of water in three-dimensional structures called gels. Sorption isotherms for gels extend over the whole range of a_ws. The contribution of gels to food microstructure and their depression of water activity deserve further research aimed at fabricating shelf stable products. Finally it was stated by these researchers that a_w depression by capillary effects in a food is complicated by difficulties in determining pore size, swelling of the matrix during sorption, and lack of information about the actual radius of curvature of the meniscus. Additional work is needed to demonstrate and quantify the capillarity effects of a_w in foods.

D. SORPTION PHENOMENA IN MEAT SYSTEMS

IM meats are multicomponent systems as explained earlier by Chang *et al.* (1991). The isotherms of the meat or meat mixture are a relationship of averaged moisture content and the common water activity. In such systems, each component has a common water activity. However, each component may have a different moisture content. The added soluble solids will increase the average moisture content of the IM meat mixture within the specific water activity range of 0.60–0.90 as shown by Chang *et al.* (1991). Indeed, the soluble solids in the amorphous state adsorb more water than that of the muscle solids within a water activity range of IM meats. In production of IM meats, in addition to selecting raw muscle with good sorption properties, one should try to modify the shape of the isotherm in the meat by formulation (adding sugar and/or salt). Added sugar and salt change the sorption phenomena of the meat solids by addition of these nonmeat ingredients. Thus, in the range of a_w 0.60–0.90, which is equivalent to an open storage relative humidity of 60–90%, the meat mixture will have a higher moisture content than that of the muscle alone. The purpose can be achieved by manipulation of the involved solids through selection of the proper components and composition and by altering the structure of the solid matrix, such as developing a gel or capillary structure.

E. INFLUENCE OF MUSCLE PROTEIN DENATURATION ON SORPTION ISOTHERMS

Water holding capacity refers to the potential of the meat solids to bind the water in a high-moisture range as explained by Hamm (1960). Muscle with a high water holding capacity will have good water adsorption properties at a moderate to low-moisture range. Consequently, raw muscle with less protein denaturation is preferred for IM meat formulations. Raw muscle with good water adsorption properties will improve the textural properties of IM meats within the specific a_w range (Chang *et al.*, 1991). Water sorption in relation to texture will be discussed further later herein.

IX. MECHANISMS INVOLVED IN MEAT DEHYDRATION SYSTEMS

A. MOISTURE REMOVAL DURING IM MEAT PROCESSING

Van Arsdel (1963) and Keey (1972) have explained that dehydration is a process of moisture removal from a solid by thermal means. This definition distinguishes drying from mechanical methods of moisture removal from solids, but does not fully differentiate between drying and evaporation in which heat is used to evaporate large amounts of water from solutions or slurries.

Predrying osmotic treatment of meat causes shrinkage of muscle fibers as outlined by Offer and Trinick (1983) and Offer and Knight (1988a,b). They stated that shrinkage of the fibers leads to a greater proportion of loosely held water in the extracellular space. Mechanical pressing of the muscle separates the loosely held liquid from the solids. The pressing operation removes most of the moisture from the muscle. However, some solids are lost in the expressed liquid. The predrying heating of muscle decreases its water holding capacity. The cooked muscle exudate in combination with the muscle per se can further be heated and boiled to "dryness," with the leached solids being reabsorbed. The "cooked-dry" boiling process also removes most of the moisture from the meat but without solid losses. The predried meats or meat mixtures are generally further dried by thermal dehydration (Chang *et al.*, 1991).

Weight losses during the heating process are caused through exudative and/or evaporative moisture losses. Prevention of the cooking loss is a major concern in heat processing of meat. In meat dehydration, however, the weight lost by evaporation must be effectively achieved, but solid losses should be avoided (Sebranek, 1988).

Chang *et al.* (1991) have studied the dehydration process in relation to IM meats. They stated that if the unbound moisture in meats is defined as that which exerts water vapor pressure like that of pure water, all unbound moisture must evaporate before equilibrium can be achieved with air that is less than saturated. In other words, the water will evaporate until the water vapor pressure of the meat is equal to the partial water vapor pressure in the air. Data on the equilibrium moisture content–relative humidity (i.e., isotherms) of meat or meat mixtures are needed over a wide range of temperatures for dehydration applications. For example, isotherms for meat/meat mixtures below ambient temperature are needed for salami and raw ham, and isotherms above steam temperatures are needed for high-temperature finished dried IM meats (Chang *et al.*, 1991).

Dehydration is basically a simultaneous heat and mass transfer operation as explained by Van Arsdel (1963). In applications where rates of drying are low, such as in IM meats, consideration of heat transfer alone is a quite satisfactory approach, and often a preferred one. However, in order to obtain a true understanding of drying and to develop a sound fundamental theory, one must better understand the mass transfer process, both internally and externally (Lubuza, 1976). In addition, one must develop a better understanding of the forces that bind liquids to solids and control their movement (Aguilera and Stanley, 1990).

Most thermal dryers embody convective heating as the drying condition and can be readily controlled by the temperature and humidity of the (warm) air that evaporates and removes the moisture (Keey, 1972; Chang *et al.*, 1991). Air dryers for handling solid materials are by far the most common type of equipment. Thus, the discussion that follows is devoted to air drying. Potter (1986) stated that in a strict sense dehydration refers to the nearly complete removal of water from foods under controlled conditions that causes minimum or ideally no other changes in their properties. In the dehydration process, the technological challenge is especially difficult, since very low moisture levels are required to obtain maximum product quality, but are not easily obtained with a minimum change in the foods per se. Further, optimization of quality frequently can be attained only at the expense of increased drying costs as stated by Potter (1986). Since IM meats are produced by removing only part of the water, the increased costs of drying may not apply to these products (Chang *et al.*, 1991).

Controlled studies on dehydration by Watson and Harper (1987) have demonstrated that both the temperature and humidity change as the air moves past the moist material. Thus, the moisture content of the solids varies from one point to another in the dryer. This means that the operation cannot be analyzed easily to provide the drying characteristics of the material itself.

Constant control in batch drying experiments is better suited for this purpose and more generally provides a better understanding of the mechanisms involved in the drying process (Chang *et al.*, 1991). The concept of a constant rate of drying period followed by one or more falling rate periods, with sharp discontinuities in a rate at critical moisture contents, is firmly entrenched in the literature and may be regarded as constituting the classical theory of drying (Keey, 1972; Watson and Harper, 1987).

B. DRYING RATE CURVES FOR HEATED MUSCLE BUNDLES

Chang *et al.* (1991) designed a series of experiments to investigate the structural modifications in cooked muscle bundles during predrying tumbling with regard to possible shifts in moisture removal mechanisms. The drying rate curves in the study were shown to vary in a stepwise fashion, since the muscle bundles had more than one constant rate period (Fig. 1). Muscle bundles tumbled for longer times developed more constant rate periods. This was true even though the greater amount of disintegration could not be seen without magnification of the sample.

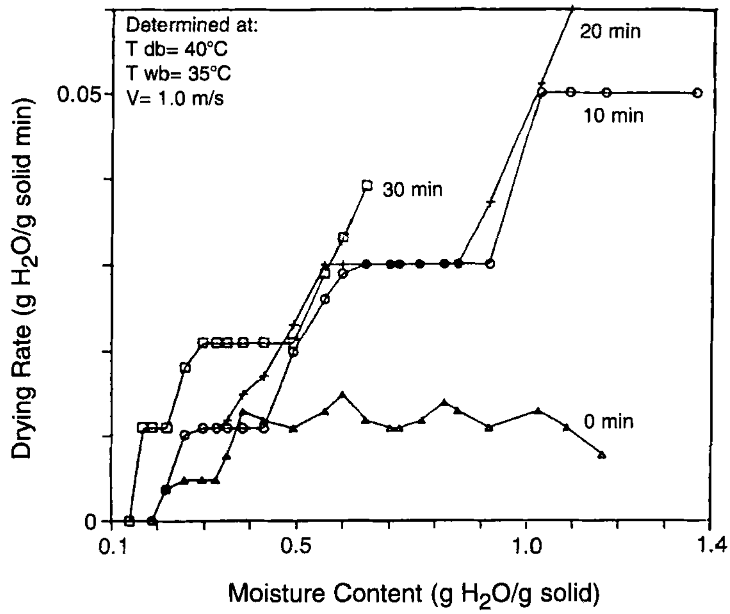

FIG. 1. Drying rate curve for heated pork muscle bundle. Drying rate curves were determined at a dry bulb temperature (T_{db}) of 40°C, a wet bulb temperature (T_{wb}) of 35°C, and an air velocity (V) of 1.0 m/sec. The specified time in minutes for each curve (0, 10, 20, and 30 min) represents the tumbling time for the heated muscle bundles before the determination. Source: Chang *et al.* (1991). Reprinted with kind permission from Elsevier Science Ltd.

The reappearance of each constant rate period followed each transient falling rate period. Among the treatments, the drying rate varied with length of tumbling, with those bundles tumbled longer having a faster drying rate than those tumbled for a shorter period of time at the same moisture content (Fig. 1). The samples dried without tumbling (0 min) became hard and dry, whereas samples tumbled for 10–30 min were soft and porous in texture.

Predrying tumbling was shown by Chang *et al.* (1991) to play an important role by modifying the structure of the muscle bundles. The tumbling-created shear force overcomes the adhesion of the heated connective tissue. The loosened muscle structure modified by the previous heating and tumbling is intensified by the stress caused by connective tissue shrinkage, which separate it from the elements of the bundle and further aids in fiber dehydration. During development of separation, there is an instant increase in the internal free surface vaporization, which is considered to contribute to the reappearance of the constant drying rate period that follows each transient falling rate period as shown in Fig. 1. This contributes to an increase in the drying rate of the tumbled muscle bundles. Otherwise, the drying rate will fall continuously, giving the bundles a hard and compact texture similar to the heated untumbled muscle bundles. Norback (1980) has summarized some techniques that may be utilized in optimizing the drying process.

The stepwise drying rate curves obtained by Chang *et al.* (1991) are quite different from those for so-called "structureless" material. Conventional drying curves generally consist of one constant rate period with one or two consecutive falling rate periods. The stepwise curves obtained by Chang *et al.* (1991) can be explained in term of specific changes due to modification of muscle structure that occur during predrying heating and tumbling and in the subsequent effects of those developed during the drying process per se. The key explanation is that heating and tumbling intensifies formation of a "capillary-like" structures in the supporting connective tissues, which are partially solubilized during heating. Some of the capillary-like structures formed in connective tissues may then gradually contribute to a more open structure as the drying process progresses. The changes during the constant rate of drying period mean that more vaporization of unbound moisture is occurring at the free and open internal surfaces, which correspond to openings in the bundles/fibers surface during the complex effect of heating, tumbling, and drying. Muscle bundles tumbled for longer times developed more constant rate periods because their internal structure disintegrated more than those subjected to shorter tumbling times (Chang *et al.*, 1991).

Drying rate curves for cooked muscle bundles implies that the classical fundamental studies on drying properties and mechanisms under constant external drying conditions are empirical in nature. This is shown in the specific study of controlled muscle bundle dehydration, which indicated that for intact tissue the embedded capillaries may become more open and thus create internal free vaporization surfaces as demonstrated in studies by Chang *et al.* (1991). Internal free surface vaporization operating during unbound moisture removal resulted in identification of the mechanism and is reflected in the reappearance of the constant drying rate periods (Fig. 1) and the multiple critical points and by the porous texture of the product.

These studies by Chang *et al.* (1991) showed that during muscle dehydration, the shifting of the drying mechanisms and drying properties are always possible if the pretreatment and/or drying conditions are varied, which can cause structural modifications in the muscle. If the embedded connective tissue network is intact, capillary movement and external surface vaporization become the major mechanisms for moisture removal. On the other hand, if the connective tissue network is open, below surface and free vaporization become the major mechanisms involved. With meat mixtures of a complex structure, the relative importance of each mechanism depends on the specific structure of the meat and the manipulative changes that occur in the process. If below surface free vaporization of unbound water is involved, the apparent moisture diffusion path decreases since the drying rate increases sharply (Chang *et al.,* 1991).

C. PHYSICAL AND STRUCTURAL CHANGES IN IM MEATS

Loss of water from both raw and precooked meat is accompanied by a decrease in the space between groups of muscle fibers and between the individual fibers and by a progressive reduction in muscle fiber diameter as explained by Wang *et al.* (1953). The rate of moisture removal and of muscle fiber shrinkage is more rapid with heated than with raw meat and proceeds further. Jason (1958) studied the falling-rate period during drying of cod muscle. Although he did not observe the capillary or porous structure, a "continuous gel structure" was seen, which behaved almost as an isotropic medium. He concluded that the main mechanism of water removal was molecular diffusion in a solid medium. The capillary channels were closed after the capillary movement of the moisture was complete. Whether other mechanisms functioned during the altered stages of drying depended on the state of the modified connective tissue, i.e., if it had been torn or solubilized during rigor development or precooking, respectively.

In summary, drying rate data do not ordinarily provide sufficient information to distinguish the mechanisms involved in moisture removal. Further, the mechanisms will usually change as drying proceeds. Drying rate data have been analyzed mathematically on the basis of particular mechanisms for moisture movement through the solid. The complex nature of the moisture movement process, however, makes it impossible to attach any fundamental significance to rate constants obtained from such analysis. The fact that experimental data do not conflict with a theory does not prove its validity.

Essentially all moisture movement mechanisms may lead to the same general form of drying rate curves. Drying rate constants can be looked upon only as empirical expressions of the rate of moisture loss during dehydration. Because of the empirical nature of the constants, data must be obtained over a much wider range of variables than would be necessary if there were a dependable theory. The moisture content at the dividing point between the constant and falling rate periods on the drying rate curve is commonly called the critical moisture content. However, critical moisture content is not entirely a property of the material, but depends on the manner of loading on the bed and on drying conditions (Chang *et al.,* 1991). The stepwise drying rate curve of the tumbled cooked muscle bundles as discussed by Chang *et al.* (1991) further proves the above statement (Fig. 1). Indeed, reappearance of the constant rate period makes it impossible to approximate the critical moisture content. Limited knowledge on the critical moisture content restricts its application in prediction of drying rates during the falling rate period. However, the real value of the more fundamental approach is that once it is related to practice through actual large scale experiments, it provides a basis for determining the effects of variation in operating conditions and to establish optimum drying schedules without the necessity of extended experimental programs for each individual situation.

D. DEHYDRATION PARAMETERS AND PROFILES IN RELATION TO PHYSICAL CHANGES DURING DEHYDRATION OF IM MEATS

One main reason for the difficulty in developing a broad fundamental theory for drying is due to the fact that many foods and other solid materials are dried. Differences in the structure and the chemical composition of various foods and other solid materials make it difficult to develop a sound theory of drying based on internal moisture flow that would be applicable to all materials. The drying theories that have been developed over the years have originated from two points of view as explained by Keey (1972): (1) the effects of the internal mechanisms of liquid flow within a product include (a) air temperature, (b) humidity, (c) air velocity, (d) agitation of the solid material, (e) method of supporting the solid material, and (f) contact between the hot surface and wet solid. (2) The external theory of drying considers the effects of external variables to be more useful in correlation of operational data and equipment design than the internal theory. Internal mechanisms of liquid flow are a function of its solid structure. The internal mechanism of drying may be more fundamental and provides a better insight on how a solid dries than the external variables, which may be more useful for design purposes (Keey, 1972).

Factors affecting heat and mass transfer, such as temperature, humidity, and air velocity, are relatively easy to control and largely determine dryer design (Keey, 1972). Far more subtle are the properties of food materials that affect heat and mass transfer and that may change during dehydration. Dehydration profile (time–product temperature–moisture content/a_w) of a material can be discussed mainly in terms of air conditions (dry bulb temperature, air velocity, and wet bulb temperature/relative humidity) and relative efficiency of heat transfer vs mass transfer of the material to the surrounding air as explained by Sebranek (1988) and Chang *et al.* (1991). The difference between dry bulb and wet bulb temperatures or product temperature is an index for the driving force of heat on the material and the potential for dehumidification or vaporization of water from the raw material. If heat transfer efficiency is greater than mass transfer efficiency, less moisture is evaporated. On the contrary, if mass transfer efficiency is greater than heat transfer efficiency, the product cools with greater evaporation of moisture. If heat and mass transfer efficiency are in balance, the product is at the medium temperature and suffers a moderate moisture loss. Indeed, product temperature, which fluctuates between the dry and wet bulb temperature of the air, depends on the instantaneous relative efficiency of heat vs mass transfer in the dehydration system (Sebranek, 1988; Chang: *et al.*, 1991).

E. DEHYDRATION IN PRODUCTION OF IM MEATS

Discussion will focus on meat dehydration based on information that is derived from heat processing of meat in which dehydration is not the major concern, but is a necessary step in its preparation, i.e., cooking of raw meat. However, the partial surface drying that occurs in cooking of meat is similar to that involved in dehydration. Sebranek (1988) has discussed heat processing of meat as it applies to both fresh and cured pork. In addition to heat transfer and diffusion considerations in processing of meat cuts, heating rates are influenced by mass diffusion and mass transfer characteristics. These are a result of water release by meat proteins, diffusion of the water through the product and evaporation (or drip) loss from the surface. The primary effect of mass transfer on the heat process is the evaporative çooling that occurs at the product surface during the phase change of liquid to water vapor. Since the phase change alone absorbs 1000 BTU per pound of water evaporated, when surface evaporation occurs considerable energy is used without any increase in product temperature (Sebranek, 1988). Consequently, methods of heating that minimize evaporative cooling result in more efficient transfer of energy to the product. One implication of this is that the humidity of the air during heat processing (or in dehydration) is an important factor that affects heating (or drying) rate efficiency to a greater extent than air temperature. However, relative comparisons between heating methods in terms of permitting or limiting evaporative cooling are dramatic. For products heated in various situations involving air, relative humidity becomes a major consideration since evaporation of water from the product will continue during heating until the partial water vapor pressure in the air equals that of the product. Thus, heat transferred, in the case of air heating, is dependent not only on temperature differential (air velocity and product thermal conductivity) but also upon the moisture content of the air (Sebranek, 1988).

Complete convective heating without moisture loss by evaporation is rarely encountered in processed meat products. Accordingly, heat processing of meat in a convective air stream can be considered as a specific case of dehydration. For example, the drying phenomena in comminuted meat products heated in air and the concomitant heating and drying effects best can be observed in meat gels. Mittal and Blaisdell (1983) evaluated the moisture mobility in frankfurter emulsions during cooking. Since they did not observe any water removal rates, they concluded that internal moisture movement was the controlling factor in moisture losses. They suggested that the bulk of unbound moisture is fixed in the gel matrix, thus, bulk flow of moisture could not contribute to a constant rate period.

Evaluation of the effects of relative humidity at 69°C by Mittal and Blaisdell (1983) showed variable results. As relative humidity was increased from 41 to 60%, moisture losses increased. As relative humidity increased further to 87%, the moisture loss was reduced. The low relative humidity probably permitted excessive surface drying and skin formation or case hardening in the frankfurters, thus limiting further removal of moisture. Higher relative humidities permitted a balance between heat transfer and evaporative cooling, thus reducing moisture losses. Steep moisture gradients were present within the frankfurters during heating in the air, with virtually no moisture removal from the center. Thus, the authors concluded that even though muscle proteins may release water at around 50°C, low moisture diffusivity in the frankfurters will not allow the water to migrate to the product surface. Among physical stabilization factors in meat mixtures, the heat-set protein gel matrix is generally recognized as the predominant factor controlling water retention. Gelation of meat proteins during heating takes place to some degree in all products. It first involves unfolding, then the interlinking of muscle proteins (or even possibly nonmeat proteins if included) to form a three-dimensional continuous network (Offer and Knight, 1988a). This network is effective in trapping and stabilizing water in the mixture. During extended dehydration, the heated gel will shrink severely, resulting in a very tough texture.

F. FERMENTED IM MEATS

Fermentation lowers the pH toward the isoelectric point of the meat proteins (Bacus, 1986), which assists in the removal of water from fermented sausages. Carbohydrates are added to provide food for the bacteria, and thus, accelerate fermentation. Acton *et al.* (1977) have discussed utilization of various carbohydrates and their role in the fermentation process.

Fermentation and simultaneous dehydration of meat products is one of several basic processing steps (Campbell-Platt and Cook, 1995). However, few meat products are dehydrated as a separate process. In many processed meat products having a reduced moisture content, drying occurs simultaneously with ripening. Ripening occurs under controlled dehydration conditions as explained by Romans *et al.* (1985). This process involves keeping the manufactured products for varying time periods under controlled temperature and humidity conditions. The length of the ripening period for different products varies from a few days to several months. The actual fermentation process requires specific environmental conditions for optimal product quality and has been described in reviews by Incze (1991, 1992). Larger dry sausage processors typically use a greening room to hold the product during fermentation. This room can be carefully controlled for temperature, humidity, and air velocity. Dry sausage is typically fermented at 20–25°C and 75–80% relative humidity with slow steady movement of air until the desired pH is attained (usually 1 to 3 days). The final pH of fermented sausages typically ranges from about 4.8 to 5.4, depending on the tanginess desired and the individual product.

Carefully controlled environmental conditions are also critical during the drying process as explained by Bacus (1986). If the product dries too fast, a problem known as "case hardening" occurs. Case hardening refers to a condition in which the outside of the sausage becomes hard and dry, inhibiting further moisture migration from the interior of the sausage that still has a high moisture content. Sausages that have undergone case hardening are prone to internal spoilage by anaerobic bacteria. Case hardening is caused by the humidity being too low during drying. On the other hand, excessive humidity causes the product to dry too slowly and will often result in excessive mold or yeast growth and bacterial surface slime on the product surface. Theoretically, the drying rate at the surface of the sausage should be slightly greater than that required to remove the moisture which migrates from the inside of the sausage. Good drying conditions are achieved by various combinations of temperature, humidity, and air velocity. There is little agreement as the the most effective combination of these three variables. As a general recommendation, the temperature of the drying room should be maintained between 15 and 18°C at a relative humidity of 70–72%. Air velocity in the room should be between 15 and 25 air changes per hour.

According to Demeyer *et al.* (1986) a large amount of water is retained within the three-dimensional protein network of manufactured sausage batters. The water has two functions: (1) as a hydration layer it separates the coherent protein aggregates and (2) it constitutes a link between the protein threads via the hydrogen bonds. The firmness of the coagulated batter is still rather unstable and is weakened by the intermediate layer of water molecules. The coagulated structure of the batter is still capable of flowing and is flexible. Final firmness of the coagulated batter, however, can only be achieved by release of the immobilized water molecules that occupy the spaces between the protein aggregates. Fermentation and dehydration are thus essential prerequisites for firmness in the sausage batter as explained by Incze (1991, 1992). For continuous dehydration, it is necessary that at the onset of dehydration conditions in the ripening chamber be properly adjusted and controlled, so that the degree of moisture differs only slightly (3 to 5%) between the sausage and air in the chamber (Incze, 1992). At this moisture differential, the sausage continuously loses considerable water. The loss of water is accelerated by an increase in nonprotein nitrogen and free amino acids as fermentation and drying occurs (DeMasi *et al.*, 1990).

Water losses from the interior of the sausage take place in part by diffusion due to the moisture difference between the sausage and the ripening chamber and partially by water lost by capillary moisture movement via slits and gaps as explained by Incze (1992). The formation of slits and gaps results from syneresis, halolytic, and enzymatic processes of decomposition between myofibrils and the larger meat particles, i.e., between the perimysium and endomysium as well as the muscle cells. Therefore, it can be concluded that the initially unstable coagulation bonds of the manufactured batter are gradually converted into firmer condensation bonds by acid denaturation and gradual drying of the sausage, i.e., the viscous protein system is transformed from the sol state into the colloidal viscous gel state (Demeyer *et al.*, 1986; Incze, 1992). Indeed, water losses are achieved both in manufacturing and in the ripening–dehydration of the meat batter of fermented sausages.

Many different chemical compounds have been identified as contributors to meat flavor by MacLeod (1986). Lipolysis and protein breakdown are responsible for development of flavor in fermented sausages and hams according to Demeyer *et al.* (1979a,b, 1986) and Verplaetse (1994). This is supported by results obtained by Dominguez-Fernandez and Zumalacarreui-Rodriguez (1991) during ripening of chorizos and by Lopez *et al.* (1992) for the hams from Iberian pigs, in which the diet of the pigs was shown to have a marked effect. However, the particular compounds responsible for the specific flavors have not been identified. Drying, no doubt, is responsible for the concentration of the compounds.

G. DEHYDRATION BY HEATED OSMOSIS/INFUSION OF IM MEATS

Many drying techniques or treatments given to a food before drying are aimed at making the structure more porous so as to facilitate potential mass transfer and thereby speed up the drying rate (Demeyer *et al.*, 1986). However, porous structures are excellent insulating bodies and will slow down the rate of heat transfer into the food. The net result depends on whether the change in porosity has a marked effect on the rate of mass

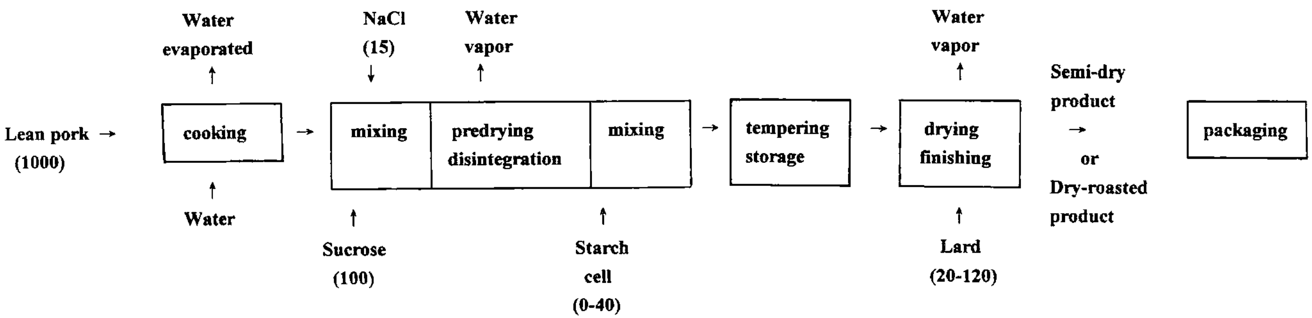

FIG. 2. Flow diagram showing the successive steps (processes) involved in production of Zousoon. The numbers in parentheses are given as weight ratio relative to raw meat = 1000. The starch cell preparation may be varied from 0 to 40 (weight ratio) and has a proximate composition of 22.4% protein, 68.0% carbohydrate, 1.9% fat, 0.8% ash, and 7.5% moisture. Source: Chang *et al.* (1991). Reprinted with kind permission from Elsevier Science Ltd.

transfer or heat transfer in the particular food material and drying system. A new direct dehydration method for producing Zousoon improves both heat and mass transfer efficiency throughout the process and uses the benefits of the readily controllable direct drying system as outlined by Chang *et al.* Figure 2 shows a flow diagram for production of Zousoon. In the traditional method, indirect heating is applied in the drying process, which results in specific structure problems as a result of an inadequate porous muscle system and poor time–temperature control of the product.

The muscle is subjected to heating–osmosis, i.e., infusion, and boiled dry prior to dehydration as described by Chang *et al.* (1991). The compositional and structural properties of the muscle have been modified and most of the moisture in the muscle is removed during the predrying treatment. Chang *et al.* (1991) have discussed in some detail the possible moisture removal mechanisms of the heated meat mixture and described the design and operation profile developed to achieve balanced disintegration and drying of cooked muscle fiber bundles in a rotary dryer. The dryer was equipped with concave baffles to achieve greater shear force on the muscle bundle during tumbling in the dryer. The profile makes use of intermittent drying and tempering operations.

In the process described by Chang *et al.* (1991) the heating (drying) cycles operated at 0–40, 80–120, and 160–200 min at a temperature of 70°C with complete exhaustion of the air. During each period of heating, the moisture was removed along with the exhausted air, which decreased the moisture content of the muscle bundles. At the same time, the dry bulb temperature was increasing with a corresponding decrease in relative humidity. The tempering cycles were operated from 40 to 80 and from 120 to 160 min at a temperature setting of 35°C, with complete recirculation of the air but without exhausting it. During the tempering cycles, the moisture content of the muscle bundles was relatively constant since no moisture was removed by the air. At the same time, the dry bulb temperature of the air was decreasing and was accompanied by a corresponding increase in relative humidity. The tempering cycles were designed to minimize the moisture gradient within the muscle in order to prevent case hardening, which can result from excessive local surface drying while the interior moisture content is still high. The intermittent operation of the heating (drying) and tempering cycles helped to achieve a balance between drying and disintegration of the muscle bundles.

Superheated steam drying–finishing of the predried muscle bundles makes use of the potential drying properties of steam at temperatures above 100°C as explained by Chang *et al.* (1991). However, the relative humidity at the steam temperature range is rather higher than that of the ambient air heated to the same temperature. Thus, superheated steam drying–finishing achieved a greater drying effect than dry air could have done at the same temperature. The application of superheated steam in the finishing process was designed to achieve a controllable browning effect, which is characteristic and needed for the flavor and color of the product (Huang *et al.,* 1989), but which cannot be fully controlled in the traditional indirect drying–finishing method (Chang *et al.,* 1991). Overall results from the studies by Chang *et al.* (1991) indicate that finishing Zousoon with steam heat is a viable procedure, with the best color and consistency being achieved by using steam at a temperature of 150°C for 7 min. It may be possible to further refine the time and temperature for finishing Zousoon by controlling steam injection, temperature, steam velocity, and relative humidity during processing.

Figure 3, which is taken from the research of Chang *et al.* (1991), shows a schematic diagram of a proposed mechanism by which muscle bundles disintegrate and form the fibrous characteristics that is typical of Zousoon at the end of the drying process. As indicated in the diagram tumbling creates a shear force, which causes disintegration of the muscle bundles as the heat is absorbed and the water evaporates. The combined forces cause the bundles to be separated into their component fibers, which on further drying and disintegration and final drying–finishing form the long fibrous Zousoon. The finished product is a light yellowish–brown in color and has a fibrous appearance, although some bundles persist due to the collagenous fibers holding small units together. The drying and disintegration processes should take place simultaneously and be balanced in order to achieve optimum drying–disintegration.

H. MORPHOLOGICAL CHANGES IN MUSCLE BUNDLES DURING HEATING–DRYING

Figure 4, which also comes from studies by Chang *et al.* (1991), illustrates the morphological changes that occur in the appearance of the muscle fiber bundles during balanced disintegration–drying in a convective heated rotary dryer. Figure 4A shows a bundle of fibers after removal from the boiling water and demonstrates that the fibers are bound together in a compact bundle. Figure 4B and 4C illustrates how the bundle size is gradually reduced by the effects of heating and tumbling during the early stage of predrying in the modified clothes dryer. Figures 4D, 4E, and 4F show how the apparent bundle size is expanded with the endomysial capillary moisture being removed. Figure 4F shows the texture of the muscle bundle as it becomes more loosened. The residual osmotic-held sarcoplasmic moisture may diffuse to the fiber surface and evaporate in the final stages of predrying. Each successive stage of convective heating in the predryer and

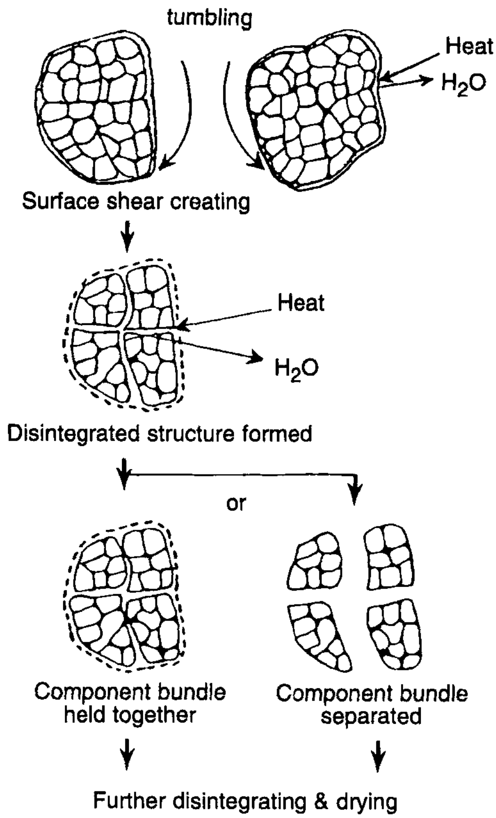

FIG. 3. Proposed mechanism for muscle bundle disintegration during tumbling and drying. Simultaneous application of tumbling and heat creates shear forces and drives off moisture causing the muscles to separate into smaller bundles. Source: Chang *et al.* (1991). Reprinted with kind permission from Elsevier Science Ltd.

dryer–finisher results in greater separation of the large bundles into smaller bundles to achieve a proper (optimum) size bundle, which has a coarse hair-like exterior. The fibers still retain their identity as bundles due to the presence of some residual connective tissue (Chang *et al.*, 1991).

X. QUALITY ATTRIBUTES AS AFFECTED BY DEHYDRATION AND ITS ASSOCIATED PROCESSES

Quality attributes on IM meats are mainly affected by a_w, temperature, and the state of other crystalline components (i.e., sugars and other carbohy-

FIG. 4. Photographs showing normal pork muscle fibers during different predrying steps in production of Zousoon. (A) Muscle fibers following cooking before predrying. Note how fibers are held together in compact bundles. (B) and (C) show muscle fibers as they separate into smaller bundles during early predrying process. (D) and (E) show fibers as they progressively expand as drying continues. (F) shows Zousoon following predrying operation. Note the loosened fibers being held together by connective tissue. Source: Chang *et al.* (1991). Reproduced with kind permission from Elsevier Science Ltd.

drates). Troller and Christian (1978) and Troller (1972, 1980) have pointed out that development of microbiology during the 18th and 19th centuries led to recognition that addition of salt, sugar, and dehydration was merely a way of preserving food through delaying or preventing microbial growth. The influence of such processes on other characteristics of foods, such as nonenzymatic browning, oxidative rancidity, flavor, texture, and nutritional quality, was only recognized and understood much later (Troller, 1987; Chang *et al.*, 1991).

Specific changes in color, aroma, flavor, texture, stability, and acceptability of raw and processed food products have been associated with relatively narrow a_w ranges (Huang *et al.*, 1989; Chang *et al.*, 1991). The a_w may have direct uncomplicated effects upon various chemical reactions (Labuza, 1980), enzymatic reactions (Schwimmer 1980), and the proliferation of microorganisms (Troller, 1972, 1980; Troller and Christian, 1978).

A. a_w AS AN IMPORTANT PARAMETER

Rockland and Nishi (1980) have explained that the a_w theory involves the basic premise that independent and interdependent reactivities of individual chemical moieties are related to the aqueous molecular environment surrounding the reactive materials which affect the properties of natural products. Within heterogeneous systems, i.e., food products, the reactivity of each constituent is influenced by its affinity for water molecules and the competing influences of neighboring hydrophilic or hydrophobic chemical groups. Therefore, the structural–chemical architecture of the system is influenced by these forces. Changes in the environment–heat treatment, pH, modification of partical size, light, and pressure may alter the molecular state of the water and thereby influence the constituent reactivities and their functional properties. In more general terms, the properties of a system are influenced by the water binding energies of specific molecules and interactions among hydrophilic chemical constituents. The total binding energies of constituent chemical groups are reflected in the equilibrium water vapor pressure. At constant temperature, the vapor pressure may be expressed as equilibrium relative humidity, i.e., a_w.

It is clear that for some heterogeneous food systems, at least two a_w optima exist, as indicated in the uppermost curve shown in Fig. 5, which is taken from Rockland and Nishi (1980). This curve represents the relationship between a_w and the integrated resultant relative stability based on the summation of a series of independent and/or interdependent chemical reactions, which are characterized diagrammatically in the figure. This figure presents an updated diagrammatic summary of a_w and its major effects upon some chemical, enzymatic, and microbiological properties of foods.

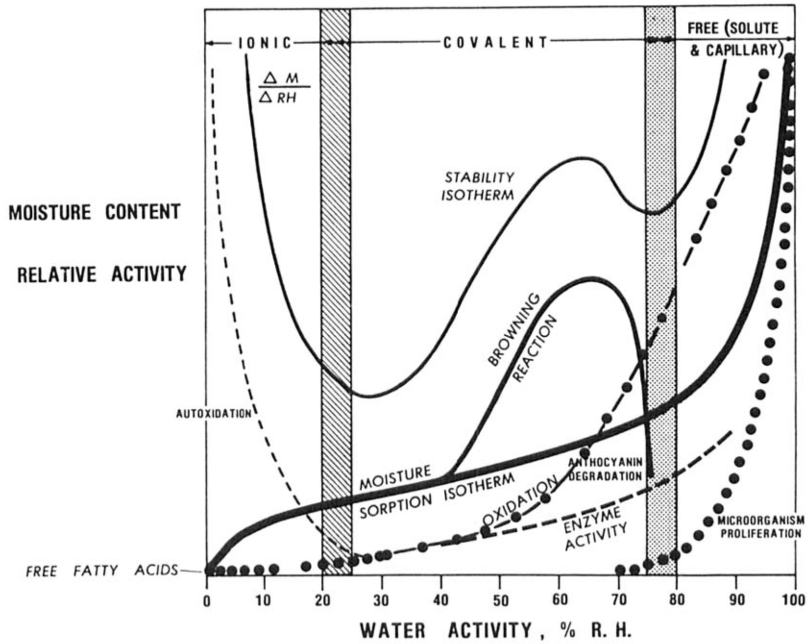

FIG. 5. Diagrammatic representations of the influence of water activity upon some chemical, enzymatic, and microbiological changes and on overall stability and moisture sorption properties of food products. Source: Rockland and Nishi (1980).

Aguilera and Stanley (1990) pointed out that the term water activity as defined is valid only at equilibrium. Since equilibrium may not prevail in many processes or even during storage of foods, they pointed out that the concept of water activity has to be used cautiously.

B. INFLUENCE OF NONTHERMODYNAMIC FACTORS ON QUALITY OF IM FOODS

Recently Gould (1989b) has suggested that the mobility or the diffusivity of molecules in foods, or the intrinsic viscosity, may be more useful than a_w or equilibrium relative humidity as a meaningful determinant of biological and chemical activity. Extreme cases, such as glass transition formation, may raise viscosity by many orders of magnitude (Slade and Levine, 1987) so that for practical purposes biochemical and chemical changes are arrested. More accurately, such changes are greatly slowed down so as to be irrelevant over a normal time scale. However, such systems are metastable and therefore, are not at equilibrium, so they are not defined by equilibrium concepts like thermodynamic water activity. Slade and Levine (1991) proposed that the potential for microbiological activity in partially dried or intermediate moisture foods could also be estimated through a knowledge of the distance (in terms of moisture content or temperature of a particular food or component) from the glass transition point. However, more work needs to be carried out before the potential value of such new correlations can be judged.

Removal of water by evaporation results in formation of an amorphous state according to Vuataz (1988) and Roos and Karel (1991a,b, 1992). Amorphous foods are produced from carbohydrates by rapid cooling. The most important change that is characteristic of the amorphous state is noticed at the glass transition temperature (Tg), which involves transition from a solid "glassy" to a liquid-like "rubbery" state. Some diffusion-limited deteriorative reactions are controlled by the physical state in the vicinity of Tg. The "state diagram" shows the physical state is a function of temperature and concentration and illustrates the roles of relevant water content, temperature, and the time-dependent phenomena on the amorphous food components according to Roos and Karel (1991a,b, 1992). The viscosity at the glass transition temperature is about 10–11 Pa·sec or about 10–14 cP and it decreases above Tg. The most dramatic changes occur within a fairly narrow temperature range above Tg. At the temperature range of Tg to Tg + 100°C, various time-dependent physical phenomena become evident, for example, stickiness, collapse, and crystallization. Roos and Karel (1991a) found that the widely used "sticky point" was governed by Tg. The critical viscosity for stickiness of about 10.7 Pa·sec correlates with the viscosity at the end point of glass transition. Materials, such as fruit juices with high amount of monosaccharides (e.g., fructose), exhibit low Tg values and a low sticky point. Isoviscosity lines can be used to show critical viscosities for stickiness and the time needed to a given degree of crystallization or collapse, which may be used as a quantitative prediction of stability. Crystallization in the glass state below Tg is kinetically inhibited. It is initiated concurrently with structural changes above Tg, showing an increasing rate with increasing $T-$Tg.

Crystallization can be accounted for by the moisture dependence of Tg according to Roos and Karel (1991b). Crystallization releases water, which in closed containers is absorbed by the amorphous portion of the food. As a result when Tg drops, $T-$Tg increases and rapid crystallization follows. Products, which have high moisture transfer rates in the environment, will lose water, but the moisture content in the amorphous part remains fairly constant. Crystallization proceeds at a rate defined by a constant $T-$Tg. Crystallization leads to a complete change in physical structure. It may considerably decrease stability. Lactose crystallization in milk powders leads to an increase in free fat and concomitant flavor deterioration as explained by Roos and Karel (1992). They found that the increase in water activity caused by crystallization also increased the browning rate and loss of lysine in whey powder. Crystallization also resulted in complete release of any encapsulated compounds. Thus, volatiles are lost and lipids become exposed to oxygen. State diagrams showing the relationships between product composition and its physical state provide means for formulation or reformulation of food products to meet processing requirements and product stability during storage. State diagrams may also be used to design processes, equipment, packaging, and storage conditions that meet product requirements and achieve maximum stability (Roos and Karel, 1991a,b, 1992). It should also be noted that the Tg values of amorphous food components decrease linearly with increasing a_w within the typical range of low and intermediate-moisture foods. Roos (1995) has pointed out that at temperatures about Tg various physical properties of foods, such as molecular mobility and viscosity and collapse (loss of structure) and crispness, are significantly affected.

C. QUALITY ATTRIBUTES OF IM MEATS

Leistner (1987) stated that the most successful applications in development of intermediate-moisture meats have been utilized in production of pet foods. He gave several reasons why novel IM meats for humans have not become more acceptable: (1) newly developed intermediate-moisture meats are often not sufficiently palatable, (2) they are too expensive, (3) they contain too much additives (chemical overloading of the food), and (4) they may pose legal problems with respect to approval of greater amounts of new additives. However, there are many traditional IM meat products, which are highly acceptable in different parts of the world. In Europe meat products in the a_w range 0.60–0.90 are not very common. Yet, traditional meat products, such as raw ham, fermented sausage, and dried beef, are dried sufficiently to reach an $a_w < 0.90$. Traditional meat products in the intermediate-moisture range are frequently found in countries where the climate is hot and refrigeration is expensive or unavailable. For industrialized countries, traditional IM meats found in developing countries are of interest from the standpoint of shelf stability and adding variety to the diet. By studying the principles involved in production of IM meats, processing and shelf life may be improved without impairment to their sensory and nutritive properties. Leistner (1990a) pointed out that for most raw sausages, e.g., Italian or German salami, fermentation by microorganisms, which grow in the interior and also on the surface of some products, is essential for preservation and acceptance. An exception is Chinese raw sausage, which is stabilized by a_w only, since a low pH caused by fermentation would not be acceptable to Chinese consumers (Lin *et al.*, 1983a,b; Kuo and Ockerman, 1985). Similarly, consumers of the Western world object to the sweet taste of Chinese dried meat.

Buckle *et al.* (1988) observed that Indonesian dending has a sweet taste due to its high-sugar content together with the strong flavor of the spices. The sweetness and spices in the dried meat give dending a characteristic flavor, which is highly acceptable to most Asian consumers. Hodge (1953, 1976) stated that the appetizing aroma of fresh bread, coffee, roasting nuts, pralines, and barbecue depend largely on sugar-derived browning products. Although training in food science is not a prerequisite to appreciation of the art of the chef and his masterful control of induced browning reactions, it does require one with some scientific background to determine exactly which compounds contribute to the aroma and flavor of foods and how these sensory perceptions can be improved in less palatable products (Hodge, 1967).

D. CONTROL OF MICROBIAL GROWTH IN IM MEATS

Leistner (1987) and Gould and Christian (1988) concluded that a_w is the most important factor contributing to the storage stability of IM foods. Product a_w in itself does not guarantee the safety of a product after processing, however, since deterioration may have already occurred before treatment. The moisture removal process as well as the associated stabilization operations and/or treatments also may play an important role in controlling microbial quality of meat products.

1. Effects of Temperature

Regardless of the specific mechanism, the osmoregulatory capacity of a particular cell determines to a large extent its osmotolerance in most practical situations. This is because the environmental solutes that are most often present in foods fall into classes that do not readily penetrate the cell membrane and are, therefore, able to effectively plasmolyze the cell (Gould and Christian, 1988). Muscle fibers are more or less subject to the same effect during osmosis treatment or dehydration. Consequently, any measurement that correlates closely with osmolality in a particular substrate will normally give a good indication of the potential for growth and the metabolic activity of particular groups of food spoilage and food poisoning microorganisms. Similarly, such data can be applied to favorable microorganisms utilized in the desired fermentation process. It is for this reason that direct or indirect measurements that allow rapid estimation of water activity or equilibrium relative humidity have found increasing use. Scott (1953, 1957) was the first to propose that as far as effects on the physiology of food spoilage and food poisoning microorganisms were concerned, the thermodynamic water activity (a_w) was a key determinant, independent of the means by which the particular value was obtained. The growth limits for different types of microorganisms have since been commonly described in this way, with the "a_w limits for growth" being quoted for each species or strain below which growth supposedly does not occur (Gould and Christian, 1988). Therefore, like Eh (available oxygen supply), pH values, and temperature, a_w has been increasingly promoted as a practical useful determinant of microbial activity (Scott, 1957; Gould and Christian, 1988).

Troller (1980) concluded that a_w interacts with other stabilization factors, including numerous factors in the environment, to produce additive microbial inhibition. In fact, if one considers the many foods preserved by a_w limitation, combination effects are the rule rather than the exception. While achieving the a_w for IM meat products during the moisture removal process, the specific interaction among the other factors is more important. On the other hand, the interaction of temperature, with such factors as a_w, pH, and chemicals, has been extensively discussed as it applies to thermally processed meats by Leistner (1978, 1987, 1990a) and Sebranek (1988). However, control and inhibition of microbial growth are often manipulated with all possible involved factors independent of the category of the meat product (Leistner, 1990a).

2. *Interaction of Temperature with a_w*

Troller (1980) stated that temperature interacts directly with a_w, which suggests that a higher a_w level will limit growth as the minimal or maximal temperature for growth is approached. In terms of heating lethality, however, a different picture emerges because very low a_w levels are protective as opposed to heating at more elevated a_w levels. In this context, the terms "wet heat" and "dry heat" are used to describe the water vapor concentration existing at the prevailing heating environment (Troller, 1980; Sebranek, 1988). Dry heat is irrelevant at lower a_w values, unless the product is heated–dried to an equilibrium state. Salmonella species are especially heat-resistant in the absence of unbound water (low a_w), particularly if sucrose is added to reduce the a_w (Troller, 1980, 1987). From the viewpoint of preservation, some IM meats are heated before the moisture is removed. That is, heating is applied at a high a_w stage. On the other hand, some products are dehydrated before achieving a high temperature in the final stages, i.e., the heat is applied at low a_w. In addition to the possible different lethality effects, there may be a difference in microbial recontamination by the two processing procedures. In-package pasteurization of some IM meats has been shown to eliminate possible post-process recontamination before packaging (Chuah *et al.*, 1988). Sanitary/aseptic packaging following heat pasteurization, such as "superheat steam flashing," would be expected to be very efficient in microbial control. However, some IM meats are still preserved in the raw state, including Chinese sausage and Indonesian dending, with preconsumption heating being applied to achieve cooking effects before eating (Chow *et al.*, 1989; Chang *et al.*, 1991).

3. *Effects of pH*

Troller (1980, 1987) concluded that as the a_w of a food is lowered, the pH limits within which growth will occur are narrowed. These effects have been described by Ohye and Christian (1967) for *Clostridium perfringens* and by Troller (1972) for *Staphylococcus aureus*. Similar effects occur with yeast and molds.

4. *Influence of Oxygen*

The minimal a_w at which growth will occur is lower under aerobic than anaerobic conditions for facultative organisms. For example, Scott (1953) demonstrated that the minimal a_w at which growth of *S. aureus* occurred was 0.86 under aerobic conditions and 0.92 under anaerobic conditions.

5. *Effect of Chemicals*

The effects of nitrite, nitrate, and potassium sorbate have been determined by Gould and Measures (1977) and by Troller (1980). The role of combined nitrite and low a_w (added NaCl) in preserving meat by inhibiting the growth of *C. botulinum* has been discussed by Gould and Measures (1977), Troller (1980), and Gould and Jones (1989). As a general rule, the minimal a_w for growth of a microorganism is raised as the level of any additional inhibiting factor or substance is increased. Another way of stating this is that if bacterial growth factors are less than ideal, growth inhibition through a_w reduction is increased (Troller and Christian, 1978).

E. OTHER CONSIDERATIONS FOR CONTROLLING MICROBIAL GROWTH IN SOME IM MEATS

1. *Nonheated IM Meats*

Potter (1986) has discussed some nonsterilization aspects of the moisture removal process. Unless heated specifically for sterilization, virtually no quality dehydrated food emerges from a dryer in a sterile condition. While a large proportion of the microbial load may be killed during most drying operations, many bacterial spores are not affected. This becomes still more significant if the dehydration method is designed to be gentle to protect highly delicate foods. The nonsterilizing aspects of food dehydration also apply to certain natural food enzymes that may survive usual drying methods. In some foods, the necessity of retaining latent enzymes for later activation during hydration requires special drying regimens in which microorganisms cease to grow but latent enzymes may nevertheless survive as explained by Schwimmer (1980). In some cases microbial growth can, potentially at least, resume when these products are rehydrated and allowed to remain at room temperatures for prolonged periods. Hence, the microbial status of these products must be vigilantly monitored and reflected in specifications for such items. Microbial and enzyme management should be involved in the empirically estabished pattern which is emerging in the drying of food products. This suggests that in many instances superior product quality attainment is associated with slow removal of water at relatively low temperatures.

Low-temperature–long-time drying has been used for the manufacture of such food products as smoked sausages according to Leistner (1987). Deeper insight and better understanding of the process afforded by fundamental studies with model systems and foods can be utilized to dispel much of the empirical approach currently pervading the processing of intermediate moisture and other low moisture foods. For some products, controlled microbial activity, i.e., fermentation, is achieved during dehydration and associated operations and/or treatments and are referred to as hurdles, which are discussed by Leistner (1987). The sequence of hurdles is intricate in fermented sausages, such as salami. In salami the hurdles occur in a sequence explained by Leistner (1987) and are particularly important at certain ripening stages in order to effectively inhibit food poisoning organisms (salmonella spp., *C. botulinum* and *S. aureus*) as well as other bacteria, yeasts, and molds which cause spoilage. On the other hand, the sequence of hurdles also favors selection for the desired competitive flora (lactic acid bacteria and nonpathogenic staphylococci), which contribute to the flavor and stability of fermented sausages (Leistner, 1987, 1990a).

An important hurdle in the early stage of the ripening process for salami is nitrite, which is added with the curing salts, since addition of 125 mg/kg of sodium nitrite inhibits the growth of salmonella and clostridia as reviewed by Leistner (1987). The nitrite hurdle diminishes during the ripening process, since the nitrite is depleted. Due to the multiplication of bacteria in salami, the redox potential of the product decreases, and this in turn enhances the Eh hurdle, which inhibits the growth of aerobic organisms and favors selection of competitive flora. The growth and metabolic activity of lactic acid bacteria, which then flourish, cause acidification of the product and, thus, an increase in the pH hurdle. This is of particular importance in the microbial stability of rapidly fermented sausages, which are not completely dried. Nitrite, Eh, competitive flora, and pH diminish with time, because in long ripening salami the nitrite level and the count of lactic acid bacteria decrease, while the Eh and pH somewhat increase. Therefore, only the a_w hurdle is strengthened with time, and this hurdle, therefore, is mainly responsible for the stability of long-ripened fermented sausages (Leistner, 1987).

Leistner (1987) also discussed the stability of raw ham, in which it is essential that the initial count of organisms in the interior of the product be low. The pH should be 6.0 or less and the temperature should below 5°C at the beginning of the curing process. The low temperature should be maintained until sufficient salt (i.e., 4.5% NaCl, which corresponds to an a_w below 0.96) has penetrated into all parts of the ham. After the a_w in the interior of the ham has decreased to 0.96 or below, the product can be further ripened and smoked at room temperature in order to achieve the desired flavor associated with enzymatic action.

The microbial stability of traditional Chinese sausage is due mainly to the rapid reduction of a_w according to Leistner (1987). This is aided by the addition of salt and sugar, the thinness of the casing, and a high drying temperature at a low relative humidity. On the other hand, the pH hurdle is not important for stability, because the pH of the raw sausage is relatively high and the number of lactic acid bacteria low. The principle used in the preservation of Chinese sausage, i.e., the quick decrease of a_w, is also of interest, since the product demonstrates that raw sausage may also be successfully processed at 48°C and 65–70% relative humidity. Leistner (1987) also pointed out that the microbiological stability of Turkish pastirma is superior to biltong. The stability of biltong is apparently based on a low a_w with little contribution from the pH hurdle, whereas, in traditional pastirma several hurdles are inherent according to Leistner (1987). These include the competitive flora (lactic acid bacteria), which probably contribute to inhibition of *Enterobacteriaceae,* and salmonella spp, and the cover paste, which is added to pastirma. Thus, besides a_w, pH, and competitive flora, the preservatives present in garlic are also an effective hurdle. This results in inhibition of undesirable microorganisms, including toxigenic molds (Leistner, 1987).

2. *Heated IM Meats*

The preparation of Chinese dried meats has been described in considerable detail by Leistner (1987). Dried pork slices are dried in the raw state and heat processed before packaging. Dried pieces of meat (cubes or bundles) are preheated and then dehydrated. On the other hand, dried pork floss and Zousoon are preheated and undergoes a disintegration–dehydration and finishing process. The microbial stability of Chinese dried meats depends primarily on the heat treatment. Chinese dried meats are indeed safe products, because the heat treatment eliminates most microorganisms present in the raw material as well as the survivors and other organisms, which recontaminate the product. These microorganisms are inhibited and inactivated by a_w control.

Molds and yeasts associated with IM meats have been discussed by Hocking (1988). He concluded that a_w is the dominant factor governing the stability of IM meat products and has a strong influence upon the types of microorganisms growing on and spoiling these foods. Many manufactured meats, such as salamis, hams, and other cured meats, have a relatively high a_w of 0.80–0.95 as stated by Hocking (1988). These products rely on a combination of factors for their microbial stability, e.g., nitrite, reduced pH, addition of salt, reduction Eh by vacuum packaging, and sometimes a heat treatment during manufacturing. Dried meats, such as biltong and Chinese dried meat products, rely primarily on reduction of a_w for their stability. Consequently, the microflora of these two classes of meat products are somewhat different, although both groups contain large numbers of organisms (Leistner, 1987).

F. TEXTURE OF IM MEATS

Bourne (1975) has described texture in foods and the methods used in its measurement. The texture of meat products has been described by Purslow (1987), who stated that meat texture is affected by the structure of the solid matrix. He concluded that it is important to have a fundamental understanding of the fracture behavior of meat and how it relates to the structure of the material. The long-term aim of his studies was to explain and predict variations in the perceived texture of meat on the basis of variation in composition and structure and hopefully to able to control and optimize texture by manipulation of these factors.

Stanley (1983) stated that many researchers now believe the major structural factors affecting meat texture are associated with connective tissues and myofibrillar proteins. Therefore, he suggested that these structures merit particular attention. He concluded that two other components, muscle membranes and water, also deserve consideration, not because of their inherent physical properties, but rather as a result of the indirect influence they have on the physical properties. It should be noted that sarcoplasmic proteins may be important for the same reason, although little information on their role is available.

Chang and Pearson (1992) obtained results that indicated electrical stunning of hogs caused fragmentation and breakage of the muscle fibers so that the meat was not suitable for production of Zousoon—a semidry shredded Chinese pork product—and other similar items prepared from prerigor pig muscle. Heating and drying intensified the detachment of the myofibrils from the muscle fiber bundles, which was caused mainly by electrical stunning and improper conditioning following slaughter. The combined effects of electrical stunning and heating–drying appear to be responsible for the fragmentation of the muscle fibers/myofibrils and contribute to the unsuitability of prerigor muscle from electrically stunned pigs for use in production of Zousoon.

Katsaras and Budras (1992) reported that the protein matrix is important in production of the desired texture in fermented sausages that are suitable for slicing. They stated that formation of the protein network is predominantly induced by gelation and syneresis of myosin and actin during fermentation and drying. During chopping, the salt brings about a change in the original structure by causing swelling and partial solution of the myofibrils. The dissolved proteins are transformed into a fluid colloidal transition state or the so-called sol state with its unstable coagulation bonds. During sausage ripening, as a result of denaturation by lactic acid and due to gradual loss of water (drying), the unstable bonds are replaced by condensation bonds, and thus the sol state is converted into the gel state. Both gel formation (condensation) and water evaporation (syneresis) result in the development of the protein matrix in fermented sausage and, consequently, produce the texture in the sliceable product.

Kuprianoff (1958) referred to the possible adverse effects of removing bound water from foods, which he enumerated as: (1) denaturation of protein by concentration of the solutes, (2) irreversible structural changes leading to textural modification upon rehydration, and (3) storage stability problems. Stanley (1983) stated that the water holding capacity of muscle is related to its sorption properties. He suggested that although water accounts for approximately 75% by weight of the fresh tissue, more important than the total amount of water present is the water holding capacity (WHC) of the tissue. On the other hand, of greater importance of IM meats are the sorption properties of the muscle components. Thus, at an a_w of 0.60–0.90, muscle could bind more moisture than at a_ws outside of this range. The bound water in the muscle is primarily a result of its association with the myofibrillar proteins as indicated by Wismer-Pedersen (1971). Protein–water interactions significantly affect the physical properties of the meat (Hamm, 1960). Changes in WHC are closely related to pH and to the nature of the muscle proteins. Measuring the water vapor pressure (i.e., isotherms), however, might be a better index of water binding by muscle (Chang *et al.*, 1991).

The isoelectric point of a protein is defined as that pH at which the net charge is zero (Wismer-Pedersen, 1971). Since protein–protein ionic interactions are promoted at this point, it would be expected that the protein matrix would shrink and WHC would be at a minimum (Kapsalis, 1975). It follows that increasing the pH away from isoelectric point would also result in a higher WHC, since protein–water interactions are favored (Hamm, 1960). Bouton *et al.* (1971) were able to increase the ultimate pH and WHC of meat by preslaughter injection of epinephrine and showed that tenderness increased directly with pH values. Further work by Bouton *et al.* (1972) and Bouton and Harris (1972) showed that as pH increased from normal values of 5.5 to 7.0, tenderness of the tissue increased and became independent of the contracture state.

G. EFFECT OF PRECOOKING

The use of humectants has been especially succcessful in production of semimoist pet foods, which commonly include high levels of sugars, propylene glycol, or sorbitol (Corbin, 1992). Direct dehydration without preheating maintains a structure, which favors water binding and enhanced tenderness in dried meat products. Accordingly, most IM meats are dehydrated from the raw state, except for some Chinese IM meat products which utilize prerigor or warm muscle as a raw material (Chang *et al.*, 1991). PSE pig muscle is associated with a rapid pH drop immediately after death (Wismer-Pedersen, 1960). PSE muscle is not suitable for production of IM meats, since the proteins are denatured (Bendall and Wismer-Pedersen, 1962; Bendall *et al.*, 1963), which results in poor sorption properties. In comparison with fresh or frozen meat, freeze-dried meat is somewhat lower in tenderness and juiciness. Some of the difference is attributable to "woodiness", although this characteristic is sometimes observed in fresh (frozen) meat (Lawrie, 1979). The benefits of high ultimate pH induced by preslaughter injection of adrenaline in protecting muscle proteins and in enhancing their water-holding capacity are reflected by greatly enhanced tenderness and diminished woodiness, with these benefits being retained after freeze drying according to Lawrie (1979).

H. USE OF HUMECTANTS

Humectants are edible substances that lower the a_w to 0.60–0.90 and offer advantages in production. Webster *et al.* (1982) investigated utilization of glycerol in production of IM meats. Later they also examined sorbate and glycerol and studied their effects on meat lipids (Webster *et al.,* 1986). A specific humectant, such as sucrose, may be in an amorphous rubber state in the a_w range after the dehydration–cooling process (Chang *et al.,* 1991). The contribution of amorphous sucrose may help in explaining the plasticized texture in Chinese IM meats (Leistner, 1987), being distributed on the fiber surface in the meat mixture as a result of specific osmosis and the disintegration treatment (Chang *et al.,* 1991).

A cellular food, such as intact animal tissue, has a definitive structure and some rigidity at drying temperatures (Kapsalis, 1975). A concentrated sugar solution, on the other hand, lacks structure and softens and melts at some drying temperature (Chang *et al.,* 1991). Thus, if a sugar solution is dried the solids will be in a thermoplastic tacky condition, giving the impression that they still contain moisture (Chang *et al.,* 1991). On cooling, however, the thermoplastic solids may harden into an amorphous glass or a crystalline structure depending on the prevailing cooling rate and the residual moisture level (Potter, 1986).

When components differing in a_w are put into the same food system, those with a higher a_w give up moisture to components of lower a_w until the mixture reaches a single equilibrium a_w (Potter, 1986; Chang *et al.,* 1991). When these components are blended and reach the equilibrium a_w of the mixture, each component retains different amounts of water in keeping with its individual water sorption isotherm and texture as outlined by Potter (1986). This principle is employed in producing complex mixtures such as American pemmican. In some foods the attainment of an a_w low enough to inhibit microbial growth by dehydration alone will yield a product which is too dry for consumer consumption without adding water. The use of sugar, salt, glycerol, and other additives may impart undersirable flavors to the product and limit their use, i.e., sweet and sour pork, heavily salted meats, etc. (Potter, 1986; Leistner, 1987).

Measurement of textural changes in dending demonstrates that these changes parallel sensory scores for toughness or hardness during extended storage according to Buckle *et al.* (1988). They suggested that this is partially due to moisture losses on storing dending in polyethylene bags, but also is related to changes in proteins and possibly nonenzymatic browning reactions.

I. COLOR

Color changes in cured meats are induced by curing and/or drying and during storage (Sebranek, 1988). Depending on the process of preservation, a meat mixture may be subject to temperatures between ambient and freezing or up to above the boiling point. Forrest *et al.* (1975) have reviewed some factors that influence color changes and transformations occurring in the heme pigments of fresh and processed meats. In fermented sausages, Bacus (1986) has pointed out that cure development is necessary during fermentation and drying. When the curing mixture contains only nitrate, time must be allowed for growth of the nitrate-reducing bacteria in order to convert nitrate to nitrite. Unless nitrate is added, nitrite must be included in the cure to develop color.

Okonkwo *et al.* (1992a,b) have discussed methods used to produce intermediate-moisture smoked meats. They prepared smoked beef by cook–soak/equilibrium in a solution containing sodium chloride, sodium nitrate, and potassium sorbate. Half of the samples were smoked for 18 hr (heavy smoking) and the other for 4 hr (light smoking) at 50°C. All samples developed the pink–red color of nitrite-cured meat.

Sebranek (1988) has reviewed the effects of heat on denaturation of the proteins. Dehydration by heat denatures the muscle proteins, particularly the sarcoplasmic proteins. This induces a rather dramatic change in meat color. The heme pigments, which provide most of the color of fresh meat, serve as a general indication of doneness or temperature history. In the case of cured products, heme pigments react to form nitric oxide hemochromogen, which contributes the characteristic pink cured meat color (Pearson and Tauber, 1984).

Maillard-type nonenzymatic browning reactions in processed meat products also contribute to their external surface color (Sebranek, 1988). Pearson *et al.* (1962, 1966) demonstrated that the main browning reaction involves the reaction of carbonyl compounds with amino groups, although lesser amounts of carbonyl browning also occur. Muscle usually contains small amounts of carbohydrates in the form of glycogen, reducing sugars and nucleotides, while the amino groups are readily available from the muscle proteins. Browning occurs at temperatures of 80–90°C and increases with time and temperature. A loss of both amino acids and sugars from the tissue occurs as a result of the browning reaction. Lysine, histidine, threonine, methionine, and cysteine are some of the amino acids that may become involved in browning (Hsieh *et al.*, 1980a).

Maillard browning reactions are essential in production of Chinese shredded dried pork (Zousoon) during processing as shown in studies by Yen *et al.* (1981). Although sucrose may be degraded during processing, its effect on color is slight since it is not a reducing sugar. Soy sauce as an ingredient of Zousoon plays an important role in browning of Zousoon, since it contains Maillard browning products and reducing sugars. The effects of various sugars on the browning of Zousoon was also studied by Yen *et al.* (1981). They found the effects to be in the following order:

glucose > fructose > sucrose. The desirable color of the finished products can be reached by using only a small amount of reducing sugars, such as glucose or fructose, and drying at a low temperature.

Buckle *et al.* (1988) discussed the stability of dending and the role of nonenzymatic browning in color and flavor development. Significant amounts of browning can occur during storage of dending, even though the product is initially dark in color. They found that erroneously high results were obtained in measuring browning if absorbance due to the meat pigments and spices, etc. was not taken into account. Browning initially increased, but then decreased during extended storage, perhaps as the pigments become involved in interactions with oxidizing lipids. The addition of nonmeat ingredients, such as coconut sugar, to dending significantly increased the extent of nonenzymatic browning. Although coconut sugar increased browning, salt may cause a decrease if spices are present. During storage of dending, hydrolysis of sucrose occurs, with glucose being made available for the browning reaction (Buckle *et al.*, 1988).

Control of the Maillard reaction in Zousoon has been studied by Chang *et al.* (1991), who found that finishing Zousoon with steam heat was a viable procedure. The best color and consistency was achieved in a rotary finisher by using steam at a temperature of 150°C for 7 min. The steam drying–finishing process aided in achieving a final a_w of 0.60–0.65 and completion of browning. This process prevented drying from being too fast and causing inadequate mobility as explained by Karel *et al.* (1975). It also resulted in developing the proper product temperature–a_w/moisture relationship to produce browning and slow moisture removal, which prevented product inhibition as described by Karel *et al.* (1967, 1975).

Potter (1986) stated that Maillard browning proceeds most rapidly during drying if the moisture content is decreased to a range of 15–20%. As the moisture content drops further, the reaction rate slows, so that in products dried below 2% moisture further color change is not perceptible, even during subsequent storage. Drying systems or heating schedules generally are designed to dehydrate rapidly through the 15–20% moisture range so as to minimize the time for Maillard browning. However, some products, such as Zousoon may require longer periods of time in the 15–20% moisture range to develop the desirable color (Yen *et al.*, 1981; Chang *et al.*, 1991). Concomitant with browning, caramelization of sugars may occur and add to the brown color (Pearson *et al.*, 1966; Nursten, 1986a,b). In carbohydrate foods browning can be controlled by removing or avoiding amines and, conversely, in protein foods by eliminating the reducing sugars (Pearson *et al.*, 1962, 1966; Nursten, 1986a,b).

Maillard browning can readily be distinguished from biologically derived alterations in food quality by inspection of a_w vs response profiles or isotherms, such as the well known Labuza concept (Labuza, 1976, 1980). These profiles reveal that nonbiologically derived changes exhibit both a maximum and a minimum. Nonenzymatic browning changes can be further distinguished from biological ones by their marked enhancement at elevated temperatures. An example of the practical consequences of browning is the problem of intermediate-moisture meat products stored in the tropics, which may develop other types of deteriorative alterations such as oxidative breakdown (Obanu *et al.*, 1975a,b, 1977).

J. AROMA/FLAVOR DEVELOPMENT AND RETENTION

1. Preheating

Nonsterilization during food dehydration can result in deterioration of quality due to survival of the indigenous food enzymes that survive drying according to Schwimmer (1980). Although precooking is widely used in IM and other meat products, it does have disadvantages. This is largely due to the effects of excessive heating. It should be possible, theoretically at least, to prevent enzymatic problems by alternative means. One would be by simply removing water without excessive heating, such as by freeze drying. Fortunately, one can frequently achieve the same results by removal of only a part of the water to lower the a_w below a certain critical value as demonstrated by Schwimmer (1980). It is not always advantageous to inactivate or prevent the action of enzymes. Enzyme management may be involved in the empirically established pattern, which is emerging in the drying of food products, and suggests superior product quality can be attained by a slow removal of water at relatively low temperatures. Under such conditions, most enzymes are preserved and to some extent active. Low-temperature–long-time drying has been used for the manufacture of such diverse food products as smoked sausages, fruits, nuts, and nutritional supplements. In this range of temperatures cellular membranes are destroyed and enzymes are potentiated (Schwimmer, 1980).

2. Ripening

The process of ripening involves keeping the processed product for varying periods of time under controlled temperature and humidity conditions as explained by Pearson and Tauber (1984). Development of a distinctive flavor results from microbial fermentation during ripening. Quite often products that are subjected to ripening are not fully heat processed, but are only subjected to a cold smoke. For example, semidry fermented sausages are heat processed at a minimum temperature of 57°C, whereas, dry sausages, such as summer sausage and salami, are never held above a temperature of 32°C (Bacus, 1986).

3. Aroma and Flavor Formation

Aromas and flavors may be produced by proteolysis as outlined by Garcia de Fernando and Fox (1991). Proteolysis in fermented sausages is caused by enzymes from the starter culture as well as by the indigenous meat enzymes. Tolda and Etherington (1988) found several cathepetic enzymes played an important role in production of dry-cured hams. Rico *et al.* (1991) later confirmed that cathepsin D was present in dry-cured hams and may be involved in flavor development. Understanding of the type and extent of proteolysis can help to achieve better quality sausages, since the nature and concentration of protein degradation products may contribute to the flavor and texture.

Meat flavor development has been described as being similar to that of coffee or bread in that it is highly temperature dependent and contributes desirable aromas and flavors as explained by Sebranek (1988). Dry heating has been described as initially producing a flavor similar to moist heat, but as surface moisture evaporates, migration of soluble components to the meat surface occurs. This leads to continued concentration of compounds at the surface, which results in further chemical reactions that help to develop flavor and aroma. The carbonyl compounds that contribute to meat flavor are derived from fat as a result of heating and include several different aldehydes, ketones, and related compounds as shown by Sanderson *et al.* (1966) and are produced by condensation of carbohydrates with amino acids during cooking (nonenzymatic browning reactions) as explained by Sebranek (1988). They are believed to be significant flavor contributors. Carbonyls may not only contribute flavor themselves but also may be important in secondary reactions, such as formation of pyrazines according to Huang *et al.* (1989). These compounds are believed to be formed by reaction of carbonyls with amino-containing compounds or free ammonia. Pyrazines have been the basis of several patents involving synthetic meat flavors. Flavor development upon heating cured meat containing sodium nitrite has been reported to be different from that of uncured meat (Cross and Ziegler, 1965; Cho and Bratzler, 1970; Gray and Pearson, 1984). These studies show that the volatile compounds produced by cooked-cured meats differ from that in uncured products.

4. Control of Aroma/Flavor Development

Meat flavor can also be considered a transient characteristic since it continuously changes as heat is applied according to Sebranek (1988).

Flavor desirability continues to increase as heat is applied. It reaches a point of maximum desirability and then deteriorates into harsh unpleasant flavors if heating continues. However, there is less information concerning specific temperature effects on the volatile compounds produced. Ledl (1987) indicated that in model systems, heating can produce flavor volatiles between 70 and 140°C. The specific compounds produced during heating are temperature dependent (MacLeod, 1986). The amount of volatiles produced can be correlated with heating time at a given temperature.

Drying temperatures was shown by Huang *et al.* (1989) to be a critical parameter that determined the flavor quality of Zousoon. Cooked meat aroma increased directly as the heating temperature was increased from 134 to 172°C. Below 130°C neither cooked meat aroma nor brown color developed. Amino acid analysis confirmed that Maillard browning reactions occurred during the drying process, since basic amino acids such as lysine and arginine decreased significantly, whereas, other amino acids decreased only slightly. A selective purge-and-trap method was developed by Huang *et al.* (1989) to investigate pyrazine formation in Zousoon samples. The basic fractions of the collected volatiles identified in Zousoon contained 16 alkylpyrazines. A combination of these alkylpyrazines seemed to contribute to the characteristic cooked meat aroma of Zousoon. Although some oxidative changes may aid in development of the flavor of IM meats (Gray and Pearson, 1984), some toxic components, including cholesterol oxidation products, may be produced by oxidative reactions (Pearson *et al.,* 1983).

5. *Retention of Aroma/Flavor*

The diffusion coefficient of water in concentrated solutions behaves differently from that of other substances according to King (1988). Diffusion coefficients of water and of other solutes decrease substantially as the water concentration falls in aqueous solutions of carbohydrates and other food components. However, the diffusion coefficient of water decreases by less than those of other substances. The result of this general phenomenon is that above some dissolved solids content, the diffusion coefficients of other substances become much less than that of water (King, 1988). Therefore, it is possible to reach a high concentration of dissolved solids at the surface of the material being dried before there is any massive losses of volatile flavor and aroma constituents. The remaining volatiles may become imprisoned because the surface becomes effectively impermeable to them. The retention of volatiles during spray drying can be improved if a high concentration of dissolved solids is built up on the surfaces of the droplets early enough in the drying process according to King (1988). This goal can be accomplished by rapid initial drying, since high rates of water evaporation and transport create substantial concentration gradients within the droplets.

Build-up of high surface concentrations of dissolved solids can be assisted by supplying a more concentrated liquid feed (e.g., by adding sucrose) to a spray dryer. This will result in lower coefficients and a lower gradient, which is needed to produce the critical surface concentration.

The amorphous sucrose layer on the muscle fibers of Zousoon after boiling indicate that sucrose is deposited on the fibers by osmosis as reported by Chang *et al.* (1991), which is demonstrated by Fig. 6. Steam heating instantly increases the solid concentration on the fiber surface. However, when the internal fiber temperature reaches over 100°C, the internally generated steam passes through the concentrated melted sucrose layer. During fast cooling following finishing, the amorphous sucrose forms a layer on the fibers. Since the added sucrose has increased the initial dissolved solid concentration of the meat mixture and early fast finishing–drying achieved an increase in the surface solid concentration, most of the developed aroma/flavor volatiles are retained by the amorphous sucrose layer. Thus, muscle fibers are encapsulated in the amorphous surface sucrose layer and contain concentrated aromas and flavors (Wientjes, 1968).

6. *Control of Oxidation*

The low a_w/moisture content of IM meats may prevent lipid oxidation according to Simatos and Karel (1988). They presented data showing that water retards lipid oxidation in the intermediate moisture range. One factor that may be important is the production of browning products, which are known to have antioxidant activity. The effectiveness of nonenzymatic browning products in preventing lipid oxidation was demonstrated by Griffith and Johnson (1957) and is one of the mechanisms hypothesized by Karel (1986) to prevent lipid oxidation. Several investigators (Griffith and Johnson, 1957; Karel, 1986; Simatos and Karel, 1988) have confirmed that intermediates in the complex set of reactions involved in nonenzymatic browning are effective as antioxidants. Furthermore, intermediate-moisture contents would maximize the concentration of these intermediates according to Eichner and Ciner-Doruk (1981). Since high water activity promotes browning, this may be one of the explanations for the observed effects. Studies on purified model systems containing no components capable of forming antioxidants through browning have shown, however, that oxidation also can be retarded by increasing water content. The explanation for these effects is based on the fact that water is produced both at the initiation and termination steps of the chain reaction. In purified systems, water interferes with the normal bimolecular decomposition of hydroperoxides by hydrogen bonding with the amphipolar hydroperoxides formed at the lipid–water interface as outlined by Simatos and Karel (1988). In the pres-

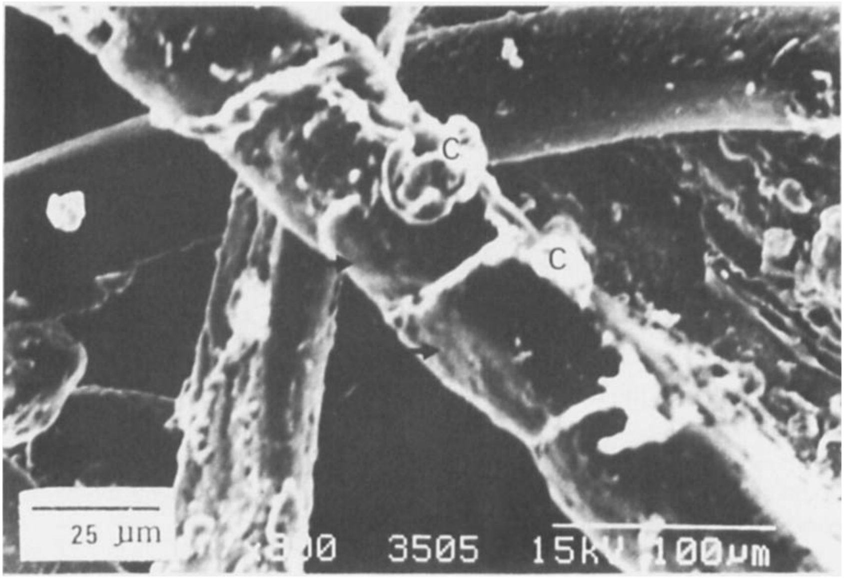

FIG. 6. Scanning electron micrograph of muscle fiber covered with a layer of crystalline sucrose (arrows). Starch cell fragments labeled C are also shown. Source: Chang *et al.* (1991). Reproduced with kind permission from Elsevier Science Ltd.

ence of trace metals added to systems of lyophilized emulsions, humidification at moderate levels retards oxidation because of hydration of metal ions. The reduction in rate depends on the type and hydration state of the added metal salt as well as on the water content. The monomolecular rate period is primarily affected by this mechanism, although bimolecular rates are also decreased (Karel *et al.*, 1967).

The effects of water on the destruction of the protective food structure in some specific dehydrated foods is probably involved in prevention of lipid oxidation in heated meat systems (Karel, 1986). In systems in which there are both surface lipids and lipids encapsulated within a carbohydrate, polysaccharide, or protein matrix, the surface lipids oxidize readily when exposed to air. The encapsulated lipids, however, do not oxidize until the structure of the encapsulated matrix is modified and/or destroyed by adsorption of water as shown by Simatos and Karel (1988). In some IM meats, muscle may be considered as being encased in or surrounded by a humectant matrix, However, free lipid may be left on the surfaces. The unwarranted overuse of lipids, which often happens in the indirect drying process to improve heat transfer and to prevent burning, is detrimental to the products. Prevention of this structural change is of considerable importance in protecting unsaturated lipids from oxidation in dry preparations. The most dramatic demonstration of the increased capability of various reactants to diffuse as water activity increases is provided by the glassy transition stage formed by fast drying of sugar-containing foods as described by Roos and Karel (1992). When the "glassy" products are humidified at high water activities, they "collapse" or crystallize, at which point some mobility is possible. The mobility allows the glassy products to be converted from an amorphous state to a mixture of crystals and amorphous components and permits the diffusion of various gases or vapors, which then may be encapsulated within the glassy material (Roos and Karel, 1992). The resistance of diffusion in foods is important, since the fat encased within the glassy products are protected from oxidation until the water activity of the matrix causes it to become sufficiently permeable to allow oxygen to penetrate.

The diffusion coefficient of oxygen in sucrose solution decreases much more rapidly with increasing sucrose concentrations than does the diffusion coefficient of water (King, 1988). According to King (1988) when diffusional limitations exist, the local oxygen concentrations may be different from those that would be expected if the head space or surrounding air were instantly and continuously maintained in equilibrium.

Studies related to oxidation of IM meats have been discussed by Okonkwo (1984) and Okonkwo *et al.* (1992a,b). With smoked beef prepared by cook–soak equilibrium in a solution containing sodium chloride, sodium nitrite, and potassium sorbate and smoked for 4 or 18 hr at 50°C, oxidation was not a serious problem. TBA values were low and all samples possessed no detectable rancidity.

In dending prepared without nitrite, the chemical changes observed in the lipids were quite complex as shown in studies by Buckle *et al.* (1988). TBA numbers invariably decreased during the early stages of storage, perhaps as intermediates of lipid oxidation, as reactants in the Maillard reaction, or as browning products or their precursors that developed antioxidative activity. Subsequent increases in TBA numbers during storage (>6 months at 37°C) were not always related to the sensory assessment of rancid odors or flavors.

Lipids are derived not only from the meat, but also from spices, such as coriander. Metal impurities occurring in the refining agent used to clarify sugar before crystallization or in unrefined salt may also increase the tendency of fat to undergo oxidation is discussed by Buckle *et al.* (1988).

Production of dried sliced pork and control of various parameters utilized in production were described by Kuo and Ockerman (1985). They considered the effects of nitrate, packaging methods, and storage time on residual nitrite, TBA values, and sensory properties. Residual nitrite decreased with increasing storage times at 1°C. The addition of nitrate plus vacuum packaging caused a greater residual nitrite level and a lower TBA value during storage. Nitrite and/or nitrate acted as an antioxidant and retarded oxidative rancidity (TBA values). Dried pork manufactured by the technique described had no major rancidity problem and had an acceptable shelf life.

Zousoon production methods were discussed by Lin *et al.* (1983a,b). They reported that the product packed in gas-impermeable bags under nitrogen or at atmospheric pressure could be kept at room temperature for at least 6 months without any major changes in quality. Vacuum packaging was unsuitable because of the poor appearance of the product and development of off-flavors during storage.

Dried beef bundles are a popular product in Indonesia and their production has been described by Chuah *et al.* (1988). The finished products are packed in aluminum laminate pouches and vacuum sealed. They are then submerged in boiling water until the temperature at the center of the product reaches 95°C. The pouches are then cooled immediately in running water until the internal temperature reaches 37–40°C. This process is similar to that of pasteurized products having an $a_w < 0.85$. After 6 months storage at room temperature, the products were still found to be acceptable with no rancid taste being detectable. The moisture content, free fatty acid, and peroxide values remained relatively unchanged during the entire storage period.

K. NUTRITIVE VALUE

Erbersdobler (1986) stated that dehydration of food is one of the most important achievements in man's history, making him less dependent upon a daily food supply even under adverse environmental conditions. Nutritional damage to food is of practical significance only if the complete daily diet does not provide an adequate intake of the nutrients in question as summarized by Schweigert (1987). In general, losses of B vitamins are usually less than 10% in dried foods. Dried foods do not greatly contribute to dietary requirements for thiamin, folic acid, and vitamin B-6. Although vitamin C is largely destroyed by heating–drying, meat per se is not a good source. Even though most amino acids are fairly resistant to heating–drying, lysine is quite heat labile and likely to be borderline or low in the diet of humans and especially so in developing countries where high quality animal proteins are scarce and expensive (Erbersdobler, 1986).

In the case of protein, heat treatment of pork does not greatly affect retention as long as the critical temperature or time is not greatly exceeded according to Sebranek (1988). This has been suggested to be about 100°C and less than 1 hr, respectively. Heating methods (microwave, steam, infrared, or hot air convection) do not appear to have any major effects on the amino acids. Losses of protein are not important as long as drippings are included for edible purposes. Some specific amino acids, however, may be lost during relatively severe heat treatments, i.e., lysine, methionine, and tryptophan as summarized by Schweigert (1987). Those losses most likely occur as a result of oxidative reactions, which are due to the direct effects of heating or from heat-induced crosslinking between amino acids. Cross-links are not hydrolyzed during the digestive process. The nutrients most susceptible to loss through heating appear to be the B vitamins, particularly thiamin. With moist heat, losses of thiamin have been reported to average 60%; niacin and B-6, 50%; pantothenic acid, 40%; riboflavin, 30%; and B-12, 20% (Schweigert, 1987). With dry heating methods, a 20% loss is likely for thiamin, niacin, B-6, riboflavin, and B-12.

Two trials were conducted by Lin *et al.* (1981) to determine the protein quality of Zousoon. The adjusted PER (protein efficiency ratio) values in the first trial for control samples (cooked freeze-dried pork) compared to Zousoon were 2.90 and 2.21, respectively, whereas, in the second trial the respective values were 3.10 and 2.28. Approximately a 25 to 30% decrease in PER and net protein utilization values for Zousoon were found in comparison to control samples. Compositional data show that the sulfur-containing amino acids were the limiting ones in both the Zousoon and control samples. The Zousoon samples had lower methionine and lysine chemical scores than control samples. The reason for the decrease in protein quality of Zousoon was thought to be partly due to the addition of a low-quality food extender (starch cells or wheat flour) and partly because of the long-time–high-temperature drying process, which may cause further destruction of the amino acids.

The available lysine content of dending is lower than that of control dehydrated meat samples according to Buckle *et al.* (1988). During storage at 50°C, available lysine levels decreased to about 60% of the original levels in the finished product. Muchtadi (1986) found the available lysine levels decreased substantially when dending was fried before serving. Protease inhibitors were found in both stored and fried dending but not in the boiled meat. The KCL-soluble N (nonprotein N) decreased by 22% during storage of dending at 50°C, while it increased slightly in dehydrated meat. Protein solubilized by sodium dodecyl sulfate and β-mercaptoethanol (i.e., denatured protein) decreased by more than 50% in dending after 3 months storage at 50°C, presumably due to development of stable cross-links and other reactions associated with browning.

Dry pork sausage was formulated, fermented, and dried for 41 days and chemically analyzed by Garcia de Fernando and Fox (1991). The amount of water soluble nitrogen, water soluble nitrogen permeate, phosphotungstic acid soluble nitrogen, and free amino acids all increased during processing. On the other hand, the salt soluble nitrogen and phosphotungstic acid insoluble nitrogen decreased. Electrophoretic studies demonstrated that proteolysis of the heavy myosin chain, α-actinin, and actin occurred during processing.

XI. PROCESS OPTIMIZATION FOR IM MEATS

A. BACKGROUND

According to Schwimmer (1980) the two major considerations upon which successful adoption of a particular step in a food processing procedure hinges have traditionally been economic feasibility and consumer acceptance. He stated that these can be translated into innovation in processing efficiency and product quality and stability, with heavy emphasis on sensory quality and appearance. Such hitherto subsidiary parameters as nutritional, environmental, and energy conservation considerations are rapidly attaining equivalent status. The preparation and distribution of dry and dried foods, especially, intermediate-moisture foods, have proven to constitute no exception to this trend and have required contributions from applied and basic research to provide relevant scientific information upon which improvement in processing can be based.

Saguy and Karel (1980) stated that improvements have been made possible by the increase in knowledge on the kinetics of food deterioration using advanced analytical methods and by the availability of computer modeling. The latter can simulate behavior of complex systems and save the time and expense of actual experiments. When no correction of the model is anticipated, the formulated model may be used for optimization, prediction and analysis.

B. CONCEPT FOR OPTIMIZATION FOR HEAT PROCESSING OF MEAT

The heating concept can be considered in many ways, but all require an understanding of the process involved, the conditions existing during the process, the range of possible results, and limitation of the equipment being used with each of these areas being reviewed by Sebranek (1988). In the case of heat processing of meat, Sebranek (1988) pointed out that the desired end results include a desirable color, flavor, texture development, gelation stability, and inactivation of the microorganisms and enzymes. Negative effects include loss of nutrients, oxidation of fat, moisture loss, and potentially undesirable flavor and texture changes. Consequently, processes first should be examined for basic principles, after which optimization can be considered. The use of mathematical models to represent processes lends a great deal of potential to finding optimum processes. The objective of these models is to optimize sensory, chemical, and nutritional characteristics while achieving the necessary effects of heat processing. The concept of model thermal processes has potential when product variables are considered, for example, predicting the effects of ingredients or handling changes. Color, texture, and shrink can be predicted on the basis of ingredient functions or modified processing steps. The advantage of predictive modeling is that it is less expensive and time-consuming than is direct experimentation. However, any predictions based on models must be substantiated with experimental products to validate the effectiveness of the model. Improved basic research would increase the successful predictability of mathematical modeling.

Additional and more precise information is needed on the thermal properties and heat transfer characteristics of meat products according to Roos and Karel (1991b). This is especially true during application of heat energy because thermal characteristics of meat are modified as the product changes during heating. Predictability of results from mathematical modeling has not always been highly successful, but is useful and should be pursued. A successful model, once developed, would be eminently useful in demonstrating the limits and flexibility of the heating process. Instead of a constant temperature or even constant step-up heat treatments (Δt), perhaps a process should be designed specifically for what is happening on a molecular basis. Such a process might be initiated to investigate the effects of high environmental temperatures. This could be followed by a step-down in temperature while passing through a critical heat rate zone for gelation and completed with a final finishing treatment to achieve microbial control. This approach might also be useful for new equipment applications as part of the process, for example, microwave heating by stages in a process where temperature rise can be achieved quickly.

Optimization of the dehydration process for IM meats can be better understood by examining the basics involved in dehydration. The complexity of the phenomena involved, e.g., destruction of heat sensitive material, during concentration and drying is obvious. Optimization of such a process is, therefore, difficult. The approach used in traditional food technology is based on employing well-experienced craftsmen, who can make decisions on a case by case basis using a combination of objective and subjective criteria "integrated" into a decision in their minds (Thijssen and Kerkhof, 1977; Karel, 1988).

Optimization fundamentals of the dehydration process for IM meats and for dried foods are likely the same. However, IM meats are dehydrated only to a water activity of 0.60–0.90 and are accompanied with a number of side reactions in the process and by rather high-soluble solids in the formulation. The solids are derived from diffusion treatments. Indeed the products are the result of a stable state and can be stored at open atmosphere and need not to be stored in isolated or closed systems for stability. However, some physical–chemical and structural changes associated with dehydrated products may also occur in some low a_w IM products.

C. MATHEMATICAL MODELING FOR HEAT AND MASS TRANSFER

Aguilera and Stanley (1990) concluded that modeling is important in order to quantitate the effect of changes in variables and parameters on the drying rate, moisture content, and product temperature of foods. The ultimate objective is to be able to predict the final conditions in the dried product and the couse and extent of the reactions taking place during drying, such as browning and microbial growth and/or inhibition.

Since the falling rate periods account for a major proportion of the drying time and is usually controlled by internal mass transfer, the model commonly has applied simple Fickian diffusion to the last stage of drying. Simultaneous with mass transfer, heat transfer also occurs. Lewis numbers greater than 60 or a characteristic dimension smaller than 3 cm thermal gradient can be neglected and the temperature considered uniform throughout the sample, but varying with time. When heat transfer is the limiting factor, then the thermal gradient inside the food particles increases. Fourier's law can then be applied and the principles become similar to those governing mass transfer according to Aguilera and Stanley (1990). The important thermal properties of foods involved in the heat transfer process include thermal conductivity, specific heat, and thermal diffusivity. The transport of water in structured food materials is difficult to describe mathematically. Several correction criteria have been introduced to compensate for the complexity in mass transfer and microstructural effects. Improved results are obtained when variable diffusion coefficients are used. Moisture distribution profiles can be obtained by modeling Fick's second law in which the diffusion coefficient varies with the moisture content. Mathematical models for drying in which particular physical or geometrical characteristics are relevant are also available. For example, Loncin (1988) developed a model for heterogeneous material having surface resistance. Another example can be found in the research of Crapiste *et al.* (1995) in drying of fruit in which the cellular structure of fruit was modeled as series/parallel arrangement with water flux between cells and along the walls being of a similar order of magnitude. This model is thought to be similar to the drying of meats and could be useful as a possible model.

Engineering calculations based on model systems can go a long way toward selecting favorable drying condition, but seldom are sufficient *per se* to accurately predict drying behavior according to Potter (1986). This is because food materials are highly variable in initial composition, in amount of free and bound water, in shrinkage and solute migration patterns, and, most importantly, in the way the properties change throughout the drying operation. For these reasons, in selecting and optimizing a drying process, experimental tests with the food to be dried must always supplement engineering calculations based on less variable model systems (Lois *et al.*, 1987).

D. DEVELOPMENT OF AN APPROPRIATE KINETIC MODEL

Karel (1988) has investigated concentration effects in a kinetic model, in which concentration was chosen as the index of quality. He stated that quality loss may then be represented as

$$dQ/dt = -dC/dt \cdot k\ Cn \cdot C\ n2\ .\ .\ .,$$

where Q is the quality index, C is concentration of the heat sensitive components, n is reaction order, d is reaction rate, t is time, and k is a constant. Various reaction orders may be involved. Nonenzymatic browning very often follows zero-order kinetics.

1. *Temperature Dependence*

Karel (1988) concluded that temperature dependence behaves according to the Arrhenius equation

$$K = K_o \exp\ (-E_a/\mathrm{RT}),$$

where K is the reaction rate constant, K_o is a constant, E_a is activation energy, R is the ideal gas constant, and T is absolute temperature. This equation constitutes the soundest approach for modeling temperature dependence.

2. *Water Activity and Moisture Content*

The equilibrium relationship between water activity and moisture content is expressed by sorption isotherms and may be used to specify local moisture contents or to calculate average moisture content as outlined by Karel (1988)

$$a_w = f(m) = f(\mathrm{x} \cdot \mathrm{y} \cdot \mathrm{z}),$$

where m is moisture content, f is a function of moisture content, and x,y,z are the coordinates specifying positions.

In many food and biological systems, physical and/or chemical changes occur concurrently with, and are often caused by, sorption of water. The kinetic model requires knowledge of the dependence of the reaction rate constant on either m *or* a_w. These relationships can be extremely complex, and simplified relations are needed. For example, in many oxidative reactions at a very low moisture content, a useful mathematical model is

$$K = b/m\ n,$$

where K is a reaction rate constant, b is a constant, m is moisture content, and n is an exponent with a value usually close to 1.0.

Karel (1988) has discussed some problems arising from complex kinetics or physical phenomena. Optimization for retention of heat-sensitive material becomes very difficult when the reaction kinetics cannot be described simply or when the properties of the materials being heated and/or dried change dramatically during the process. For example, Karel (1988) stated that many of the reactions causing deterioration of food quality involve free radicals, and the kinetics are those of chain reactions. These kinetics may be simplified by focusing on only one of the several potential indicators of oxidation and by simplifying the assumption. He further suggested that changes in structure, and particularly in glass transitions, have a profound effect on rates of chemical reactions for heat-sensitive materials and that water content affects these transitions substantially. Diffusion of sugars is also important in nonenzymatic browning. Considerable amounts of work have been conducted in these areas, with research being carried out in connection with diffusion of water and of flavors during drying. The diffusion coefficient for organic compounds drops even more rapidly than that for water. This phenomena is the basis of the selective diffusion theory, which was formulated by Thijessen and Kerkhof (1977). This theory is generally accepted with some modifications as the basis for flavor retention during drying of foods.

3. An Example of Optimization

An applicable example of optimization, which was derived from dehydration of a model dehydrated food, has been described by Mishkin *et al.* (1982). They suggested that food engineering has lagged behind other engineering disciplines in implementing process optimization techniques because the complex characteristics of foods makes mathematical modeling of their behavior difficult. For illustrative purposes, they chose a dehydration system of slabs composed of water, cellulose, and ascorbic acid, which was dried in a tray dryer. In this process, their aim was to vary the air temperature during drying in a manner that resulted in the highest ascorbic acid retention while achieving the desired final moisture content at any specific drying time.

XII. ENERGY COSTS FOR PRODUCTION OF IM MEAT PRODUCTS

A. ENERGY CONSUMPTION IN FOOD PROCESSING

In food process operations, energy requirements must be examined in relation to their contribution to total operating costs according to Flink (1977a,b). Whenever efforts are made to improve the economic efficiency of a process by reducing operating costs, energy utilization must be among the factors considered. In the past, however, when energy costs were relatively cheap, there was little incentive to make significant capital investment to improve the design or operation merely to reduce consumption of energy.

B. ENERGY COSTS ASSOCIATED WITH IM MEATS

Flink (1977a,b) has pointed out that energy costs have always been a factor of importance and concern in the food processing industry. Most aspects of production of food from the farm through the factory to the home require significant inputs of energy. Hirst (1974) has estimated that the U.S. food cycle uses about 12% of the total U.S. energy. Of this amount of energy, food processing accounts for almost 50%, with distribution and trade (wholesale and retail marketing) adding an additional 20%. Much of the remainder is energy use associated with purchasing, storage, and cooking by the ultimate consumer. For IM meats, the product could be naturally dried, even without using solar energy, to a characteristic a_w, which is in equilibrium with the relative humidity or the atmosphere, to which the meat is exposed. However, dehydrated foods need extra energy in order to remove the moisture and reach an a_w below the relative humidity of the open atmosphere. Often times, the low moisture levels for maximum product stability of a food are not easily obtained and frequently can be approached only at the expense of increased dehydration costs. For example, the high costs of freeze drying salted prerigor meat in order to maintain a high water holding capacity after rehydration make the process too expensive to be practical (Judge *et al.,* 1981). The dehydrated meat is excellent as raw material for various sausage types but costs for freeze drying are prohibitive.

1. Energy Analysis of the Dehydration Process

Flink (1977a) concluded that air drying is the cheapest in terms of energy costs and is followed by drum or pan drying while freeze drying is the most expensive process. He showed that the basic energy cost to remove 1 kg of water is much lower for air drying and drum drying than for freeze drying. Shin (1984) reported on the energy requirements for producing IM meats, while Stiebing *et al.* (1982) investigated energy savings during manufacturing of raw sausages.

2. Factors Affecting Energy Efficiency

Flink (1977a,b) pointed out that energy efficiency can affect the economic viability of the dehydration process and will depend on the weight of product per unit weight of water removed. The higher the initial concentration of solids in the food, the more economical the drying process, provided that the concentration process used prior to drying has a lower cost for removing water than the drying process per se.

One way to accomplish efficiency in the drying operation is to increase the inlet air temperature to the drying chamber (Chang *et al.*, 1991). This, in part, is related to the reduction in drying rates observed at lower air temperatures. When these kinetic factors are negligible, however, the opposite behavior occurs. As most drying operations have some heat and mass transfer kinetic limitations, the air discharge temperature can be reduced by lowering the air flow rate in the dryer as described by Chang *et al.* (1991). This will allow a longer contact time between the sample and the heating medium. The effective air discharge temperature can be reduced by using air recirculation, i.e., by operating the dryer as a somewhat closed system in which the humid air at the dryer outlet is, for the most part, reheated and used again. In this case, the amount of energy being discharged in the exit air per unit of water removed is reduced, and the energy input required to heat the air being introduced to the drying chamber is lowered by the difference in temperature between the "discharge" air and the ambient air. There will, however, be some effects associated with the increase of average absolute humidity of the air in the process. Since IM meats do not require complete drying, the process of recirculating moist air improves the overall efficiency of drying. Air recirculation will also increase the specific heat of the circulating air, thus reducing the required volumetric flow.

Most current industrial approaches involve energy reclamation in the air dryer by either heat exchange or recycling. The potential advantages of the use of osmosis as a method of increasing the solid contents of the feed material could be useful in future development of dehydration, such as for IM meats (Chang *et al.*, 1991).

3. *Equipment for Producing IM Meats*

Although the wind and sun have long been used by man to produce dried foods, this can only be accomplished under favorable climatic conditions as outlined by Okonkwo *et al.* (1992a,b). However, some novel drying methods had been proposed by the end of the 19th century. At the beginning of this century, Hausbrand (1901) wrote a short monograph on the heating and ventilation for a given drying load, but little further work was done until recently. Outstanding examples of such later work are Lwikov's (1966) analysis of heat and moisture transfer and their inseparable association and Krischers' (1963) treatise on the scientific basis for drying technology. An infusion of new knowledge of this kind into old arts is likely to bring about significant saving in costs and radical changes in practice.

Processing equipment used in traditional meat-drying is simplistic and, in some cases, primitive, making process control difficult, if not impossible. The quality of different batches of product may differ due to poor quality control, resulting from lack of proper equipment. However, these production problems are slowly being overcome with the introduction of more modern equipment, which not only speeds up the rate of production but also results in more consistent quality products due to more precise control of the processing parameters (Chang *et al.*, 1991).

Ockerman and Kuo (1982) described production of dried pork by tumbling and forced air drying techniques, which they compared to the more conventional method of dry curing with the sun and nonheated air-drying. The latter method requires more time and labor in addition to being unsanitary due to the exposure during drying. The predried pork was cooked (180 + 2°C) on a grill for 1 min on each side. They used many methods for final finishing, such as deep fat frying, radiant heat roasting, and open fire roasting.

The production of Zousoon was described by Chang *et al.* (1991) as traditionally produced in Taiwan. The production process is empirical and is more of an art than a science. These workers described a modified clothes dryer developed to tumble and dry the product, which was shown to result in improved heat transfer and greater shear force that gives better control of evaporation of water while causing the muscle bundles to disintegrate into smaller subunits. The predried product was finished in a steam-heated dryer–finisher. The final product had a yellowish–brown color and fibrous appearance, being more uniform in color and texture than that produced in the traditional gas-fired, scraping frypan.

Leistner (1990a) has described the development of dry and semidry sausages which originated in Southern Europe. He pointed out that these products first were produced by fermentation induced by naturally occurring microorganisms, but today commonly use starter cultures that preserve the sausages by fermentation and drying. Stiebing *et al.* (1982) introduced an improved method for control of relative humidity in the ripening room during sausage fermentation and achieved an energy saving of up to 70%. By using the surface a_w of the sausages as a measure of control, Stiebing and Rödel (1989) suggested that optimization and automation of the ripening process could be controlled with microprocessors.

Since freeze drying requires high capital investment and is in itself an expensive process of drying (Judge *et al.*, 1981), it has not been widely used by the meat industry. Users of the freeze-dried products have encountered no major problems except for the high costs. Some studies with IM meats have involved infusion of a low a_w solution into the sponge-like structure of freeze-dried meat to improve its absorptive properties.

4. *Control System*

Most thermal dryers embody convective/direct heating since drying can be readily controlled by the temperature and humidity of the air that evaporates and conveys away the moisture as explained by Chang *et al.* (1991). There is some insurance against overheating the drying materials, since its temperature can never exceed that of the incoming air. On the other hand, drying rates for the various methods of indirect drying are not as readily estimated as those for direct drying because the heat and mass transfer coefficients at the point of contact between solid phases are not well established. Frequently, radiation and conduction cause the temperature of evaporation to exceed the wet-bulb temperature of the air in the early stages of drying. It is necessary to estimate the true surface temperature in order to calculate the constant rate. The true surface temperature, however, can be estimated from heat transfer data using either graphical or trial and error methods.

C. FACTORS AFFECTING DRYER SELECTION

The type of dryer selected should be determined by: (1) physical characteristics of the material being handled when wet and dry, and (2) the drying properties of the material, which include (a) type of moisture being removed, i.e., free or bound moisture, (b) initial and final moisture content, and (c) the final product quality, such as shrinkage, state of subdivision, bulk density, contamination, overdrying, and chemical changes (Chang *et al.*, 1991).

The interior surface of a rotary dryer used in production of Zousoon is equipped with baffles, which are longitudinal fins extending inward toward the center, and was described by Chang *et al.* (1991). The solid material is continuously carried up by rotation of the fins until it spills off and falls through the air. The high degree of turbulence and excellent contact between the air and solids provide very high rates of drying for materials that have this capability. Material that would tend to mat or pack on a tray or belt may easily be handled in a rotary dryer. The abrasion caused by the tumbling action rules out the rotary dryer for many food materials. Furthermore, particle sizes may frequently be too large to take full advantage of rapid drying by use of the rotary dryer.

XIII. RESEARCH NEEDS FOR IM MEATS

A. EFFECTS OF ANTE- AND POSTMORTEM TREATMENTS ON PROPERTIES OF IM MEATS

It was pointed out by Chang *et al.* (1991) that prerigor meat was preferred for production of some Chinese IM meat products, as it yielded superior products. Chang and Pearson (1992) showed that meat from electrically stunned hogs was not suitable for producing Zousoon, since the muscle fibers did not retain the fibrous structure which is characteristic of this product. Yet there is little, if any, information on the effects of various prerigor and postrigor treatments on the structural and physical properties of other IM meats. Experimentation is needed to see if prerigor treatments improve the quality of other IM meats, especially other Chinese IM products.

What are the effects of using prerigor meat on the efficiency of the drying process? It has been shown by several researchers (Bacus, 1986; Demeyer *et al.*, 1986; Katsaras and Budras, 1992) that lowering the pH toward the isoelectric point of the muscle proteins aids in the dehydration process. This would suggest that the efficiency of water removal would be improved in postrigor meat, particularly at low pH values. Since PSE pig muscle loses water readily (Briskey, 1964; Borosova and Oreshkin, 1992), it would be interesting to see if its use would improve the efficiency of drying. If not, would there be an advantage for using dark, firm, and dry muscle for production of IM meats? What whould be the effect of altering postmortem pH by feeding sugar to pigs, or, conversely, to deplete the muscle glycogen by exhaustive exercise as reported by Briskey *et al.* (1959) on the efficiency of drying and the quality of IM meats? If either a low or high pH should have an advantage for production of IM meats, this could be achieved by enzymatic manipulation as explained by Bouton and Harris (1972) and by Bouton *et al.* (1971, 1972).

B. INFLUENCE OF FREEZING AND THAWING

Pearson and Miller (1950) studied the effects of freezing rate and length of freezer storage on the quality of beef and found that freezing rate was relatively unimportant but drip losses increased during 90 days of freezer storage. The increased losses of water associated with freezing and freezer storage suggest that this phenomenon could be utilized to assist in removal of water in order to lower the a_w during production of IM meats. It has been shown by Judge *et al.* (1981) that freeze drying produces a high quality product that is useful as a sausage ingredient. However, the process is too expensive to be economically feasible. It is not known whether there would be an advantage in using meat that has been frozen and thawed with the resultant water losses improving the efficiency of water removal. Studies need to be carried out to see if this technique could be used to improve transfer of moisture in both conventional drying and freeze drying of meat.

C. FERMENTATION

It has been known for many years that fermentation plays an important role in production of IM meats (Lawrie, 1995; Campbell-Platt, 1995; Zeuthen, 1995; Kröckel, 1995; Leistner, 1995). The fermentation process assists in preservation in two ways as pointed out by the above-listed authors. First, the production of acid during fermentation lowers the pH and inhibits growth of spoilage microorganisms. Second the drying process is accelerated by fermentation since the lowered pH assists in removal of moisture as it moves toward the isoelectric point of the meat proteins. Thus, the acidic pH helps in lowering the a_w. Although bacterial fermentation is commonly used in producing sausages (Bacus, 1986), it has not been commonly used in other products. Jessen (1995) has reviewed the procedures involved in production of meat products by bacterial cultures. Thus, research on the use of bacterial fermentation in production of other meat products is needed. Lowering the pH by adding acids should also be explored as a means of lowering a_w and imparting an acidic environment, i.e., especially the use of organic acids.

Fungal growth is generally considered to be responsible for toxins in meat (Pestka, 1995), yet some traditional fermented meat products are produced by selected fungal strains (Cook, 1995). Leistner (1990a,b) and Leistner *et al.* (1989) have demonstrated that a commercial culture of *Penicillium nalgiovense* can be utilized in production of mold-ripened sausages. The number of molds and yeasts that have been investigated as cultures for meat fermentation still need further investigation (Pestka, 1995). A dense coating of *P. nalgiovense* protects against growth of undesirable molds (Leistner, 1995). However, the mechanism by which they protect against undesirable molds needs further study.

Yeasts also have been utilized as starter cultures in sausages according to Leistner (1995), usually *Debaryomyces hansenii,* which reduces the Eh and causes the meat to turn red. The cultures produce catalase, which delays development of rancidity and improves the aroma of the sausages as was demonstrated by Miteva *et al.* (1989). Nevertheless, the use of yeasts for fermentation of meat needs additional research particularly in regard to the utilization of different strains and their mechanism(s) of action.

D. SYNERGISTIC STABILIZATION

Leistner (1978, 1987, 1995) has explained the synergistic affects of various treatments, such as salt, nitrite, smoke, and a_w, on production of IM meats. Some or all of these factors may be involved in providing hurdles that assist in producing safety in IM meats. Further research is still needed to ascertain the role of each hurdle in preventing both spoilage and growth of food pathogens in various IM meat products as pointed out by Leistner (1987).

E. EFFECTS OF HEAT

Although application of heat or cooking has been widely utilized in production of IM meats (Keey, 1972; Ledward, 1981; Okonkwo 1984; Buckle *et al.,* 1988; Leistner, 1987; Chang *et al.,* 1991), only a few of these investigations have concentrated on the role of heat in the transfer of moisture from the product to the environment. Large scale studies are needed on factors influencing the efficiency of water removal.

F. EFFECTS OF OSMOTIC TREATMENTS

Although Lerici *et al.* (1988) demonstrated that osmotic treatment greatly affected drying rate, little research has been done on a combination of heat and osmotic treatment. It may be that altering the solid matrix by adding salt and sugar assists in removal of water, yet such information is not available.

Offer and Trinick (1983) and Offer and Knight (1988a) have demonstrated that osmotic treatment causes shrinkage of the muscle fibers. This may assist in removal of water during heating and not only prevent growth of food spoilage and pathogenic microorganisms, but also aid in lowering the a_w. Investigations are needed to ascertain the role of altering osmotic pressure by use of additives, such as salt and sugar, on the efficiency and rate of water removal in production of IM meats.

G. GEL FORMATION

In a number of sausage products, gelation is involved (Aguilera and Stanley, 1990). This phenomenon probably plays a key role during fermentation, although virtually nothing is known about the effects of gelation on the rate of water removal. Since gels bind water, the question needs answering if gel formation slows down water losses or if by some unknown mechanism may assist in water removal. Since fermentation lowers the pH toward the isoelectric point of the muscle proteins perhaps gel formation is not involved in fermented meat products. These questions need to be answered in order to help in understanding whether gelation is involved in water transfer of IM meats.

H. ROLE OF GLASS TRANSITION

Slade and Levine (1987, 1991) have shown that heated foods may form a glassy transition phase, yet little is known about the effects of this transition. Does it accelerate or delay heat transfer? Does the glass transition have an advantage or disadvantage in production of IM meats? These questions need to be answered before recommendations can be made on the influence of the glass transition on drying.

I. MODELING

Mathematical modeling of the effects of drying on IM meats are needed similar to those carried out by Karel (1986, 1988). However, results of the modeling studies then need to be applied to the IM meat system to show that the results are applicable in the IM meat system. The model is only good if the results are applicable to IM meat products.

J. DESIGN OF DRYING EQUIPMENT

Chang *et al.* (1991) demonstrated that the process of producing the Chinese IM meat product, Zousoon, could be improved by developing new equipment. They also demonstrated that recirculation of the air improved the efficiency of the process. The need for new equipment designed for more efficient operation and more effective removal of water during the drying process is an urgent one. Newly designed equipment for producing IM meat products could lead to their wider availability and greater popularity.

K. THERMAL DATA

Chang *et al.* (1991) pointed out that data is needed on the properties of IM meats that affect drying rates and efficiency of drying. What compositional and structural constraints result in changes in drying efficiency? Furthermore, the factors controlling mass transfer need to be elucidated. Mass transfer efficiency vs heat transfer efficiency needs to be understood in order to improve the efficiency of drying IM meats.

L. HACCP Systems

Mortimore and Wallace (1994) have published a practical approach to HACCP, which needs to be developed for IM meats. HACCP is important since salami has been found to have been contaminated with *Escherichia coli* 0157:H7 (Anonymous, 1995a) and salmonella organisms have survived processing in Lebanon bologna (Anonymous, 1995b). With emphasis on food safety, critical control points (CPs) in production of different IM products must be developed. The CPs will, no doubt, be quite different from product to product. Thus, systems must be developed for each different process and put in place before production parameters are set. One cannot assume that IM meats are safe, but recognize possible problems before they cause difficulty. HACCP must be an important part of each IM meat product. Safety will be crucial to the success of all products and must be developed during the experimental stage of production.

XIV. SUMMARY

IM meat products are produced by lowering the a_w to 0.90 to 0.60. Such products are stable at ambient temperature and humidity and are produced in nearly every country in the world, especially in developing areas where refrigeration is limited or unavailable. Traditionally IM meats use low cost sources of energy for drying, such as sun drying, addition of salt, or fermentation. Products produced by different processes are of interest since they do not require refrigeration during distribution and storage.

Many different IM meat products can be produced by utilizing modern processing equipment and methods. Production can be achieved in a relatively short period of time and their advantages during marketing and distribution can be utilized. Nevertheless, a better understanding of the principles involved in heat transfer and efficiency of production are still needed to increase efficiency of processing. A basic understanding of the influence of water vapor pressure and sorption phenomena on water activity can materially improve the efficiency of drying of IM meats. Predrying treatments, such as fermentation and humidity control, can also be taken advantage of during the dehydration process. Such information can lead to process optimization and reduction of energy costs during production of IM meats.

The development of sound science-based methods to assure the production of high-quality and nutritious IM meats is needed. Finally, such products also must be free of pathogenic microorganisms to assure their success in production and marketing.

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