FISH AND SHELLFISH PRODUCTS

1. Introduction

It is known that humans have used rather advanced techniques for obtaining and processing seafood throughout recorded history. A main source of protein for the ancient Egyptians was fish from the Nile, Mediterranean, and pond culture. Fish was consumed fresh and salted for preservation by the Greeks. Dried fish became a major source of animal protein in Europe when the Roman church banned meat consumption on Fridays and during Lent.

It is known that American Indians used fish as an important part of their diets 10,000 years ago. The early European settlers coming to the New World brought processing and preservation practices such as drying, salting, pickling, and cooling. During colonial times salted dried cod was exported back to England. A major part of the diet of American northwest Indians and Eskimos was salmon that was sun dried and smoked over a wood fire.

It was not until the 19th century in the Great Lakes region that fish were frozen by using the combination of salt and ice to lower temperatures below freezing. The growth of commercial freezing processes over the last 100 years has made freezing the leading means of preserving seafood for human consumption. As will be seen, the early fresh fish handling and freezing technology was not developed with good knowledge of the biological and physical factors that must be considered. Hence, the fishy odor of fish along with certain rancid and spoilage off-tastes were considered normal in fresh, frozen, and dried products.

Today it is realized that quality control of fish, as much or more than any other food, must be practiced from harvest to table. The seafood chain (Fig. 1) begins with the boat builder or hatchery designer and ends with the consumer. All must practice good techniques of sanitation, temperature control, and packaging protection. As the fish story unfolds, it will be seen that any break in this chain can be disastrous to the quality of seafood. If a processing plant, market, restaurant, or home smells fishy, then there has been a break in the chain. Good fish looks good, has a neutral fresh odor, and has firm flesh. Good fish is a healthful, highly nutritious protein food that has an unlimited market.

2. U.S. Fishery

There are more than 2,000 species of finfish within the U.S. coastal marine waters, of which about ca 2% are consumed as food fish (1). In fact, the U.S. consumer is familiar with only a few of the some 200 species of finfish and 40 species of shellfish that are consumed throughout the world. There was little change in the amount of fish consumed by the average U.S. citizen from the early 1900s to 1970s. Over the last 20 years, although still considerably below that of the rest of the world, the U.S. per capita consumption has risen about 30%. Most of this increase has been during the last 5 yr. With the increasing emphasis on eating lighter and leaner foods, this U.S. consumption is continuing to rise.

2.1. Fishery Landings. The commercial domestic landings, by species, of marine fish and shellfish in the United States as of May 2007 is shown in Table 1 (2). Almost 60% of the total fish and shellfish landings by the United States are caught 3–200 mi offshore. Much of the harvest in these waters is in the Fisheries Conservation Zone, which extends fishing jurisdiction beyond that normally considered international waters.

There is a large variation in the value of different species based on the consumer acceptance and the economics of harvest. Two relatively low-cost species, menhaden and pollock, accounted for 55.1% of the total fish and shellfish landed. Menhaden is reduced to fish meal for animal consumption, whereas pollock is the basis for the rapidly growing surimi and pollock fillet industry. Conversely, high-value salmon accounted for only 4.4% of the catch but represented 18% of the total value.

It is important to include the production of fish and shellfish from the rapidly growing aquaculture industry when considering total fish and shellfish availability. Although long established in other parts of the world (particularly Asia) aquaculture is a relatively new and rapidly growing industry in the United States.

3. Harvesting

3.1. Harvesting Gear

Static Gear. Although early fishing depended on spear fishing and later was the basis for sophisticated harpoon systems, modern commercial fishing methods use either static gear or moving gear when a vessel is used for towing or dragging. There are three basic types of static gear used in the commercial fisheries. The hook-and-line technique is familiar to all sports fishermen. The fish is attracted to the hook by an edible bait or by an attractive device such as a feather. As the fish tries to take the food from the bait or attacks the lure, it becomes attached to the barbed hook and cannot shake the hook from its mouth. A technique called long-lining is the major commercial use of hook-and-line fishing. A series of baited hooks are suspended from a buoyed horizontal line. This use of multiple hooks greatly increases the chances of catching fish and makes the fishing a viable commercial venture.

There are two basic types of trap used to catch fish and shellfish. One is an enclosure placed in the pathway of a moving or migrating animal while the other is a container or pot in which bait is placed. An animal crawls or swims into the tunnel entrance and then cannot escape because it is unable to find its way out of the narrow opening. Traps usually have a one-way wire door that can be easily pushed aside to enter but prevents regression.

Static nets, called gill nets, are a form of static gear closely related to traps. Nets are suspended from a few fathoms up to 50 fathoms into the water from a buoyed line. They are placed in the water where fish are known to be passing. The moving fish hits and penetrates the net. As it realizes that it has hit an obstruction, it tries to pull back. This causes its gills to become entangled in the webbing where the fish is securely held until the fishermen pull the net to the surface (3).

Towed or Dragged Gear. It is often necessary to sweep large areas of the ocean to catch sufficient volumes of fish or shellfish. This is done by trawling, in which large nets are towed through the water, or dredging, in which gear is towed along the bottom.

A trawl net is constructed like a large net bag that has a restricted end called the cod end. As a fishing vessel pulls the funnellike nets, fish are swept into the nets and collected in the bottom or cod end. The vessel must travel at sufficient speed to insure that the fish being collected into the net cannot swim out of the opening. The goal of a trawl operation, lasting from less than an hour to several hours is to fill the cod end (3).

Encircling Gear. Encircling gear is used for catching large amounts of fish that are schooled or densely concentrated. One end of the net, called a seine net is pulled from the fishing vessel and completes the operation by encircling the school of fish and bringing the end back to the vessel. Most seines have a line on the bottom that can be pursed to close the net and prevent fish from escaping. Typical fish that can be exploited by this method of harvest include anchovy, pilchard, sardine, salmon, herring, and tuna.

3.2. Fishing Vessels. The subject of fishing vessel design, construction, and operation is a most complex subject and will only be mentioned here. Fishing vessels range from small outboard motor boats operated by artisan fishermen to large oceangoing vessels, which require a sophisticated crew for efficient operation. The smaller vessels operate close to shore and return with the catch each day.

The length and sophistication of modern near-shore fishing vessels depends on the fishery, the fishing location and distance from shore, the distance that must be covered going to and from the fishing grounds, and the value of the catch. It is common to find vessels 20–50+ ft in length operating in the near-shore fishery and catcher-processor vessels of several hundred feet in length operating offshore on the high seas. The crews number from one to five on near-shore vessels and up to several hundred (including process crew) on the large catcher-processors. Likewise, the cost of fishing vessels varies tremendously, from about $200,000 for a small near-shore vessel to approximately $30,000,000 for the large offshore catcher-processors.

4. Maintaining Quality of the Catch

Quality is a term that has many definitions, depending on the background and interests of those queried. To some, the measuring of the product degradation by biological factors such as microorganisms or enzymes is the only means of determining quality. To others the aesthetic values that make a product look good are just as important in defining quality. In reality the biological factors determining safety and nutritional values and the physical factors used in a grading system (ie, size and weight uniformity, color, and blemished surfaces) are integrated to mean quality to most people.

The maintenance of quality or the fresh nature of landed seafood depends on many operations from the catching, landing, and shipboard handling to the transporting, storing, processing, and distributing. A biological specimen can only decrease in quality as it travels through the various steps of a commercial venture. Enzymes and microorganisms cause spoilage and degradation that are irreversible. Physical damage not only affects the appearance of a product, but such damage as skin ruptures allow microorganisms to invade the tissue and cause earlier deterioration. Therefore, all participants in the commercial seafood chain are important for maintaining high-quality products.

4.1. The Impact of Fishing Methods. Fishing gear is usually designed to give maximum efficiency in catching fish. The total cost of catching a given amount of fish includes vessel cost and operation, fishing gear cost and maintenance, manpower required, and other costs involving machinery and equipment. All factors are combined to give the cost of a given harvest known as the catch per unit effort (CUE). However, the best CUE does not insure good quality in the fish landed, and a processor is somewhat at the mercy of the fishing operation for initial quality of raw materials from the sea.

The type of gear used in fishing has a definite bearing on the quality. When a fish dies after or during vigorous exercise, such as struggling on a hook and line, metabolic activity including that of protein and lipid degrading enzymes, adversely affects the subsequent spoilage rate of the dead animal. If a fish has been feeding and has food in its stomach, the increased metabolic activity greatly accelerates the loss of quality in the slaughtered animal. The so-called soft belly of a fish is caused by this enzyme activity after the fish is dead. Because the amount of time that a hooked fish struggles is directly related to the subsequent spoilage rate, troll-caught fish are often of better quality than longline-caught fish that are allowed to die thrashing in the water.

The quality of gill net-caught fish is extremely variable depending on the length of time that the net is in the water. Hence, there can be a tremendous difference in the quality of fish taken from a given set, the last caught often being of higher quality. This factor is certainly realized by the wholesale buyers in that troll-caught fish consistently command a higher price than gill net-caught fish.

Certain visual or aesthetic factors also affect the market price of fish even though there may not be any real difference in the quality of the flesh. Marks from the web of a gill net are often caused when the fish struggles back and forth to release its entrapped gills. Unless the web causes cuts that allow bacteria to enter the flesh, these marks normally do not adversely affect the biological quality of the flesh. Hence, the word *quality* has different definitions, depending on whether it refers to the biological state of the edible portion or the visual appearance of the fish.

There are several types of fishing gear that cause abrasions and punctures during the catching and subsequent handling. Trawling, dredging, spearing or harpooning, and gillnetting all cause different degrees of damage. Trawling, which accounts for ca 40% of the world's fish catch, exerts extreme pressure on the fish as the cod end becomes full. In addition to scale abrasion, ruptures in the skin and internal portions release gut bacteria and decrease shelf life of the subsequent product.

The best quality is maintained in fish that are caught by trapping. As long as the trapping device is emptied on a reasonable cycle, the fish remains alive and is quickly killed prior to sale or processing. Some species, such as crabs, must be kept alive prior to butchering or there will be a blue color in the meat. This is due to the blood chemistry of crabs; they have a copper complex instead of the heme, or iron, complex found in most animals. If the crab is not butchered live and the blood removed prior to processing, the copper will oxidize, giving a blue color to the meat. Although the aesthetic value of the crab is impaired, the eating quality is not affected. However, as in the case of abraided fish skin, the consumer is not willing to consider blue crabmeat as anything but a low-grade, poor-quality product.

Aquaculture is somewhat akin to catching wild fish in trapping devices. The fish or shellfish are raised in an enclosed area and then removed when ready for market. As in the case of trap-caught fish, farmed fish are live when harvested.

4.2. Shipboard Handling of the Catch. The proper handling offish during harvesting and on shipboard can minimize the adverse effects of gear. Of utmost importance when fish are first landed is that they are segregated and placed in a sanitary chilled environment. Minimizing the bacterial and enzymatic activity by fast reduction of temperature in freshly landed finfish and shellfish is probably the most important step in the entire chain of events that takes a fish from the water to the table.

Figure 2 shows the extreme variation in storage life of fresh and frozen commercial fish prepared for the market. This curve has been compiled from many published sources that give the shelf life of fish as related to the handling methods (5). It has been shown that landed high-quality fish that is chilled rapidly and carefully handled, processed, and packaged can be acceptable for up to three weeks after being caught. On the other end of the scale, a fish that has undergone poor handling on shipboard (eg, 70% of as caught quality) and subsequent marginal handling during the processing and marketing stages is inedible after four days.

Fish that has been properly handled, processed, packaged, and frozen can be held up to one year without significant deterioration. However, there are many factors that must be considered in discussing shelf life of a fresh or frozen product. The species, the oil content, the catching technique, and the state of the fish when harvested are all uncontrollable factors that have a major bearing on the shelf life of a seafood product.

5. Processing Seafood

5.1. Inspecting As-Received Seafoods. Seafoods received in the processing area of a vessel or in a shore-based plant vary tremendously in the state and form. This is the situation when batches of product from different sources or catching vessels are mixed in the received lot. A sensory inspection must be made to insure that the raw material passes the criteria specified by the buyer or processor.

A sensory evaluation utilizes touch, odor, and sight to determine the acceptability of a given lot of seafood (6). An on-site inspection should concentrate on microbial contamination, enzymatic degradation, and other chemical and physical factors that reduce the marketability of the seafood. A faint fresh, nonfishy odor; firm and elastic flesh; bright and full translucent eyes; bright pink gills; and bright and moist skin surface with no heavy deposits of mucus or slime are all properties of a good fresh fish.

In addition to microbial and enzymatic degradation that can take place in improperly handled seafood, the oil in fatty fish that have not been chilled rapidly or adequately protected from the environment are subject to oxidative rancidity. This is both an aesthetic and nutritional problem. Oxidation from the air (and sometimes autooxidation within the seafood) not only affects the odor and taste acceptability of the product but also destroys the omega-3 ($n-3$) fatty acids in the oil that are so important for human nutrition.

5.2. Preprocessing As-Received Seafoods. Preprocessing begins on shipboard where the seafood is, at the minimum, segregated and chilled. Many fish destined for the fresh market are butchered and washed. The minimal butchering operation consists of removing the visceral portion and often the gills. The ultimate in shipboard butchering is heading and gutting, which consists of removing the viscera, head, and often the tail and fins. Shrimp are normally iced but sometimes the head is removed on shipboard. Crab are either delivered live directly to the shore plant or are kept alive in seawater tanks until delivery. In all shipboard preprocessing operations the most important procedure is to lower the temperature of the catch as soon as possible after it is taken from the water.

Preprocessing operations not carried out on shipboard are completed in the processing plant. After a second visual inspection, fish are butchered. This primarily consists of eviscerating but also can include scaling, trimming, and further cleaning when necessary for a specific processing operation.

Finfish are portioned for processing or direct marketing by filleting, steaking, or dressing a whole fish or section for roasting or broiling. Depending on the size and sophistication of the processing plant, these operations are carried out either by hand or machine. Crustacea (eg, crayfish, lobster, and crab) and mollusks (eg, clams, oysters, and mussels) are handled and processed quite differently from fin-fish.

Shrimp are iced on shipboard and unloaded by basket and conveyor into the plant receiving area. In the plant they are segregated and graded as to size by machine, passed over a visual inspection table for removing substandard specimens, cooked, and then headed and peeled (normally by machine). Large prawns are sometimes headed and handled individually on shipboard or in the plant. Those destined for market in an unpealed condition are then frozen. Prawns with head off and not cooked are called headed green prawns in the trade. Shrimp, regardless of whether they are marketed cooked and peeled, green fresh or frozen, or in other forms are sold by the count to designate size. For example 21–25 count shrimp means that there are 21–25 shrimp per 1b.

Crab is cooked prior to processing or marketing. It is important that the crab are alive when butchered just before being cooked whole. This is due to the high copper content in the crab blood, which oxidizes to a blue color if allowed to remain in the meat of a dead crab. Crab, depending on the species, are sold in the shell whole (eg, blue and dungeness), segregated with shell on into legs and body portions (eg, king and snow), or as leg and body meat. Meat is removed or shaken from the cracked shell portions by hand.

Bivalves must be alive when purchased and subsequently cooked in a plant, restaurant, or home. A healthy live oyster, clam, or mussel will have a tightly closed shell. Anygapers, eg, those with an open shell, must be discarded. This requirement for handling only live molluscs is important because they normally are not iced after being harvested by digging, picking, dredging, or tonging, but are delivered directly to the receiving station or plant.

Problems involving toxins (eg, paralytic shellfish poisoning) or communicable diseases being transmitted to the consumer by mollusks have become increasingly more prevalent as the coastal waters become more polluted (7). These animals are static so they are particularly vulnerable to any fluctuating environmental pollution problem that may exist. Furthermore, the conditions causing the meat to be inedible cannot be detected by simple in-plant inspection. This has resulted in an intricate system involving surveillance of mollusk-growing areas by federal and local government agencies who are responsible for closing harvest areas when there is a potential problem.

5.3. Total Utilization. There is a growing emphasis on improving the total utilization of seafood raw material (7,8). For many years, only the most desirable portion of the fish, often accounting for 20 or 30% (eg, fillets) of the fish, was used. The remainder was considered waste or a raw material for preparing cheap animal feeds. Environmental and economic considerations dictate that this gross misuse of base raw material must be stopped. Hence, the modern attitude is that there is no such thing as fish waste. The portions remaining after the initial edible portion is removed should be considered secondary raw materials that can often equal or exceed the amount of the primary edible portion. The initial preprocessing operation must consider the ultimate total utilization destination of all portions of the raw material. Some of the products that can be prepared or manufactured from, secondary raw materials are outlined in Table 2.

The developing operations and markets that use minced flesh for human consumption are beginning to have an impact on the economics of operating and the market for seafood products. Minced fish is used in engineered and formulated foods, the fastest growing segment of the food industry. Sources of minced flesh include

1. Frames (remaining skeleton) from a fillet operation.
2. Industrial fish presently being used for meal and oil.
3. Small fish currently being discarded or converted into fish meal that cannot be economically filleted or otherwise processed.
4. Freshwater fish presently being underutilized.
5. Low-fat fish that do not have good keeping properties due to rapid enzyme action (eg, pollock).

Minced flesh can be used in many products that require a protein base or binder. Such items include sausage (much lower saturated fat and calories than those made from pork), wieners, other cased meats, extruded meat products, nutrition-controlled foods (eg, low fat, high protein, and low sugar or carbohydrate), and other foods requiring ingredients with highly functional properties.

In the past, fish oils have been by-products from the production of fish meal. This low-grade oil has been used for industrial purposes or for making margarine. The large amount made into margarine has been manufactured in foreign countries because fish oil is not allowed for this purpose in the United States. The recent interest in fish oils for health has created a challenge for researchers to develop satisfactory refining techniques and subsequent edible products from the refined oils.

Some 30 years ago it was recognized that fish oil has beneficial fatty acids that are active in preventing or minimizing the effects of certain cardiac problems and other diseases. However, it was not until the early 1980s that highly publicized work demonstrated that diets of Greenland Eskimos, high in marine fish and mammals, were associated with greatly reduced numbers of deaths due to ischemic heart disease when compared to populations in more developed countries consuming low fish and high animal fat diets (9). Fish oil, through the consumption of more fish and formulated foods containing fish oil, is now considered a valuable contribution to a more healthful diet (4,10,11).

5.4. Heat Processing

Methods of Heating. Seafood, like any other food is cooked or heated to make it taste good by changing the texture and bringing out flavors and odors. If sufficient heat is added to pasteurize the food, microorganisms that can cause public health diseases and illnesses are destroyed or inactivated. Enzymes are also inactivated by heat so that protected cooked food stored under refrigeration is subjected to a minimum of degradation by hydrolysis.

The ultimate in heat processing is sterilization whereby the product is heated for a sufficient time at a given temperature. If the product is hermetically sealed so that there is no postprocessing contamination, it will have an indefinite shelf life free from degradation by microorganisms and enzymes.

Seafood is cooked and pasteurized by standard radiant energy baking ovens, infrared heating ovens, and microwave ovens. The heating in any oven is due to a combination of conduction, convection, and radiation. Food in a standard oven receives conduction heating from the pan or oven rack, convection heating from the air that is heated by the walls of the oven, and radiant heating from the exposed heating units. Infrared ovens do not have open heating elements because there is little convection heating from the air being heated by conduction.

Microwave heating is a specialized form of dielectric radiant heating that has certain advantages over other dielectric methods. Because the molecular polarizations are reversed many millions of times per second, the friction of molecules contacting each other cause heat and subsequent rapid, uniform heating of a food. Microwave heating has risen rapidly over the past decade. There are now microwave ovens in about 80% of U.S. households. Restaurants and institutional kitchens are rapidly increasing the use of this fast way of heating and cooking foods. The microwave oven with additional convection heating is becoming popular in that it combines the advantages of fast, uniform heating with the advantages of a conventional convection oven.

The growing popularity of microwave ovens has greatly increased the demand for microwavable foods. The major challenge to the food scientist developing microwavable foods is lack of radiant heat that causes the surface of a food to brown. Hence, cooked nondeep-fried potatoes, chicken, white fish, etc remain white on the surface and do not take on the normally expected desirable browning on the surface. Microwavable batter and breadings have been developed that are the color of deep-fried products. Hence, the future of microwaved foods will indeed be insured if low-fat, consumer-acceptable microwavable batter and breaded foods can be developed that take the place of deep-fried products. Fish fillets and formed patties from minced fish base stand to benefit as much from this development as any other food product. Fish sandwiches and batter and breaded fish have been growing in popularity, especially in fast-food restaurants. However, as shown in Table 3, the desirable omega-3 fatty acids suffer and the fat calories are tremendously increased when a fish is deep fried (8).

Commercial sterilization is carried out in steam retorts, which can process at temperatures above that of boiling water, normally at or above 117°C (242°F). The time and temperature required for sterilization must be sufficient to kill *Clostridium botulinum* spores that, when viable, can grow in an anaerobic (non-oxygen) atmosphere and produce lethal toxins. These spores must be held for 32 min at 110°C (230°F) to insure total destruction. Many low pH (high acidity) products such as certain fruits, vinegar-packed foods, and highly acid formulated foods prevent *C, botulinum* spores from growing. Many of these foods do not have to be sterilized at the temperatures required for high pH (low acidity). However, near neutral or high pH vacuum-packed products, such as seafood, are particularly vulnerable to anaerobic spore growth and sterilization must be insured.

To ensure a margin of safety, the sterilization requirement for canned fish is that the geometric center of a can or pouch must be held for 32 min at 116°C (240°F) (12). Each food and each different geometric form of container requires a different total processing time to accomplish sterilization. These processing times, determined by thermal death time laboratory studies, are mandatory for each processing company that is canning hermetically sealed food. Each batch of canned food must be coded and retort processing records kept to prove that the product was sterilized.

It should be emphasized that anaerobic conditions often prevail in a canned food even though an incomplete or no vacuum is drawn on the can prior to sealing. This is a result of the subsequent oxidation of components in a food by the remaining oxygen in the air.

Another precaution that must be practiced by processors is the venting of a steam retort prior to beginning the official retorting time. This is to prevent air pockets from insulating some of the cans so that there is nonuniform temperature in the retort. Of course, hydrostatic retorts. that heat containers in a column of water kept above normal atmospheric boiling temperature by hydrostatic water pressure do not have a problem with entrapped air.

Effects Of Heating. Fresh or frozen seafood being cooked for a meal should be heated for the minimum time required to improve the texture and the taste for the consumer. The normally dangerous microorganisms, those known as public health disease organisms are destroyed at relatively low temperatures. As shown in Table 4, the most heat resistant of the group, thermophiles, have an optimum growth at 50–60°C (122–150°F). Hence, a seafood is normally safe to eat if the geometric center has been raised above 150°F when it is actually pasteurized.

Overcooking causes heat degradation of nutrients, oxidation of vitamins and oils, and leaching of water-soluble minerals and proteins. The retention of B vitamins, zinc, and iron is particularly important for populations that consume fish as the major source of meat in their diet. In addition, overcooking causes too much water to be released and the drying effect causes flesh to become tough, thus nullifying the desired effect of texture improvement.

5.5. Refrigeration and Freezing Technology. As has already been stressed, the most important factor in handling fresh fish is to lower the temperature to just above freezing as soon as it is removed from the water. Because the condition of the harvested fish and the subsequent handling determines the shelf life of a fresh fish, it is not possible to state exact times that a seafood can be held in ice or under refrigeration and be considered a high-quality food. This is shown in the wide range of shelf life that has been published in the literature (Fig. 2). In general, fish with a high oil content or enzyme activity have greatly reduced shelf life and are often of marginal quality after a few days.

High-quality seafood, when frozen properly soon after being removed from the water, is often far superior to fresh fish available on the market. This is due to the fact that all microbial action is stopped and enzyme action is significantly reduced in frozen fish. However, the initial quality of the fish being frozen, the rate of freezing, the temperature at which the frozen seafood is held, and the uniformity of the freezing temperature are all important to maintaining a high-quality product. It is surprising how many people involved in the seafood chain do not understand some of these basic factors in ensuring the high quality of a seafood. Thus the constant challenge of those involved in seafood technology is the continual education and reeducation of everyone involved in the commercial seafood chain.

Freezing Seafood. During the freezing of seafood, structural changes take place in the cells and cell walls as well as in components that are between the cells. Many of these adverse changes are caused by water crystals that expand and rupture the cell walls. This allows liquid within the cells to leak out when the flesh is thawed. Hence, free liquid, called drip, exudes from seafood when it is thawed. This loss of free water reduces the water content of the seafood causing economic loss to the seller and greatly reduces the fresh qualities of the thawed product.

As seafood is cooled above and below approximately 28°F in a constant-temperature environment there is a near linear relationship between the temperature decrease and the time. However, as the water in the flesh begins to freeze, there is a long period of time during which the temperature remains almost constant. This period is a critical range for freezing and is caused by heat (heat of fusion) being removed from the fish to freeze water rather than to lower the temperature of the flesh. This relationship is shown in Figure 3.

The longer a product remains in the critical zone, the larger the ice crystals formed in the cells will be. When water is frozen rapidly, small crystals form and do not have time to increase in size due to the nucleation characteristics of a water molecule. Experience has shown that if seafood passes through the critical zone in ca 1.5 h, there will be little damage to cell structure as a result of large crystals formed during freezing. Fast freezing of seafood is essential to maintaining the quality of frozen products.

There is wide variation in commercial freezing facilities available to the seafood industry, and it is most important that commercial operators carefully study their options when purchasing and installing new equipment. The most efficient methods of freezing involve both conduction and convection freezing in an immersion system. Liquid refrigerants such as the freons have been used for this purpose but have proven too costly. Immersion freezing using refrigerated brine is fast and efficient but a considerable amount of salt is absorbed into the flesh during freezing and can be a problem to product marketing. Refrigerated seawater is used extensively, especially in Alaska for rapidly chilling and holding the fresh catch on shipboard.

Plate freezers rapidly freeze, by conduction, products that are in contact with the plates. Plate freezers are used to their best advantage when the plates can be brought together to contact both sides of a package. This is the case for rectangular packaged seafood portions or prepared formulations. A disadvantage is that irregular items, particularly large fish, can only contact the plate on one side and the exposed side must be frozen by convection. Another disadvantage is using plate freezers for whole fish, because the plate only contacts one side of the large irregular shaped item and causes one side of the finished product to be flat while the other side is the nice rounded shape of the live fish. However, unless the fish are suspended by hooks, this same condition prevails in any freezer where the fish are placed on shelves during freezing.

Convection blast freezing, where cold air is circulated over the products, is less efficient than conduction freezing but can be used for larger volumes. A disadvantage to blast freezing is that the rapidly moving dry air can dehydrate a product that is exposed for any length of time. This can be eliminated by proper packaging protection, but it also greatly decreases the heat transfer rate and lengthens the time of freezing and the subsequent time at which the product is in the critical range.

The problems with blast freezing can often be minimized or eliminated when a combined blast-plate-freezing system is used. This can be demonstrated by comparing Figures 4 and 5 in which chum salmon weighing 4 lb were frozen in two commercial units (13). Figure 4 is the freezing curve for a conventional blast freezer in which whole (headed and gutted) fish were placed on racks and frozen. Note that the time in the critical range was about 4 h and the total time to reduce the temperature to 0°F was about 8 h. The freezing curve shown in Figure 5 was that of a 4-lb chum salmon in a combined blast and plate freezer. The time in the critical range for this system was about 40 min, and the total freezing time to reach 0°F was slightly over 1.5 h. The fish frozen in the combined blast-plate freezer were far superior to those frozen in the blast freezer alone. Furthermore, the reduction in weight due to drip loss gave a significant economic advantage to the more rapidly frozen fish.

Holding Seafood in Cold Storage. Good freezing practices involving fast freezing and minimal dehydration of fresh seafood insures that high-quality products are delivered to the cold storage for holding. Equally important to the continuing maintenance of high quality is the environment under which the products are kept during the cold storage period. Unless frozen seafood is kept at extremely low temperatures, there is a certain amount of free water (not frozen) remaining in the product. This is a result of the antifreeze effect of soluble salts in the cell, which become more concentrated as water freezes. Depending on the specific food, the physical and chemical conditions of the food, and the composition (including water content), the point at which all of the water is frozen is in the range of −45°F. Because few, if any commercial cold storages are held at that low temperature, there is a certain amount of free water remaining in all frozen food (8). This is depicted in Figure 6, indicating that the normal commercial cold storage temperatures are well above -45°F. In fact, different commercial cold storage warehouses in the United States range in temperature from slightly above 0°F to a low that seldom is below -20°F.

Not only is the average commercial cold storage facility maintained at a temperature at which several percent of the water remain unfrozen but there is normally a significant fluctuation in the base cold storage temperature. Thus when the temperature fluctuates above and below the average, some of the water in the product is continually frozen, thawed, and refrozen. The effect of this fluctuation is to greatly increase the effect of enzyme action that essentially digests the protein in the same manner that it is digested in the gut of an animal. This is emphasized by the fact that continual thawing and refreezing is not limited to the original free water and causes the enzyme action to spread throughout the flesh. This is why the meat in seafood held for long periods can be extremely soft when thawed. This effect is even more noticeable in many home freezer units where temperature fluctuations are greater than those found in commercial facilities. Hence, holding a product at a higher but constant cold storage temperature can result in a better product than when it is held at a fluctuating lower temperature. This concept is depicted in Figure 7.

It can be important to know how much fish a given size cold storage unit will hold. The true density of a seafood ranges from 70 to 80 lb/ft^2. Because frozen fish blocks are essentially composed of solid fish flesh, they have about the same density as the natural flesh. At the other end of the spectrum, individually frozen and loosely packed fish range from 30 to 50 lb/ft^2. A well-run cold storage, allowing for the average distribution of product forms and allowing for air spaces and movement within the room, usually holds about 20–30 lb/ft^2.

Refreezing Seafood. Often it is necessary for a processing plant to receive frozen fish (either whole, butchered, or partially processed portions) for subsequent final processing or reprocessing. This occurs when fish are frozen at sea or other remote areas where total processing is not practical due to limited facilities or economic considerations. A typical example is when fish blocks are shipped to a plant for thawing, trimming, battering and breading, and re-freezing. A similar situation occurs when frozen fish or pre-processed raw materials are held in cold storage until they are processed in response to a specific market demand. For example, if fresh salmon are cut into steaks and frozen, there is no opportunity to sell the fish in the fillet form if the demand or price of fillets takes a sudden increase.

It is often said that seafood cannot be thawed and re-frozen. This is based on the too-often encountered situation whereby the fresh fish has been abused, the products have not been frozen rapidly, or have been held at high or fluctuating cold storage conditions. However, if the fish have been properly frozen and held in cold storage as described above, there will be little cell damage and the thawed product will have minimum water loss and reduction in quality from that of the original fresh raw material. Thus it can be thawed, reprocessed, and refrozen without significantly altering the quality of the finished product from that of the fresh fish.

The increase of high-seas processing vessels encouraged by the 200-mi limit (Fishery Conservation Zone) has greatly accelerated the final processing of frozen products prepared at sea. The future will probably bring an even greater acceleration of this trend as such products as batter and breaded (nondeep-fried) portions, whole fish, and (products engineered and formulated from minced flesh or chunk portions are being developed for microwave cooking. These are inexpensive low-fat products with good sensory properties especially acceptable to the increasingly large number of nutrition-conscious consumers.

5.6. Commercial Refrigeration Systems. There is a distinct difference between selecting facilities for freezing or for cold storage for a commercial seafood operation.

Freezing Facilities. The freezing facility is related to the products that will be processed, the throughput of product, and the space availability in the processing area. The differences between various freezing techniques lie in the control of the type of heat transfer between the product and the refrigerant. The types of freezer as related to the products being frozen are as follows.

Natural Convention Freezing. This facility is a room or chamber in which the product is frozen by natural convection. There are minimum problems with dehydration but the freezing rate is slow. Only products not affected by slow freezing should be frozen in this type of freezer. These would include formulated products or very small items where the water loss or cell damage through slow freezing is not a problem.

Combined Conduction and Natural Convection. The addition of freezer plates on which the product is placed greatly accelerates the freezing rate and maintains the advantage of minimum hydration during freezing.

Blast Convection Freezing. Blast freezing is a popular method of freezing irregularly shaped seafood items such as whole or partially dressed fish, A major disadvantage of this facility is that considerable loss of water through hydration can cause an unsightly surface condition known as freezer burn. This hydration, if allowed to continue, can remove a considerable amount of water from the flesh, making the fish inedible. Such is the case when a product is frozen and then allowed to remain (actually to be stored) in the freezer for some length of time before being removed.

When unpackaged products are destined for storage in a cold room with fast moving air, they are glazed to protect against dehydration. This consists of immersing the frozen product in cold water and then allowing the water film to freeze on the surface. The layer of ice protects the fish, because the air removes water from the glaze rather than from the product.

Combined Conduction and Blast Convection Freezing. This facility normally consists of refrigerated plates in a forced-air cold room. This freezer has the advantage of fast conduction freezing assisted by convection air on portions of the seafood that are not in contact with the plate surface. The tremendous increase in freezing rate by this combination of freezing techniques as compared to that of a blast freezer were previously discussed and compared in Figures 4 and 5. Normally the freezing rate is high enough to eliminate the problem of surface dehydration.

Conduction Freezing. When small rectangular products or packages with two parallel surfaces are placed between two refrigerated plates in a cold room or chamber, fast freezing takes place with minimum harm to the products. These types of facility have mechanisms that allow the plates to be vertically adjusted. This allows the plates to open, or separate, during loading and then they come in contact with the product for freezing.

Immersion and Cryogenic Freezing. Immersion in a cold liquid that will not affect the safety of the product (eg, brine, liquid nitrogen, or freon) is the fastest method of freezing. Freezing takes place by both convection from the circulating fluid and conduction from being in direct contact with the liquid. Immersion freezing in extremely cold refrigerants such as nitrogen or freon is called cryogenic freezing. Brine freezing utilizes saturated salt solutions that freeze rapidly due to the combined convection and conduction but takes place at about 0°F.

Cryogenic freezing has two limiting factors for extensive use in freezing seafood products. The first is that the freezing is so rapid that it causes extreme internal tension due to the freezing of the fiberous materials at a differential rate. This causes the flesh to rupture. It can be minimized by allowing the product to temper at room temperature before further handling, packaging, and placing in cold storage. The splitting problem can be fairly well overcome for small items such as fillets and steaks but large fish cannot be satisfactorily frozen by this means. Brine, on the other hand does not have the splitting problem and is a major means of freezing whole tuna fish on high-seas catcher vessels.

The second problem with cryogenic freezing is that it is uneconomical to operate unless the freezer is used continuously, because a considerable amount of heat from the cryogen is lost each time a processing unit is shut down and restarted. Most seafood-processing plants do not operate on an extended basis so that the cost per pound for intermittent freezing limits cryogenic freezing to a few fish processing plants.

Modern cryogenic freezing no longer uses liquid immersion true freezing. It is more economical to spray the liquid refrigerant on the food as it moves along on a conveyor belt. This uses less refrigerant and still gives the same advantages as immersion. Furthermore, when extremely cold liquids are used for freezing, especially in immersion freezing, vapor bubbles are formed that insulate the liquid from the product and prevent the rapid heat transfer expected from such a large temperature difference between the product and the liquid.

Cold Storage Facilities. Cold storage facilities must meet the requirements for long-term storage of commercial seafood products ranging from large whole glazed fish to cases of packaged retail products. Of particular importance in purchasing or contracting for such facilities in a plant or choosing a public cold storage for use include the following:

1. A design with proper insulation and construction materials that will insure a minimum of heat loss through the walls, ceiling, and floor.
2. Properly designed protection to minimize heat loss through doors and other openings, while the product is being taken into or out of the cold storage room.
3. Refrigeration machinery that will have sufficient capacity to hold the cold storage at the desired temperature.
4. Sufficient refrigeration capacity to insure that the temperature in the cold storage rooms does not fluctuate to the extent of adversely affecting the

products being stored. This is probably the major problem encountered with commercial cold storage facilities. So often a low bid is awarded to a contractor who is the lowest due to cutting back on the amount of refrigeration machinery and thus the ability to main tain constant storage temperature during variable and seasonal outside weather conditions.

5.7. Cured and Dried Seafood Products. Control of water activity, defined as the ratio of the vapor pressure of water in a product at any given temperature divided by the vapor pressure of pure water at the same temperature, not only applies to smoking and drying but also to salting, pickling, and product formulation. Product stability, the growth of microorganisms, and chemical reactions occurring during processing and storage are all dependent on the water activity, that is, the ability of water to move and interact with other ingredients in the food. The importance of water activity (a_w) in foods is shown in Table 5. The many facets of water activity and its relation to the preservation, safety, and shelf life of foods has been summarized by a group of internationally recognized experts (14).

Dehydration. Drying or dehydration is a means of controlling water activity by reducing the water content of a product. Many dried products, such as cereal grains, legumes, and many nuts and fruits, are dried by nature in the field prior to harvesting. In the past humans dried seafood products in the sun, long before they were aware that they were controlling water activity. In fact, today many developing countries located in tropical parts of the world use the sun as a major means of drying seafood and other food products.

The most efficient means of drying a seafood product is through dehydration by forced-air drying, vacuum drying, or vacuum freeze-drying. In each case the drying mechanism is a combination of adding heat to increase the temperature and vapor-driving forces between the product and the environment. The drying time is divided into two distinct periods: constant drying rate and falling drying rate. During the constant rate period, all of the heat added to the product is used to evaporate water from the surface and near surface of the product. In this case, there is free water in contact with the environment and drying occurs similarly to that of an open container of water. During the falling rate period, part of the heat energy is imparted to the product to cause water to migrate to the surface. Therefore, the product is heated during this period of the drying cycle.

Excellent highly nutritious dried formulated fish-base products can be prepared from the minced flesh of seafood.Shaped into forms such as patties and air dried, these items have a long and stable shelf life (15).

Curing. Whereas dehydration removes sufficient water to inhibit growth of microorganisms, curing consists of adding sufficient chemicals (eg, sodium chloride, sugars, and acetic acid) to prevent degradation of a product by microorganisms. Although sufficient water is not removed to accomplish this objective, the water activity is reduced to the point where growth is prevented.

Curing methods currently practiced include dry salting, where split fish is covered with salt and the brine liquor is allowed to escape, and pickling where products are immersed in a strong brine, or pickle, allowing salt to penetrate the product and water to be exuded into the brine solution. Low-fat white fish such as cod are dry salted by the heavy (hard) cure and fatty fish are-cured in airtight barrels by the Gaspe (light) cure. Figure 8 shows the process for the hard cure; the last step is air drying, which results in a salted-dried product with long-term, room temperature shelf life and a water activity of between 0.75 and 0.85. The Gaspe or light-cured product remains edible only a few days in the wet-stack stage (a_w = 0.85–0.90) at room temperatures and must be pressed and mechanically dried for longer-term storage.

Smoking. The age-old practice of smoking has changed drastically over the last few decades. The process as originally practiced by Eskimos and American Indians to preserve fish for the winter months was essentially a drying process whereby heat from a fire was used to reduce the moisture content sufficiently for extended storage. The smoke flavor was somewhat incidental to the process. In fact in some areas the fish were dried by the sun and the natural air currents and the smoke was used to prevent flies and insects from consuming and contaminating the product. This dried smoked fish, which takes days to cure, is known as hard smoked.

Today, most smoked fish is smoked for the flavor and there is relatively little loss of water in the process. The change in processing is a reaction to the consumer, who prefers a soft, moist texture rather than the tough texture of a dried product, and to the processor, who cannot afford to tie up large processing areas for longer-term smoking. Furthermore, the minimizing of moisture loss greatly improves the economics of processing and marketing smoked products. Hence, although smoked fish are considered to be processed in the same manner as fish in which water activity is altered, in reality the modern product is a partially or whollycooked fish that has smoke added as a condiment (16).

Most of the smoked fish prepared in the United States has little shelf life stability beyond that of a fresh fish. The commercial process of smoking involves splitting and cleaning the fish, salting or brining (soaking in a brine solution) to firm the texture of the meat, draining to remove excess moisture, and smoking. Smoking is carried out as a cold smoke, the temperature of the smoke does not rise above 85°F, or as a hot smoke, the smoke is hot enough (eg, 250°F) to raise the center temperature of the fish to above 140°F. It is also common to smoke the fish with colder smoke and then to raise the smoke and air temperature during the terminal part of the smoking to pasteurize the fish.

Today, much of the smoking is carried out in commercially constructed smoking facilities, or kilns, that have smoke generators (using sawdust), controlled temperature forced air, and humidity control of the air. There are as many specific smoking procedures as there are processors in the business. Each processor has a favorite method, including the use of certain additives in the brine, controlled-temperature drying, smoking, cooking, and cooling. Modern kiln smoking has allowed precise control of the variables in smoking and has removed much of the artisan approach that was so prevalent when all smoking was carried out using open wood fires.

Specialty hard-smoked fish, known as jerky, is prepared by smoking and drying fish to a hard, chewy consistency. This product is popular in the bar and tavern trade and for hikers who wish to carry a meat product that will not spoil during a several-day outing.

5.8. Irradiation. The United States is out of step with the rest of the world when considering the use of irradiation for preserving food. During the early 1980s, the World Health Organization gave ionizing radiation its blessing after an extensive review of many years of scientific work and investigation (17). Since that time, many countries in the world have been using irradiation on a wide variety of foods (8). A1though there has been steady progress in the United States toward approval of the process, there is still a widespread disagreement between scientific, government, and consumer groups regarding the pros and cons of using this form of energy for processing foods (18).

Two factors probably have equally contributed to this battle, namely the association in the minds of people between ionizing radiation and nuclear warfare, and the DeLaney Clause of the 1958 Food Additive Amendment to the Food, Drug and Cosmetic Law. The amendment, best known for the prohibition of a food additive that is shown to be carcinogenic in a test animal at any dose level, states that irradiation is a food additive and not a food-processing technique. It is interesting to note that the U.S. Department of Agriculture has issued an extensive list of publications that showthe safety and wholesomeness of irradiated foods (19).

Some confusion exists about the units used for measuring radiation doses that a product receives. This is because the original unit of measurement, the rad, was changedto kilograys (kGy); 100,000 rad (100 krad or 1 Mrad) is equivalent to 1 kGy (100,000 Gy). As shown in Table 1, the doses for processing range from 0.75–2.5 kGy for pasteurization to 30–40 kGy for sterilization. Note that specific process terminology has been suggested for the various operations. Pasteurization is radurization, sani-tization is radicidation, deinfestation is the process for destroying eggs and larvae, and sterilization is radaper-tization. Two radioisotopes, Co-60 and Ces-137, and electron-accelerator-generated electron beams meet the requirements for producing sufficient energy and intensity to penetrate food and accomplish the four basic processes. Both finfish and shellfish are highly perishable unless frozen on board fishing vessels or very shortly after harvesting. If unfrozen, their quality depends on rapid ice cooling. Irradiation can play a role in preservation and distribution of unfrozen fish and shellfish, with minimal sensory problems. The subject is reviewed extensively in Refs. 20 and 21.

Strategies for irradiation treatment of frozen fish products, dried fish, fish paste and other fish products have been investigated (22).

The radurization of fresh seafood has an excellent potential for extending shelf life. Being in the low-dose range, this process should not meet the resistance that is found for the publicized high doses that accomplish sterilization, but result in some off-flavor (23). The, extra week of shelf life that can be given to a fresh fish by radurization would be of economic benefit to the entire industry. The extra shelf life would eliminate product loss at the retail level and would extend the market range for delivering fresh fish.

There is every reason to believe that irradiation will eventually become an accepted and extensively used processing technique for seafood, especially seafood for the fresh market, where all parties will benefit. Perhaps during the next decade the radurization of seafoods will be commonplace. After all, 30 years ago there was the same consternation over the use of microwave ovens, and today they are in most U.S. homes.

6. Economic Aspects

6.1. Consumption. Total U. S. Fish and shellfish supply and disappearance from 1991 to 2005 are listed in Table 7(24).

6.2. Exports and Imports. U.S. fishery product exports were valued at over $\$4 \times 10^9$ in 2006, an increase of 4% or $\$138 \times 10^6$ compared with 2005. Exports increased in three of the five top markets, which account for 87% of U.S. fishery product exports (25).

The European Union −27 (EU) is now the largest export market for the United States, with 26% of total value of exports. Exports climbed to over $\$1 \times 10^9$ and 308,198 metric tons (t) in 2006, jumping 13% in value and 5% in volume from the previous year. Continued increases in demand for quality whitefisn contributed to the surge. Top product exports to the EU include pollock, lobster, salmon, cod and scallops.

Japan ranked second, with exports dropping to $\$937 \times 10^6$ and 286,257 t in 2006, a 13% decrease in value and 18% decrease in volume from the year earlier. Salmon product exports of $\$135 \times 10^6$ accounted for over two thirds of the decline due to a reduced sockeye salmon harvest. Japan continues to be a major market for U.S. fishery products as competition stiffens and demand increases in other foreign markets. Top product exports include surimi, pollock and salmon.

Exports to Canada dropped to $\$695 \times$ and 10^6 146,791 t in 2006, declining 2% in value and 12% in volume from the previous year. Salmon exports of 28,094 t accounted for over 40 percent of the decline in volume due to a reduced 2006 U.S. salmon supply. Top products exported to Canada include lobster, salmon and halibut. U.S. fishery product exports to China increased 25% to $\$445 \times 10^6$ and 13% in volume to 229,373 t in 2006. China is growing both as a market and as a processing center where product is processed and then re-exported to markets such as Japan and the United States. Top products include salmon, cod, sole, and squid.

Exports to South Korea increased to $\$406 \times 10^6$ and 140,567 t in 2006, increasing 3% in value and 7% in volume from the previous year. Increased salmon and sole exports contributed to the rise as product is often stored in Korea for further processing in Korea or in other markets such as China. Top products exported to Korea include pollock and surimi.

Table 8 gives the value and quantity of U. S. exports and imports of selected seafood products (26).

6.3. Aquaculture. U. S. seafood consumption as of 2006 is likely to see a high consumption of food from foreign sources. These imports stem in a large part from aquaculture production. Almost all foreign countries are in the same situation as the United States with limited ways to increase wild harvesting. The continued growth of the Atlantic salmon and tilapia provides good examples of how farm-raised product is being used in the rapidly expanding parts of the U.S. Seafood industry. The cost of energy affects this industry. Higher disposable income and low fuels prices will have a positive impact on the restaurant and seafood industry overall (26).

Aquaculture provides nearly 50%, or 59.4×10^6 t (2004), of the annual world fisheries production of 120×10^6 t. Half of all aquaculture production is finfish, a quarter is aquatic plants, and the remaining is made up of crustacea, such as shrimps, prawns and crabs, and mollusks, such as clams, oysters, and mussels. Table 9 gives production and value data for the top ten ISSCAAP (International Standard Statistical Classification of Aquatic Animals and Plants) species groups for aquaculture production for 2004 (27).

7. Packaging

Proper packaging of products is necessary to protect food from adverse losses and changes in weight, texture, flavor, nutritional components, and protection against contamination and physical damage. With the growing demand for high-quality seafood, the major emphasis is on packaging for fresh and frozen products. Basic types of packaging, in order of increasing ability to protect fresh or frozen food, include paper, coated paper, fiber, foil, films, laminates, and combinations.

One of the primary considerations in selecting packaging for fresh and frozen foods is the gas and water permeability of the material, usually plastic films, plastic containers, and treated paper products. There is always a balance between the cost of the package and the degree of protection given to the seafood. A very low cost uncoated cellophane has a moisture permeability that is so high that frozen and even cold fresh products are rapidly dessicated during holding. A film such as poly(vinyl chloride) (PVC) costs more but gives moisture-barrier protection that improves the overall economics of the processing and marketing chain.

The same economic analysis must be made for gas permeability, because oxygen entering the package tends to oxidize lipids and give off-flavors while some of the desirable volatile taste and odor components may be lost from the product. The fact that some films give good vapor-barrier protection but allow moisture to pass while others act in a reverse manner has encouraged the development of laminated films for food packaging. Laminates for seafood packaging often consist of polyethylene (which is cheap, is heat sealable, is usable over a wide range of temperatures, and is a good moisture barrier) and another film that has a low permeability for gas (eg, CO_2, O_2, and N_2). Examples of laminates used in frozen seafood products include polyethylene laminated with low-gas-permeability poly(vinylidene chloride) (PVDC) or saran), polyester, cellulose, aluminum, or nylon.

Packaging not only protects the food but is also an important factor in the sales appeal of the product. Packaging that shrinks film to give better evacuation of air from the package, overwraps for multiple packages and trays, overwraps to give rigidity to a package, allows see-through to the product, uses vacuum to minimize oxidation of the product, and uses gas flushing to expel further air are all popular methods of protecting processed seafoods. Packaging materials have become quite sophisticated and the accompanying use technology has been developed to meet the requirements for economic applications, long-term storage of products (particularly frozen), and enhanced consumer appeal.

The market for fresh food products has become increasingly popular. A system combining closely controlled combinations of low temperature, high: humidity, and proper ventilation has allowed extensive in-crease of the shelf life of perishable fresh foods. This system, hypobarics, was awarded the Institute for Food Technology's Technology Industrial Achievement Award in 1979 (28). Although hypobarics is a container system rather than a package, it can be considered a package in that it is used to contain a fresh product during the plant storage and transport time required to move the product to market. Originally developed for fruit, the system was extended to all fresh food items including seafood. Although the system has not been used extensively on seafood, it has been very successful with numerous products and should certainly be mentioned as a potential use for extending the shelf life of fresh seafood.

Another important area involving packaging technology is modified-atmosphere packaging (MAP), which has been shown to increase the shelf life of many perishable foods and formulated products by reported values of from 50 to 400% (29). However, there has been considerable concern by both regulatory authorities and researchers over maintaining the safety of MAP foods as they travel through the channels of commerce. The system, consisting of modifying the gaseous environment with a package, results in various combinations of carbon dioxide, nitrogen, and oxygen. Carbon dioxide is the important factor replacing much of the oxygen and nitrogen in the air (eg, 75% CO_2, 15% N_2, and 10% O_2). Of concern is maintenance of the proper refrigeration temperatures and the gas ratios for a given product so that microbial growth does not present an undue safety hazard.

Fish: fresh white fish, packaged in a mixture of 30% oxygen, 30% nitrogen and 40% carbon dioxide, should have a shelf life of 10–14 days at a temperature of 0°C. Such packages should not be exposed to a temperature above 5°C, because of the risk of botulism. Fatty fish are packaged in mixtures of carbon dioxide and nitrogen (30).

A considerable amount of research has been carried out in the MAP of seafood products (31). A significant amount of effort is being expended on developing the processor-distributor combination to improve quality and value of fresh seafoods.

8. Seafood Safety

8.1. Mercury in Fish. Fish and shellfish are an important part of a healthy diet. Fish and shellfish contain high-quality protein and other essential nutrients, are low in saturated fat, and contain omega-3 fatty acids. A well-balanced diet that includes a variety of fish and shellfish can contribute to heart health and children's proper growth and development. So, women and young children in particular should include fish or shellfish in their diets due to the many nutritional benefits.

However, nearly all fish and shellfish contain traces of mercury. For most people, the risk from mercury by eating fish and shellfish is not a health concern. Yet, some fish and shellfish contain higher levels of mercury that may harm an unborn baby or young child's developing nervous system. The risks from mercury in fish and shellfish depend on the amount of fish and shellfish eaten and the levels of mercury in the fish and shellfish. Therefore, the Food and Drug Administration, (FDA) and the Environmental Protection Agency (EPA) are advising women who may become pregnant, pregnant women, nursing mothers, and young children to avoid some types off fish and eat fish and shellfish that are lower in mercury (32).

By following these three recommendations for selecting and eating fish or shellfish, women and young children will receive the benefits of eating fish and shellfish and be confident that they have reduced their exposure to the harmful effects of mercury.

1. Do not eat shark, swordfish king mackerel, or tilefish because they contain high levels of mercury.
2. Eat up to 12 ounces (2 average meals) a week of a variety of fish and shellfish that are lower in mercury.

   - Five of the most commonly eaten fish that are low in mercury are shrimp, canned light tuna, salmon, pollock, and catfish,
   - Another commonly eaten fish, albacore ("white") tuna has more mercury than canned light tuna. So, when choosing your two meals of fish and shellfish, you may eat up to 6 ounces (one average meal) of albacore tuna per week.

3. Check local advisories about the safety of fish caught by family and friends in your local lakes, rivers, and coastal areas. If no advice is available, eat up to 6 ounces (one average meal) per week of fish you catch from local waters, but don't consume any other fish during that week.

Follow these same recommendations when feeding fish and shellfish to your young child, but serve smaller portions.

8.2. The National Shellfish Sanitation Program. The National Shellfish Sanitation Program (NSSP) is designed to prevent harvesting of shellfish in polluted waters containing pathogenic organisms or other contaminants (33). The program, begun in 1925 following illnesses culminating in typhoid fever outbreaks caused by contaminated sewage, is administered cooperatively among the federal government, states, and industry through the interstate Shellfish Sanitation Conference. The Food and Drug Administration is responsible for appraising each state's shellfish program to insure that they are complying with the specified requirements. NSSP gives each state the responsibility of defining or classifying its waters from which shellfish are harvested. The waters are tested and analyzed on a continual basis and classified as follows:

1. *Approved*. These waters may be harvested for the direct marketing of shellfish at all times.
2. *Conditionally Approved*. These waters do not meet the criteria for the approved waters at all times but may be harvested when criteria are met.

3. *Restricted*. Shellfish may be harvested from restricted waters if subjected to a suitable purification process.
4. *Prohibited*. Harvest for human consumption cannotoccur at any time.

The term harvest limited is used to refer to conditionally approved, restricted, or prohibited waters. A closure area is an area in which some restriction on harvest has been placed (eg, a harvest-limited area).

8.3. Hazard Analysis and Critical Control Point Principles. As the popularity and volume of refrigerated foods have been significantly increasing over the last decade, there has been an accompanying increase in the risks of food-borne disease. The overall safety record of a wide variety traditional refrigerated fresh fruits and vegetables; raw meats, poultry, and seafood; pasteurized milk; cured, ready-to-eat meats and seafood; high-moisture cheeses, yogurt, and pickles; and perishable delicatessan products has been good. However, the complexity of food-distribution systems presents risk factors that are increasing. This is especially the case of a new generation of engineered and formulated foods including frozen or restaurant dinners; frozen or delicatessan entrées; dry, frozen, or canned pasta; fresh, refrigerated salads; canned, frozen, or dry gravies; canned or dry soups; and frozen, canned, or refrigerated cooked meats and seafood (34).

In response to this increasing hazard, the National Academy of Science has studied the problem and recommended a system, the hazard analysis and critical control point (HACCP) system, which “provides a more specific and critical approach to the control of microbiological hazard in foods than that provided by traditional inspection and quality control approaches” (35). The system, similar to the critical control point system used by engineers in planning design, construction, and startup of a building or operation, include the following principles:

1. Describing the product and how the consumer will use it.
2. Preparing a flow diagram for intended manufacturing and distribution of the product.
3. Conducting risk analysis for ingredients, product, and packaging; reducing the risks by making changes to the design; and incorporating these changes into the processing and packaging schemes.
4. Selecting critical control points (CCP) and designating their location on the flow diagram and describing CCP, establishing monitoring.
5. Implementing HACCP in routine activities.

The assurance of food safety is a complex subject that impacts all phases of the commercial food chain, ending with the consumer. HACCP undoubtedly will have a strong influence on the future of many food operations. This impact will especially affect the seafood industry with its myriad safety and sanitation problems, many of which are specific to products from the marine and fresh-water environments.

9. Future Developments

Fish as health food is not a marketing gimmick but truly states the merits of seafood. The demand for this highly nutritious protein food, much avowed for its healthful omega-3 fatty acids, will continue to grow in demand. This pressure on a limited resource will encourage better biological management of the natural wild stocks (including international cooperation), faster expansion of aquaculture operations, and the total utilization of the raw material.

Much of the so-called industrial fish and the waste from present processing operations, currently being reduced to cheap animal foods, can and will be upgraded to human foods. Headed and gutted industrial fish can be deboned to give a highly acceptable minced flesh for engineered and formulated foods. A fish frame from which fillets have been removed contains as much meat as the fillets. This meat can be removed by deboning, and the minced flesh, nutritionally equal to the fillet or to any other minced flesh, is a tremendous source of base protein materials for formulated foods. Modern processing machinery, growing knowledge about the technology of formulated foods, and the demand for high-quality prepared foods support the trend to use previously underutilized seafood and seafood portions for this market.

As has been discussed, the technology of handling, packaging, and transporting fresh seafoods is rapidly developing and the future will see more fresh seafood on the market. In conclusion there is an exciting future for seafood in the United States. The new generation of refrigerated and frozen seafood and formulated products, as well as better quality traditional items, will continue to encourage increased consumption of both wild and farmed fish and shellfish.

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Table 1. **National Marine Fisheries Service Annual Landings by Species for United States in 2005**[a]

AFS Species Name	Pounds	Dollars	Price/Pound
Alewife	787,231	189,849	0.24
Alfonsin	18	86	4.78
Amberjack	212,429	140,838	0.66
Greater	1,421,161	1,294,952	0.91
Lesser	49,797	55,999	1.12
Anchovy, northern	25,162,706	1,127,013	0.04
Atka mackerel	129,482,451	14,892,866	0.12
Ballyhoo	669,016	439,458	0.66
Barracuda, pacific	78,942	56,132	0.71
Barracudas	157,377	112,936	0.72
Barrelfish	13,918	27,772	2.00
Longtail	658	675	1.03
Rock	1,985	1,906	0.96
Striped	7,862,425	15,302,712	1.95
White	362,824	220,761	0.61
Bigeye	10,177	5,078	0.50
Billfishes	541	488	0.90
Black driftfish	5,211	6,967	1.34
Bluefish	7,187,009	2,490,902	0.35
Bonito, Atlantic	100,026	138,854	1.39
Pacific	22,946	5,961	0.26
Bowfin	215,328	206,760	0.96
Brotula, bearded	7,452	7,916	1.06
Buffalofishes	3,967,557	740,580	0.19
Burbot	15,713	8,206	0.52
Butterfish	1,526,258	947,252	0.62
Cabezon	131,988	562,699	4.26
Carp, common	865,176	147,846	0.17
Grass	50,088	9,738	0.19
Carps and minnows	61,082	215,596	3.53
Catfish, blue	3,418,647	1,541,329	0.45
Channel	1,138,497	553,253	0.49
Flathead	271,320	130,438	0.48
Catfishes and bullheads	3,708,043	1,638,355	0.44
Chubs	1,711,491	1,086,333	0.63
Cobia	164,833	353,912	2.15
Cod, atlantic	13,919,433	20,827,826	1.50
Pacific	548,745,907	150,738,379	0.27
Crappie	4,756	7,960	1.67
Creole-fish	672	420	0.62
Croaker, Atlantic	24,127,416	8,988,652	0.37
cacific white	63,490	48,306	0.76
Cunner	5,661	8,664	1.53
Cusk	215,864	116,755	0.54
Cutlassfish, Atlantic	23,904	26,158	1.09
Dolphinfish	2,115,161	4,641,770	2.19
Dory, American John	15,355	9,787	0.64
Drum, black	4,698,484	3,735,377	0.80
Freshwater	884,239	120,782	0.14
Red	159,612	205,853	1.29
Drums	4,020	1,899	0.47
Eel, American	871,405	2,846,506	3.27
Conger	70,767	33,781	0.48

Table 1. (*Continued*)

AFS Species Name	Pounds	Dollars	Price/Pound
Eels	7,501	16,568	2.21
Snake	25	77	3.08
Emperors	1,776	4,053	2.28
Escolar	99,547	71,509	0.72
Finfishes, fw, other	2	3	1.50
UNC bait and animal food	6,120,698	3,976,198	0.65
UNC for food	112,974	96,293	0.85
UNC general	57,294,160	8,176,857	0.14
UNC spawn	7	7	1.00
Flatfish	3,891,769	2,160,989	0.56
arrowtooth	47,081,724	3,680,452	0.08
Flukes	1,894,592	2,968,699	1.57
Pacific, sanddab	543,708	250,201	0.46
Starry	327,519	147,015	0.45
Summer	17,265,354	29,360,867	1.70
Windowpane	194,420	96,856	0.50
Winter	8,084,142	10,687,953	1.32
Witch	5,847,479	8,814,696	1.51
Yellowtail	9,076,267	10,628,809	1.17
Atlantic, plaice	2,975,805	3,991,816	1.34
Pacific, sanddab	249,967	91,192	0.36
Righteye	3,799	1,600	0.42
Flyingfishes	8,664	1,600	0.18
Gag	3,353,030	9,032,260	2.69
Gars	542,216	394,909	0.73
Glasseye snapper	5,653	15,142	2.68
Goatfishes	32,296	86,527	2.68
Goldfish	19,837	3,963	0.20
Goosefish	42,112,424	42,417,480	1.01
Graysby	17	24	1.41
Grenadiers	355,605	58,898	0.17
Grouper, black	332,312	872,895	2.63
Marbled	3,389	6,914	2.04
Red	6,588,701	13,832,671	2.10
Snowy	426,918	991,618	2.32
Warsaw	161,558	332,861	2.06
Yellowedge	920,679	2,381,299	2.59
Yellowfin	9,519	24,439	2.57
Yellowmouth	522	1,140	2.18
Groupers	67,113	255,303	3.80
Grunt, white	18,469	18,014	0.98
Grunts	450,717	359,013	0.80
Haddock	16,713,943	19,136,419	1.14
Hagfishes	1,480,355	705,935	0.48
Hake, atlantic, red/white	14,139	11,430	0.81
Offshore silver	21,157	8,832	0.42
Pacific (whiting)	569,272,567	29,139,283	0.05
Red	946,757	478,430	0.51
Silver	16,529,116	8,268,557	0.50
Silver (offshore mixed)	794	518	0.65
White	5,908,466	4,979,327	0.84
Halibut, Atlantic	37,057	115,641	3.12
California	928,654	2,867,521	3.09
Greenland	5,219,457	778,202	0.15

Table 1. (*Continued*)

AFS Species Name	Pounds	Dollars	Price/Pound
Pacific	76,227,255	177,483,311	2.33
Harvestfish	116,354	127,073	1.09
Herring, atlantic	214,722,840	20,300,753	0.09
Atlantic thread	2,009,172	612,990	0.31
Blueback	8,265	1,981	0.24
Lake or cisco	504,181	259,056	0.51
Pacific	87,294,566	13,799,258	0.16
Herrings	842,167	166,277	0.20
Hind, red	16,750	34,841	2.08
Rock	17,594	55,918	3.18
Speckled	90,655	185,069	2.04
Hogfish	51,784	123,780	2.39
Jack mackerel	655,084	218,545	0.33
Almaco	109,615	89,694	0.82
Bar	34,867	27,724	0.80
Black	1,364	2,438	1.79
Crevalle	425,286	320,173	0.75
Jacks	98,721	115,597	1.17
Jobfish, green (UKU)	144,858	482,952	3.33
King whiting	1,483,009	1,325,692	0.89
Ladyfish	1,929,727	1,023,264	0.53
Leather-back	341	440	1.29
Leatherjackets	375,583	427,249	1.14
Lingcod	451,605	464,879	1.03
Lookdown	19,312	16,940	0.88
Lumpfish	164	32	0.20
Mackerel (Scomber)	11,594	8,987	0.77
Atlantic	40,800,655	7,048,793	0.17
Chub	7,851,631	575,490	0.07
Frigate	3	1	0.33
King	939,596	1,359,635	1.45
King and cero	4,576,639	7,094,025	1.55
Spanish	5,327,403	3,761,903	0.71
Margate	23,835	15,219	0.64
Marlin, black	2,344	2,740	1.17
Blue	943,570	967,127	1.02
Striped	1,191,852	1,534,381	1.29
Menhaden	1,243,722,815	62,465,369	0.05
Mojarras	431,997	463,840	1.07
Moonfish, Atlantic	60,567	54,554	0.90
Mullet, Striped (LIZA)	11,006,410	7,546,186	0.69
White	250,880	133,976	0.53
Mullets	689,330	450,111	0.65
Mummichog	3,300	14,974	4.54
Ocean sunfish	123	12	0.10
Oilfish	410,733	724,209	1.76
Opah	1,087,525	1,899,776	1.75
Parrotfishes	31,820	91,323	2.87
Perch, white	2,273,130	1,254,764	0.55
Yellow	1,791,168	2,897,656	1.62
Permit	20,956	28,470	1.36
Pigfish	30,019	7,817	0.26
Pinfish	94,948	288,839	3.04
Spottail	9,426	4,419	0.47

Table 1. (*Continued*)

AFS Species Name	Pounds	Dollars	Price/Pound
Pollock	14,366,313	7,887,321	0.55
Walleye	3,411,307,303	306,971,755	0.09
Pomfrets	646,085	1,440,166	2.23
Pompano, African	4,497	8,166	1.82
Florida	347,069	1,333,758	3.84
Porgy, Jolthead	10,536	10,883	1.03
Knobbed	21,115	17,445	0.83
Red	114,391	133,466	1.17
Whitebone	5,867	5,910	1.01
Pout, Ocean	6,332	4,345	0.69
Prickleback, Monkeyface	87	239	2.75
Puffers	27,532	19,932	0.72
Quillback	292,109	44,622	0.15
Rays	1,272	386	0.30
redfish or ocean perch	1,236,299	711,909	0.58
Rockfish, Aurora	1,054	920	0.87
Bank	35,882	29,513	0.82
Black	390,830	556,614	1.42
Black-and-yellow	22,541	146,614	6.50
Blackgill	119,722	121,890	1.02
Blue	42,134	54,919	1.30
Bocaccio	16,832	17,425	1.04
Brown	49,034	284,428	5.80
Canary	28,741	14,412	0.50
Chilipepper	147,901	75,240	0.51
China	6,706	43,754	6.52
Copper	11,629	45,489	3.91
Cowcod	85	91	1.07
Darkblotched	204,142	93,987	0.46
Flag	112	234	2.09
Gopher	40,244	263,408	6.55
Grass	28,006	256,809	9.17
Greenblotched	238	437	1.84
Greenspotted	715	1,237	1.73
Greenstriped	209	102	0.49
Kelp	1,822	8,967	4.92
Olive	2,565	4,766	1.86
Pacific Ocean perch	42,934,498	5,755,154	0.13
Pink	74	666	9.00
Redbanded	3,125	2,854	0.91
Redstripe	7,936	3,830	0.48
Rosy	28	63	2.25
Sharpchin	44	22	0.50
Shortbelly	5,907	2,304	0.39
Silvergray	154	72	0.47
Speckled	80	81	1.01
Splitnose	27,761	13,153	0.47
Squarespot	87	232	2.67
Starry	163	377	2.31
Stripetail	110	37	0.34
Treefish	1,771	13,268	7.49
Vermilion	39,712	84,420	2.13
Widow	293,917	129,182	0.44
Yelloweye	8,068	8,484	1.05

Table 1. (*Continued*)

AFS Species Name	Pounds	Dollars	Price/Pound
Yellowtail	1,826,942	851,050	0.47
Rockfishes	25,217,174	7,166,498	0.28
Rosefish, blackbelly	1,536	2,395	1.56
Rudderfish, banded	39,495	24,934	0.63
Runner, blue	350,285	212,998	0.61
Runner, rainbow	4,234	6,659	1.57
Sablefish	51,085,962	136,232,607	2.67
Sailfish	7,202	8,480	1.18
Salmon, Chinook	23,810,619	48,673,966	2.04
Chum	80,945,103	19,899,077	0.25
Coho	36,167,929	25,965,830	0.72
Pacific	934	3,651	3.91
Pink	494,614,341	49,040,883	0.10
Sockeye	264,229,452	187,205,501	0.71
Sand perch	408	748	1.83
Sardine, Pacific	190,413,012	10,193,572	0.05
Sardine, Spanish	1,009,256	247,248	0.24
Scad, Bigeye	536,331	693,858	1.29
Mackerel	147,506	329,221	2.23
Scads	1,046,098	1,057,645	1.01
Scamp	643,164	1,801,966	2.80
Scorpionfish, spiny cheek	457	423	0.93
Scorpionfishes	18,745	48,930	2.61
Sculpins	443,404	33,286	0.08
Scup	352,715	254,599	0.72
Scups or porgies	9,579,352	7,323,918	0.76
Sea bass, black	3,343,112	7,764,494	2.32
Giant	6,152	11,308	1.84
Rock	166	40	0.24
White	306,408	760,176	2.48
Sea catfishes	11,038	4,078	0.37
Sea chubs	19,435	19,844	1.02
Sea raven	601	338	0.56
Searobins	39,729	2,809	0.07
Seatrout, sand	72,804	40,035	0.55
Spotted	268,861	416,520	1.55
Shad, American	1,171,285	633,373	0.54
Gizzard	2,382,299	558,601	0.23
Hickory	227,692	47,576	0.21
Threadfin	73,206	41,655	0.57
Shark, Atlantic sharpnose	522,459	215,989	0.41
Bigeye thresher	19,506	5,909	0.30
Blacknose	100,198	45,477	0.45
Blacktip	1,353,579	434,355	0.32
Blue	1,707	1,417	0.83
Bonnethead	46,167	22,223	0.48
Bull	87,884	28,727	0.33
Dogfish	206,689	44,836	0.22
Dusky	14	8	0.57
Finetooth	114,032	61,143	0.54
Hammerhead	273,015	68,917	0.25
Lemon	70,567	23,255	0.33
Leopard	28,514	19,899	0.70
Makos	239,174	111,583	0.47

Table 1. (*Continued*)

AFS Species Name	Pounds	Dollars	Price/Pound
Pacific angel	25,496	14,030	0.55
Porbeagle	2,137	3,415	1.60
Sand tiger	354	143	0.40
Sandbar	1,698,583	516,707	0.30
Shortfin mako	310,988	247,932	0.80
Silky	4,276	1,911	0.45
Smooth dogfish	1,207,746	527,630	0.44
Soupfin	56,364	34,834	0.62
Spinner	42,342	13,830	0.33
Spiny Dogfish	3,581,600	668,110	0.19
Thresher	425,340	277,902	0.65
Tiger	10,416	1,563	0.15
Sharks	1,664,757	3,465,350	2.08
Sheephead, California	88,287	358,408	4.06
Sheepshead	1,732,581	731,041	0.42
Skates	53,948,991	7,049,061	0.13
Skippers	12,797	2,576	0.20
Smelt, Eulachon	938	1,421	1.51
Rainbow	426,865	211,442	0.50
Smelts	348,728	127,797	0.37
Snapper, black	3,987	5,576	1.40
Blackfin	4,740	9,808	2.07
Cubera	2,089	3,055	1.46
Dog	1,078	1.581	1.47
Gray	355,261	688,144	1.94
Lane	47,901	92,049	1.92
Mutton	234,187	463,973	1.98
Queen	20,090	44,175	2.20
Red	4,224,736	11,685,832	2.77
Silk	53,162	129,930	2.44
Vermilion	2,831,095	6,238,415	2.20
Yellowtail	1,326,267	3,046,490	2.30
Snappers	299,201	1,530,453	5.12
Sole butter	1,710	717	0.42
Curlfin	1,732	570	0.33
Dover	15,593,837	5,711,198	0.37
English	2,426,028	795,994	0.33
Flathead	31,945,882	5,254,590	0.16
Petrale	6,026,883	5,544,787	0.92
Rex	9,290,970	2,270,405	0.24
Rock	62,285,212	15,438,840	0.25
Sand	249,489	167,654	0.67
Yellowfin	188,105,064	23,485,027	0.12
Spadefishes	102,361	38,761	0.38
Spearfishes	465,812	419,877	0.90
Spot	5,118,796	3,193,937	0.62
Squirrelfishes	35,177	116,946	3.32
Sturgeon, green	6,342	5,640	0.89
White	414,738	756,514	1.82
Suckers	134,017	37,537	0.28
Sunfishes	4,027	4,830	1.20
Surfperches	59,087	105,199	1.78
Surgeonfishes	81,504	117,894	1.45
Swordfish	6,699,383	16,495,588	2.46

Table 1. (*Continued*)

AFS Species Name	Pounds	Dollars	Price/Pound
Tarpon, Hawaiian	640	652	1.02
Tautog	262,274	522,791	1.99
Thornyhead, Shortspine	1,390,300	1,864,075	1.34
Threadfins	331	1,903	5.75
Thresher sharks	70,453	22,336	0.32
Tilapias	139,032	85,473	0.61
Tilefish	2,367,352	4,995,614	2.11
Blueline	182,920	202,130	1.11
Goldface	34,771	51,859	1.49
Sand	30,166	56,741	1.88
Tilefishes	1,797	798	0.44
Toadfishes	2,178	2,498	1.15
Triggerfish, Gray	45,372	46,533	1.03
Queen	200	119	0.59
Tripletail	6,966	15,231	2.19
Trout, lake	415,301	164,528	0.40
Rainbow	305,828	372,170	1.22
Tuna, albacore	20,844,025	22,169,981	1.06
Bigeye	11,509,375	37,846,020	3.29
Blackfin	51,848	101,177	1.95
Bluefin	1,490,047	5,031,510	3.38
Kawakawa	3,247	4,653	1.43
Little tunny	447,627	107,050	0.24
Skipjack	2,115,176	1,421,052	0.67
Yellowfin	7,601,608	18,032,346	2.37
Tunas	284,124	1,033,964	3.64
Wahoo	972,458	2,459,928	2.53
Walleye	39,166	60,549	1.55
Weakfish	1,146,919	925,026	0.81
Wenchman	10,882	14,601	1.34
Whitefish, lake	8,541,033	6,768,545	0.79
Round	122,477	80,543	0.66
Wolf-eel	1,110	484	0.44
Wolffish, Atlantic	267,446	149,028	0.56
Yellowtail jack	21,589	28,223	1.31
--*Subtotal*--	*8,462,645,995*	*1,836,269,069*	
Abalones	1,200	4,864	4.05
Bloodworms	456,061	6,038,597	13.24
Clam, arc, blood	1,893	15,148	8.00
Atlantic jackknife	68,256	202,751	2.97
Atlantic surf	54,986,578	30,009,192	0.55
Butter	11,744	14,981	1.28
Manila	1,290,210	18,290,957	14.18
Ocean Quahog	11,891,930	9,145,328	0.77
Pacific geoduck	2,490,110	30,984,490	12.44
Pacific littleneck	38,011	83,211	2.19
Pacific razor	12,062	62,604	5.19
Pacific, gaper	3,493	7,514	2.15
Quahog	5,843,123	33,881,449	5.80
Softshell	3,365,435	22,116,376	6.57
Clams or bivalves	25,600,668	29,145,855	1.14
Cockle, nuttall	35,730	42,148	1.18
Crab, Atlantic rock	3,853,667	1,684,688	0.44
Blue	154,143,873	123,192,234	0.80

Table 1. (*Continued*)

AFS Species Name	Pounds	Dollars	Price/Pound
Blue, peeler	2,944,150	6,124,139	2.08
Blue, soft	766,108	3,441,956	4.49
Blue, soft and peeler	1,353,430	7,117,520	5.26
Deepsea golden	377,579	603,102	1.60
Dungeness	65,662,609	101,841,901	1.55
Florida stone claws	4,622,606	21,660,019	4.69
Horseshoe	1,420,829	514,854	0.36
Jonah	7,176,439	3,525,592	.49
King	23,938,929	91,042,174	3.80
Red rock	1,062,559	1,314,128	1.24
Snow	24,864,785	42,760,967	1.72
Southern tanner	3,517,925	6,178,904	1.76
Crabs	4,823,267	4,530,885	0.94
Crayfishes or Crawfishes	15,246,179	8,461,393	0.55
Echinoderm	4,185	2,196	0.52
Frogs	466	1,117	2.40
Limpets	3,396	36,051	10.62
Lobster, American	88,026,206	416,564,965	4.73
Banded spiny	4,620	56,792	12.29
California spiny	761,031	6,038,571	7.93
Caribbean spiny	3,382,045	16,742,439	4.95
Slipper	14,769	69,313	4.69
Mollusks	44,012	152,667	3.47
Mussel, blue	4,122,770	6,570,079	1.59
Octopus	61,818	92,426	1.50
Oyster, eastern	22,294,760	70,929,944	3.18
European flat	12,621	252,206	19.98
Olympia	7,426	221,558	29.84
Pacific	12,195,681	40,026,242	3.28
Periwinkles	1	30	30.00
Sandworms	438,924	2,251,754	5.13
Scallop, bay	96,503	1,221,792	12.66
Sea	56,563,438	432,481,868	7.65
Weathervane	204,732	1,637,853	8.00
Scallops	138,744	1,030,025	7.42
Sea cucumber	10,005,206	3,194,951	0.32
Sea urchins	15,748,637	11,805,156	0.75
Shellfish	28,911,419	16,860,358	0.58
Shrimp, blue mud	3,169	4,037	1.27
Brine	809,723	386,913	0.48
Brown	98,234,891	154,151,056	1.57
Ghost	58,633	116,609	1.99
Marine, other	7,390,744	13,573,875	1.84
Ocean	24,431,448	10,624,090	0.43
Pacific rock	61,269	130,860	2.14
Penaeid	2,033,052	4,670,417	2.30
Pink	13,532,137	25,799,753	1.91
Rock	1,595,828	1,400,330	0.88
Royal red	443,646	1,019,737	2.30
Seabob	2,365,835	864,406	0.37
Spot	270,372	2,816,739	10.42
White	110,555,593	191,635,715	1.73
Atlantic and gulf, roughneck	12,870	7,289	0.57
Snails (Conchs)	1,336,118	3,260,969	2.44

Table 1. (*Continued*)

AFS Species Name	Pounds	Dollars	Price/Pound
Sponges	48,070	25,000	0.52
Squid, California market	122,844,603	31,453,022	0.26
Giant	11,236	3,371	0.30
Jumbo	3,086,899	104,379	0.03
Longfin	37,389,221	28,838,011	0.77
Northern shortfin	2,981,419	881,619	0.30
Squids	373,567	184,579	0.49
Turtles	150,530,266	1,255,842	
Other			
--*Subtotal*--	*1,245,314,991*	*2,105,462,811*	
--*Grand Total*--	*9,707,960,986*	*3,941,731,880*	

[a]Ref. 2.
[b]Other includes seaweeds, turtles, frogs and sponges.

Table 2. **Total Utilization of Secondary Raw Materials from the Sea**[a]

Raw material	Product: Edible	Product: Industrial
finfish[b]	steaks roasts fillets minced flesh, surimi, formed foods, and extracted protein specialty foods refined oil roe and milt food additives	meal, oil, pet foods, pharmaceutical raw materials, and leather (skins)
industrial fish[b]	minced flesh, surimi, formed foods, and extracted protein specialty foods refined oil roe and milt food additives	meal, oil, pet foods, pharmaceutical raw materials, and leather (skins)
shellfish	whole (as caught) portions whole meat minced meat specialty products food additives	crustacea shell, extracted protein, chitin products, and calcium salts bivalve shell land fill meal and oil
seaweed	food food additives	pharmaceutical raw materials extracted products for industry

[a]Ref. 7.
[b]Process residues are an important source of recyled high-protein ingredients for on-site preparation of aquaculture-raised fish and shellfish feed.

Table 3. **Effect of Processing on Omega-3 (n – 3) Fatty Acids**[a]

species	Product	Lipid, %	Fatty acid in oil: EPA, %	Fatty acid in oil: DHA, %
cod	fresh	0.29	18.67	27.98
	batter and breaded	0.47	12.53	12.25
	batter and breaded, deep-fried in liquid vegetable oil	5.53	0.03	0.09
	batter and breaded, deep-fried in solid vegetable fat	9.14	0.21	0.65
	batter and breaded, deep-fried in beef shortening	7.07	0.66	1.51
salmon, sockeye	fresh	—	6.25	9.73
	canned	—	5.0	5.35
	canned (added salmon oil)	—	5.76	8.61

[a]Ref. 8.

Table 4. **Optimum Growth Temperature Range for Bacterial Group**[a]

Bacterial group	Optimum temperature range
psychotrophs	14–20°C (58–68°F)
mesophiles	30–37°C (86–98°F)
faculative thermophiles	38–46°C (100–115°F)
thermophiles	50–66°C (122–150°F)

[a]Ref. 12.

Table 5. **Importance of Water Activity in Foods**[a]

a_w	Phenomena	Food examples
1.0		water-rich foods ($a_w = 0.90$–1.0): foods with 40% sucrose or 7% NaCl, cooked sausages, bread crumbs, and kippered fish
0.95		
0.90	general lower limit for bacterial growth	foods with 55% sucrose or 12% NaCl, dry ham, mediumage cheese, and hard-smoked fish
0.85	lower limit for growth of most yeast	intermediate-moisture foods ($a_w = 0.55$–0.90): foods with 65% sucrose or 15% NaCl, salami, old cheese, and salt fish
0.80	lower limit for activity of most enzymes	flour, rise (15–17% water), fruitcake, and sweetened condensed milk
0.75	lower limit for halophilic bacteria	foods with 26% NaCl (satd), marzipan (15–17% water), and jams
0.70	lower limit for growth of most xerophilic (dry loving) molds	
0.65	maximum velocity of Maillard reactions	rolled oats (10% water)
0.60	lower limit for growth osmphilic or exrophilic yeasts and molds	dried fruits (15–20% water), toffees, and caramels (8% water)
0.55	DNA becomes disordered (lower limit for life to continue)	dried foods (a_w 0–0.55)
0.50		noodles (12% water), spices (10% water), and fish protein concentrate (10% water)
0.40	minimum oxidation velocity	whole egg powder (5% water)
0.30		crackers and crusts (3–5% water)
0.25	maximum heat resistance of bacterial spores	
0.20		whole mild powder (2–3% water); dried vegetables (5% water), and cornflakes (5% water)
0.00	maximum oxidation velocity	

[a]Ref. 14.

Table 6. **Dose Ranges for Food Irradiation Processes**[a]

Process	Dose range	
radurization (pasteurization)	75–250 krad	0.75–2.5 kGy
radicidation (sanitization)	250–1,000 krad	2.5–10 kGy
destroy eggs/larvae (deinfestation)	below 100 krad	below 1 kGy
radapperatization (sterilization)	3–4 Mrad	30–40 kGy

[a] Ref. 20.

Table 7. **Total U.S. Fish and Shellfish: Supply and Disappearance $\times 10^6$ lb[a,b]**

		Supply				Disappearance			
								Food disappearance[c]	
Year	U.S. Population July 1 $\times 10^6$	Production	Imports	Beginning stocks	Total supply[c]	Exports	Ending stocks	Total	Per capita, lb
1991	253.493	3,090	2,200	633	5,923	1,484	695	3,744	14.8
1992	256.894	3,157	2,100	695	5,952	1,602	598	3,752	14.6
1993	260.255	3,349	2,100	598	6,047	1,580	620	3,847	14.8
1994	263.436	3,305	2,180	620	6,105	1,562	602	3,941	15.0
1995	266.557	3,397	2,173	602	6,172	1,586	654	3,932	14.8
1996	269.667	3,251	2,285	654	6,190	1,672	613	3,905	14.5
1997	272.912	3,099	2,416	613	6,128	1,626	613	3,889	14.3
1998	276.115	3,088	2,597	613	6,298	1,660	636	4,002	14.5
1999	279.295	2,991	2,826	636	6,453	1,572	734	4,147	14.8
2000	282.403	3,122	2,931	322	6,375	1,758	326	4,291	15.2
2001	285.335	3,077	3,265	326	6,668	2,149	322	4,197	14.7
2002	288.216	2,979	3,487	322	6,788	1,976	312	4,500	15.6
2003	291.089	2,786	3,901	NA	6,687	1,938	NA	4,749	16.3
2004	293.908	3,119	4,091	NA	7,210	2,356	NA	4,854	16.5
2005	296.639	3,114	4,033	NA	7,147	2,363	NA	4,784	16.1

[a] Ref. 24.
[b] Edible meat weight.
[c] Computed from unrounded data.

Table 8. **Value and Quantity of U.S. Exports and Imports of Selected Seafood Products, $\times$ 10^3\$ January to June**[a,b]

Commodity	2002	2003	2004	2005	2006	2002	2003	2004	2005	2006
	\$1,000					1,000 lb.				
				Exports						
ornamental fish	4,348	4,369	5,152	3,275	3,128	NA	NA	NA	NA	NA
trout, live	141	205	1,231	169	286	NA	NA	NA	NA	NA
trout, fresh and frozen	982	4,017	1,000	692	879	744	2,042	574	414	414
Atlantic salmon, fresh	10,462	5,509	16,818	7,917	7,544	5,583	2,738	8,655	4,398	3,744
Pacific salmon, fresh[c]	9,459	7,005	12,604	9,154	4,296	6,103	4,936	8,185	5,711	2,436
Atlantic salmon, frozen	102	101	134	407	86	47	48	66	217	39
Pacific salmon frozen[c]	26,512	29,069	31,682	31,159	29,153	21,985	22,884	21,369	21,874	21,052
canned and pre. salmon[d]	57,937	51,384	66,077	72,322	78,708	41,244	35,761	46,357	46,425	53,389
shrimp, frozen	29,913	29,712	21,361	15,736	14,254	7,891	9,366	6,844	4,713	3,809
shrimp, fresh and pre.[e]	24,608	31,695	20,040	17,652	21,931	6,387	8,489	5,672	5,474	5,889
oysters[f]	3,717	4,264	6,069	9,486	7,329	1,763	2,275	3,222	4,284	3,268
mussels[g]	868	919	599	543	1,387	709	726	545	413	1,317
clams[h]	2,792	4,248	3,312	2,972	3,264	1,709	2,030	2,175	1,841	1,850
scallops	15,490	22,184	31,437	50,939	65,781	4,186	5,608	7,327	10,512	12,100
				Imports						
ornamental fish	20,811	22,093	21,979	23,918	26,257	NA	NA	NA	NA	NA
trout, live	52	132	76	286	478	NA	NA	NA	NA	NA
trout, fresh and frozen	7,025	7,345	7,151	5,782	83,212	4,408	4,316	4,222	3,126	4,139
Atlantic salmon, fresh	360,246	362,381	345,772	400,288	515,518	186,435	183,176	157,691	182,760	181,724

Table 8. (*Continued*)

Commodity	2002	2003	2004	2005	2006	2002	2003	2004	2005	2006
	$1,000					1,000 lb.				
Pacific salmon, fresh[c]	18,803	21,215	25,385	25,002	23,910	11,305	9,667	11,278	11,377	9,186
Atlantic salmon, frozen	49,083	69,963	81,999	84,598	124,214	29,320	29,834	34,148	34,245	39,848
Pacific salmon, frozen[c]	9,947	15,666	29,076	33,028	40,876	8,936	12,611	22,500	22,051	22,931
canned and pre. salmon[d]	18,903	30,765	33,889	32,093	45,881	7,145	11,475	12,837	11,294	14,590
shrimp, frozen	1,049,279	1,197,950	1,180,980	1,063,010	1,200,198	297,307	343,640	390,289	340,163	372,820
shrimp, fresh and pre.[e]	276,238	292,461	328,459	326,118	434,471	78,927	84,519	109,382	115,181	151,988
oysters[f]	14,697	18,621	20,676	23,127	25,957	7,394	9,692	10,469	11,008	12,005
mussels[g]	31,107	26,013	30,903	35,173	34,232	26,189	24,170	28,202	27,727	27,419
clams[h]	3,372	4,029	3,361	3,360	2,728	3,417	4,339	3,752	3,432	2,148
scallops	67,453	67,640	74,200	71,700	115,807	24,126	23,786	26,289	22,575	31,700
tilapia[i]	80,628	120,293	143,613	176,153	227,291	69,700	98,921	117,222	129,865	163,080

[a]Ref. 26.
[b]NA - Not available.
[c]Also includes salmon with no specific species noted.
[d]Includes smoked and cured salmon.
[e]Shrimp, canned, breaded, or prepared.
[f]Oysters, fresh or prepared.
[g]Mussels, fresh or prepared.
[h]Clams, fresh or prepared.
[i]Frozen whole fish plus fresh and frozen fillets.
Source: Bureau of the Census, U.S. Department of Commerce.

Table 9. **Top Ten ISSCAAP Species Groups for Aquaculture Production of Aquatic Animals 2004**[a,b]

Species group	Production, t	Production % of world total	Value $\times 10^9$ \$
carps and other cyprinids	18,303,847	40.3	16.4
oysters	4,603,717	10.1	2.8
clams, cockles, arkshells	4,116,839	9.1	3.3
miscellaneous freshwater fishes	3,739,949	8.3	6.0
shrimps, prawns	2,476,023	5.5	9.7
salmons, trouts, smelts	1,978,109	4.4	6.6
mussels	1,860,249	4.1	1.0
tilapias and other cichlids	1,822,745	4.0	2.2
scallops, pectens	1,166,756	2.6	1.7
miscellaneous marine molluscs	1,065,191	2.3	0.6
other species	4,334,931	9.5	12.9
Total	*45,468,356*	*100.0%*	*63.4*

[a]Ref. 27.
[b]Not including aquatic plants.

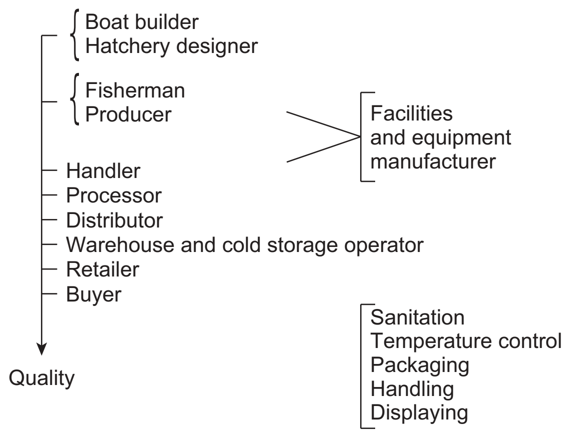

Fig. 1. The seafood chain from the harvest to the table.

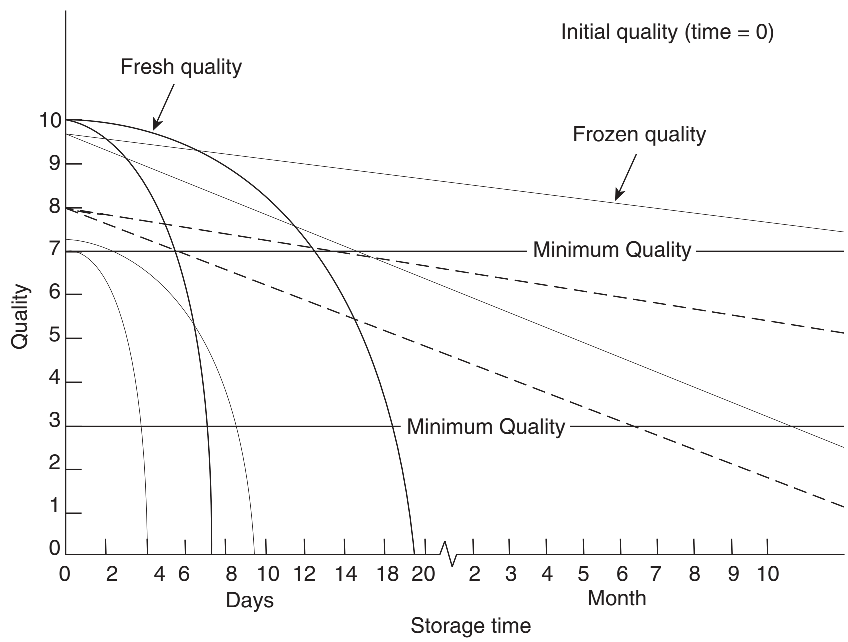

Fig. 2. Shelf life of fishery products (4).

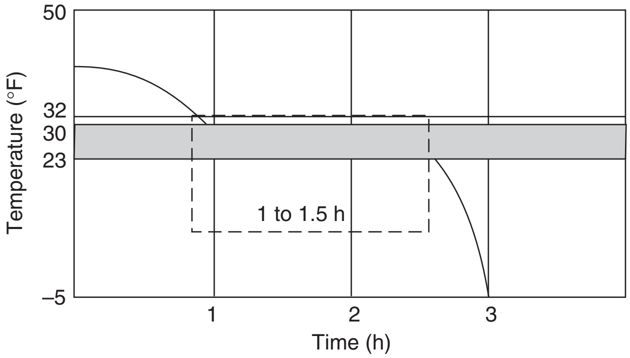

Fig. 3. Idealized freezing curve for fish muscle.

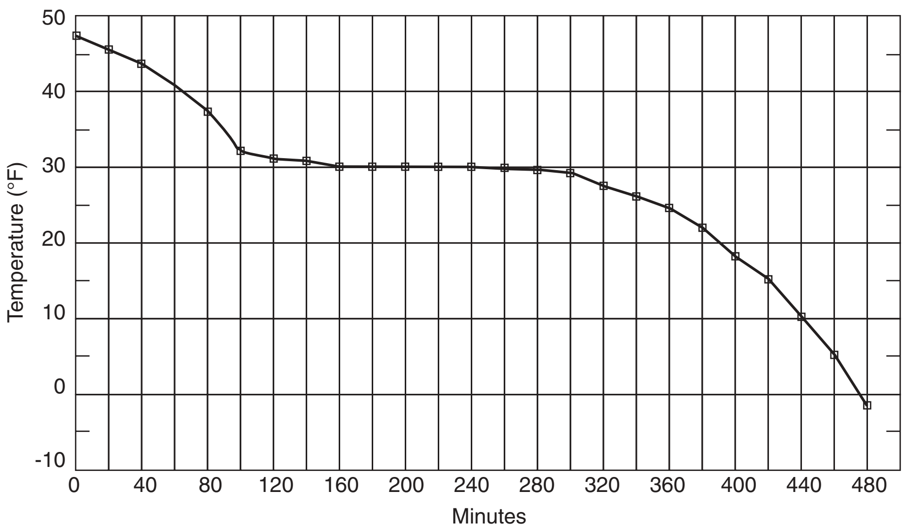

Fig. 4. Freezing curve for blast freezing of chum salmon (4 lb).

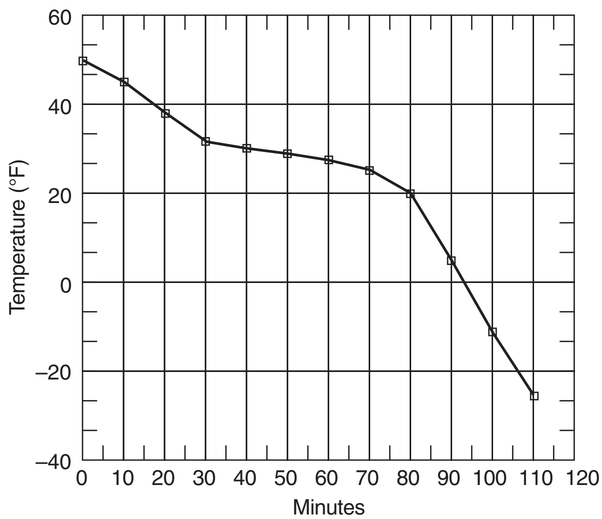

Fig. 5. Freezing curve for blast-plate freezing of chum salmon (4 1b).

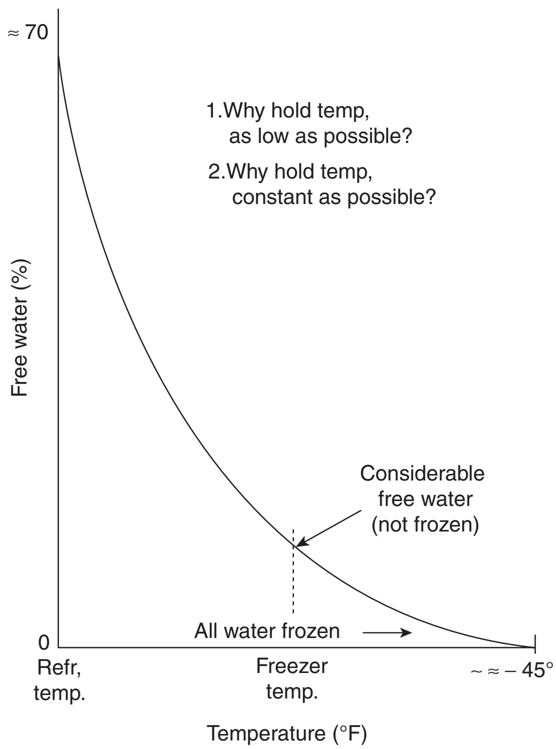

Fig. 6. Remaining free water in frozen food held at different temperatures.

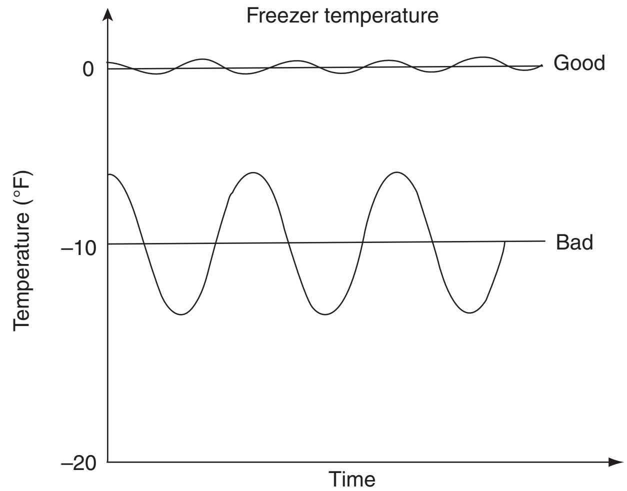

Fig. 7. Time-temperature relationship of food during cold storage holding.

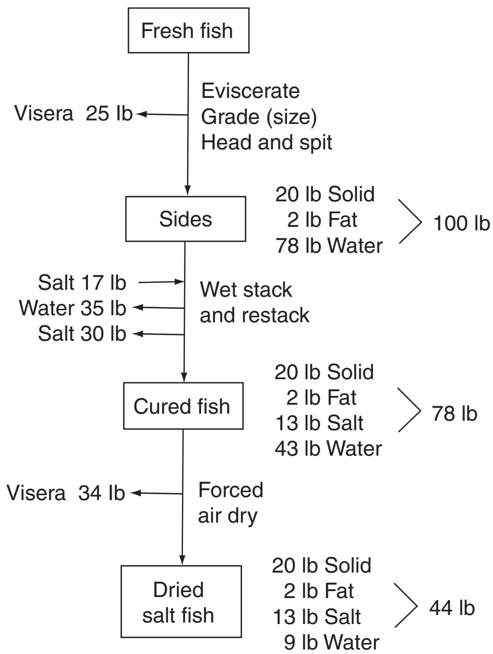

Fig. 8. Process for hard curing and drying of fish.