Processing Tuna, Scombridae, for Canning: A Review

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ABSTRACT—This manuscript is a review of canned tuna, Scombridae, processing from fish receiving through to the labeling and casing of the finished product. The topics of this review include history, Regulatory Environment (LACF, FSMA, Canned Tuna SOI), HACCP, the food safety hazards of Scombroid fish poisoning or histamine and Staphylococcus aureus, *and quality issues including struvite formation and prevention. Canned tuna processing operations are detailed, including receiving, sorting, production planning, recovery and labor-hours, thawing, butchering, pre-cooking, cooling, skinning, deboning, loin cleaning, can filling, seaming, retorting, labeling, and casing.*

Included is an in-depth review of changes to the HACCP guidance for processing tuna over the past 25 years (through 2021), and recommendations on how to use the HACCP guidance to improve tuna processing safety. The manuscript reviews the changes over the decades by the FDA toward a better understanding of the regulations and sampling protocols for attributes of tuna decomposition and for a safer canned tuna product. A goal of this document is to record the details and advances in canned tuna processing through 2021, while recognizing that the only constant in the tuna business is change.

Introduction

This paper reviews the processing of tuna, Scombridae, for canning from beginning to end. It follows the entire process from receiving the frozen fish at the cold storage until the cleaned loins are either a) put into the can, pouch, or container and retorted or b) frozen and shipped elsewhere for further processing. Retorted tuna in cans, pouches, cups, or jars is a nutritious and high-protein shelf-stable food with a shelf life of 2–5 or more years, depending on the container and packing medium. Although the individual processing steps for canned tuna have received much effort and investment to improve or optimize them, these individual unit operations and the total process have seen little fundamental change over the past five decades (Finch, 1963; Dewberry, 1969).

Modern tuna processing consists of many distinct processing steps with specialized equipment in multiple separate areas of the canning factory. The success of each step of the process depends on the success of the previous step so that product safety is maintained, quality is retained, and recovery or yield is maximized. This review addresses the regulatory environment as well as other processing considerations. Various significant developments in the tuna processing industry over the past 50 years will also be reviewed. This paper is written for tuna processors and anyone else interested in the processed tuna business.

The authors of this review are uniquely qualified with extensive experience in the world-wide tuna processing business, with most of them having 30–40 years or more of individual experience in one or more areas of the tuna business. Collectively they have worked in, started up, or developed over 30 tuna factories in all of the world's tropical oceans, as well as conducted basic or applied research in tuna processing to improve the food safety and quality of canned tuna.

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doi: https://doi.org/10.7755/MFR.83.3-4.1

Early and Recent Tuna Processing History

Northern bluefin tuna, *Thunnus thynnus*, have been captured and handled for human consumption for over 10,000 years. These tunas were captured in the Black and Mediterranean Seas, and the raw meat was preserved in salt. A fish sauce (garum) was produced as well from the salty liquid runoff (Di Natale, 2014). However, only within the last 150 years has tuna been canned and retorted to produce a shelf stable product (Mongruel et al., 2010) often called "tuna fish."

Mongruel et al. (2010) reported that albacore, *Thunnus alalunga*, were first canned in France in 1866 in the islands of Yeu, and canning tuna became an established business in France (Douarnenez, Brittany) around 1880. In the United States, albacore was first canned in California before 1903 (Felando and Medina, 2012). All of this tuna that was processed in France and the United States must have been precooked in some manner, probably in large water pots, before being packed into cans. One of the authors of this review (Lord[1]) has photos of 100-year-old water pots for cooking tuna in Libya (Fig. 1). The whole fish would have been precooked or pieces boiled in a pot to make cleaning easier and allow people packing the fish a bit more time to handle the fish. Boiling the fish will stop histamine formation for a while so the fish could be canned and retorted. Boiling would have also indicated any visual evidence of honeycomb. We discuss histamine and honeycomb later in this paper.

The first method for canning tuna that did not use precooking, known as a raw pack, was produced in 1936 in France (Paulet[2]). Prior to the commercialization of modern refrigeration technology, the tunas were held on fishing boats and delivered with no refrigeration or on ice (Wright, 1991; Mongruel et al., 2010).

Business Models

One tuna cannery business model is to land and process the tuna and then ship the sealed retorted shelf-stable containers (cans or pouches) within the country of manufacture or to export the canned and retorted product to another country. This is the common historical business model. A second business model is to land, store, thaw, precook, and clean the tuna loin meat in one country, pack the meat for frozen shipment in air-tight, high-oxygen-barrier plastic bags, freeze the bags of tuna meat, and ship the frozen bags (loins, chunks, flakes) to another country for actual packing in cans or other shelf-stable containers (Nolte[3]). These frozen bags of tuna meat can be held in a frozen state for up to 18 months. Current examples of the second model include frozen bags of tuna loins from Fiji to the United States, from Thailand to the United States and to the European Union (EU), and from Ecuador to the EU (Spain and Italy) and to the United States (Havice and Campling, 2018; DeBeer[4]).

Figure 1.—100-year-old tuna cooking pots in Libya.

Tuna processing began as a coastal business close to the fishing grounds with access to good shipping lines (in and out). Availability of fish, labor, and shipping determined the location of the factories with local unloading of the frozen or fresh fish from the fishing vessel. As the industry progressed, large, refrigerated transshipment carrier vessels were also employed to transport frozen tuna to the factories. This development also coincided with the further global growth of the tuna canning business, which thrived on the exploitation of inexpensive labor. When one of the co-authors (DeBeer) started his career (1971), there were at least 14 factories based in the United States or its territories processing whole round tuna into canned products that were then shipped to domestic and international markets (five in Puerto Rico; two in San Diego, Calif.; three in San

[1]Lord, C. W. 2014. Personal commun. (email: protech1993@live.com).

[2]Paulet, O. 2017. Personal commun. (email: olivier.paulet@yahoo.fr)

[3]Nolte, F. 2017. Personal commun. (email: nolte@shaw.ca).

[4]DeBeer, J. 2019. Personal commun. (email: jdebeer2005@gmail.com).

Pedro, Calif.; one in Astoria, Oreg.; one in Hawaii; and two in American Samoa), all processing raw, round fish. Fifty years ago, the factories in Puerto Rico depended on direct deliveries from purse seiners fishing in the eastern Pacific Ocean, as well as fish transshipped from frozen carrier vessels. The U.S. west coast and Pacific Islands factories primarily depended on direct deliveries from fishing vessels in the eastern or western Pacific Oceans.

At present (2022), there are only three tuna factories in the United States. Two of them process frozen, pre-cooked, and cleaned tuna loins as indicated previously. These bagged and sealed pre-cooked tuna loins are produced and shipped by a factory that processes whole fish to a factory in either Lyons, Ga., or Santa Fe Springs, Calif., that then produces canned product from these tuna loins. The third remaining U.S. factory is a traditional, whole raw tuna processing plant in American Samoa which has been there almost 70 years. The two-location business model, mentioned earlier, has been optimized with cooking and cleaning the fish and preserving it, frozen in plastic bags, in one location and canning the frozen loins in another location. Separating the processing of the whole fish from the final canning processing in two locations is now an important part of the tuna processing supply line.

Many of these changes to the canned tuna processing supply lines have developed over the years because of the industry's search for and response to finding inexpensive labor in areas that meet the other industry needs of fishing and shipping access. In 2022, other changes, such as closures of fishing areas for sustainability reasons, have increased the need for harvested and frozen whole round fish to be shipped long distances by carriers of frozen fish to keep the factories operating.

Transshipping means that the tuna fishing boats unload their cargos of frozen tuna onto refrigerated carriers. Thus, the harvest vessels can continue fishing while the frozen-tuna carriers move the fish from one location to another (Sylvester[5]). After the harvest vessels catch the tuna, the round tuna is quickly frozen. Frozen tuna travels well, in refrigerated containers or bulk carriers, from one ocean to another as the supplies and demands shift during certain periods of the year or the availability round fish changes (Sylvester[5]). However, tuna of the same species that are harvested from different areas of the oceans and the world may react differently to cannery processes, and the factory operations teams need to understand potential variables and adjust the process as needed (Correa-Gonzalez[6]).

Depending on the food available for the tuna, the precooked meat can be quite dry or very oily, so much so that some meat from fish with lots of oil in the flesh will have to be packed into cans with an oil medium rather than a water medium. Skipjack tuna, *Katsuwonus pelamis,* captured off New Zealand, or surface caught albacore caught off Spain or in the Northern Pacific are well-known as instances of high-oil tuna.

Every day in a tuna factory is unique, but the many daily issues and variations that need to be resolved are universal. There are many aspects of processing tuna of all sizes that differ from processing other fish. Variables in capture, chilling, and freezing impact canned tuna processing and intended usage, because different at-sea refrigeration systems can affect tuna quality and pack style. Incoming quality conditions need to be addressed and resolved. Modern tuna canneries process and pack different species of tuna in different container styles, sizes, and labels, using a multi-stage processing operation with different process times and controls. Many of these processes have prescribed times, there may be continuous steps, and the times will vary with different fish species or can size.

The tuna processing business is a dynamic business that can be relocated quickly, and ease of entry is limited only by capital and labor. Factories can be built, opened, and closed relatively easily. Much of the machinery has become standard and easily available and can be moved, reused, or resold. Examples of standard equipment include cold storage facilities, forklifts, fish boxes (bins), pumps, butcher-and-cleaning tables, tuna packers, can seamers, retort basket loaders, retort baskets, boilers, retorts, labelers, and casing equipment.

Locating factories often involves finding areas with low labor rates, high fish availability, and possibly the best tax advantage with good supply lines (Thailand/Philippines/Ecuador/Seychelles) (DeBeer[4]). The tuna business is a significant source of wages and foreign exchange for countries having tuna canneries built on their shores, thus, sometimes a coastal country with good fishing grounds will demand that a cannery be built and a workforce be trained in order to gain access to these fishing grounds (Papua New Guinea) (Lord[1]). However, as we shall see, the actual operation of a cannery is complicated and difficult. In 1960, the cost of raw tuna made up 70% of the cost of the canned product, as estimated by Erickson and Loewe (1960a). Remarkably, this cost ratio has remained the same for 60 years in the United States (DeBeer[4]).

Many international regulations and agreements govern the catch of tuna. There are also food safety and other laws regulating all aspects of the processing of tuna and other seafoods. The laws, regulations, and agreements for the capture of tunas are addressed elsewhere (ISSF[7]) and will not be covered in this review.

Raw Material Description

The world-wide harvest of tuna is about 4.9 million metric tons (t) (Hamilton et al., 2011; McCluney et al.,

[5]Sylvester, J. 2018. Shared excerpts from "The First Forty Years", Marine Chartering Co., Inc., 163 p. (email: John@chartering.com).

[6]Correa-Gonzalez, G. 2019. Personal commun. (email: gerson.hernando@gmail.com).

[7]ISSF (International Seafood Sustainability Foundation). 2017. Available at https://iss-foundation.org/knowledge-tools/databases/rfmo-management-database/, accessed 28 Oct. 2017.

2019; ISSF[8]). The tuna canning business uses 2.5 million t of raw tuna, about half of the total catch, all of which are wild-caught on the high seas (Hamilton et al., 2011). The fish are captured by a variety of methods and gears, including jig-boat trollers, pole-and-line baitboats, longline vessels, and purse-seine vessels. The commercial capture per day on these vessels can vary from a single fish up to 400 t on a purse seiner (DeBeer[4]).

The harvested fish are preserved at sea using ice, chilled seawater, air blast, or salt-brine freezing (DeBeer et al., 2019b; DeBeer[4]). Modern at-sea preservation methods reduce fish temperatures to 0°C (32°F) or below by chilling and freezing them as quickly as is practical (Burns, 1985). All large commercial tuna fishing vessels, including jig boats, pole-and-line baitboats, longliners, and purse seiners, are constructed to provide sufficient refrigeration capacity to chill and freeze the expected daily catch for the type of fish and capture method (DeBeer[4]).

Tuna Species

The United States Canned Tuna Standard of Identity (SOI) (FDA_SOI, 2001) lists 14 species of tuna that can be used to manufacture canned tuna, although a 15th, Pacific bluefin tuna, *Thunnus orientalis,* should have been included also. The primary species used for canned tuna in volume and value are skipjack tuna; yellowfin tuna, *Thunnus albacares;* bigeye tuna, *T. obesus;* and albacore (ISSF[9]). Other less-used species are longtail tuna (tonggol), *Thunnus tonggol;* bluefin tuna; Pacific bluefin tuna; southern bluefin tuna, *Thunnus maccoyi*; blackfin tuna, *Thunnus atlanticus*; little tunny, *Euthynnus alletteratus;* black skipjack, *E. lineatus*; kawakawa, *E. affinis;* slender tuna, *Allothunnus fallai;* bullet mackerel*, Auxis rochei;* and frigate mackerel, *Auxis thazard.*

Markets for each species of tuna are usually based on fish handling and quality and may be very different, such as for sashimi, sushi, other fresh or frozen markets, or for canning. Bluefin tuna are of very high value and generally sold fresh or frozen for raw consumption. The majority of albacore are destined for premium canned packs (DeBeer[4]). Most of the skipjack tuna are sold into the cannery trade. Yellowfin tuna can enter all of the markets depending on handling and distribution networks. Tonggol is locally valuable in Southeast Asia and the Indian Ocean and may be sold fresh or to be canned.

Yellowfin tuna and small bigeye tuna often are packed together into cans as the meat from the smaller bigeye has the appearance of yellowfin tuna meat in the can (Lord[1]). Smaller bigeye can easily be confused with yellowfin tuna as round fish, but the bigeye have larger eyes and a striated liver (Deriso et al., 1998). Identifiers such as body shapes and fins of the yellowfin and bigeye tunas diverge as they get older and larger, and the meat from the larger bigeye tuna is too dark for use in a light-meat pack (DeBeer[4]**)**. The striated liver of the bigeye is very good for a quick positive identification at tuna dockside and has been used in enforcement actions during the yellowfin or bigeye tuna fishing closures in the Eastern Tropical Pacific (DeBeer[4]).

Individual tuna can range in size from less than 1 kg each (*Auxis* sp.) to many hundred of kgs (bluefin, yellowfin, and bigeye). The Northern Atlantic bluefins are by far the largest, and the *Auxis* sp. are the smallest tuna species. All tuna are predators that feed on other fish, and all tuna can control their internal body temperatures to some extent (Dickson and Graham, 2004). Although some species of tuna inhabit or migrate through temperate water, all tunas spawn in warm equatorial water, over 24°C (Graham and Dickson, 2004; Bernal et al., 2017), except for the most primitive species, *Allothunnus*.

Tunas have regional endothermy, which is the ability to conserve metabolic heat with vascular countercurrent heat exchangers (Dickson and Graham, 2004). This means their body temperatures can be maintained above that of the surrounding water (Katz, 2002). Species of *Thunnus* are separated into two different clades or groups, depending on whether they have a central heat exchanger or not. Yellowfin, blackfin, and tonggol tunas have a central and lateral heat exchanger system in the slow muscle (red meat) (Altringham and Block, 1997). The bluefin (three species), albacore, and bigeye tunas have either lost or have a reduced central heat exchanger system. The bigeye, albacore, and bluefin tunas have striated livers, while the yellowfin, skipjack, and tonggol species have smooth livers (Block and Stevens, 2001). An excellent discussion of the physiology of the different species of tuna is presented in Bernal et al. (2017).

Tunas are caught at various times throughout the year in all oceans between lat. 72°N and 58°S depending on the temperature of the water column and the amount of primary ocean productivity at that time of the year (Bernal et al., 2017). The purely tropical tunas like tonggol, yellowfin, skipjack, and small bigeye can form schools with individuals close and dense enough to catch with a purse seine. The albacore and larger bigeye tuna may form schools, but the schools are not close enough or near enough to the water surface for harvest by purse seine gear. These tuna species are caught using trolling gear, longline gear, or drift nets (generally illegal). Sharp (2001) gives an account of this phenomenon.

Why are these differences in capture methods important for tuna processing? Schools of yellowfin, skipjack, smaller bigeye, and tonggol tunas are generally caught by purse seiners or baitboats in warmer water, while the albacore, larger bigeye, and bluefin tunas are usually caught by hook in cool-

[8]ISSF (International Seafood Sustainability Foundation). 2019a. Interactive Stock Status Tool (avail. at https://iss-foundation.org/about-tuna/status-of-the-stocks/interactive-stock-status-tool/, accessed 26 June 2019).

[9]ISSF (International Seafood Sustainability Foundation). 2019b. Status of the world fisheries for tuna: March 2019. ISSF Technical Report 2019-07 (avail. at https://iss-foundation.org/knowledge-tools/technical-and-meeting-reports/download-info/issf-2019-07-status-of-the-world-fisheries-for-tuna-march-2019/, accessed 20 Aug. 2019).

er waters. Since the onboard handling and preservation methods are different based on catch methods and area, the raw fish quality can vary and impact cannery processing and packing. For example, albacore being caught by hook on a longliner and frozen on board in an air-blast freezer has no salt added to its flesh. On the other hand, light meat tuna frozen in salt brines on purse seiners or baitboats can have varying amounts of salt absorbed into their flesh. Brine-frozen tuna should be tested for salt before processing and require controls to prevent producing or packing the cans or pouches with tuna that has too much salt (DeBeer et al., 2019b). More information is presented in the section on Sodium and Salt Control on page 33.

Types of Tuna Muscle for Canning

The tunas have two types of striated muscle: red meat and white or light meat. The white/light meat is considered the edible tissue and can be sold for human consumption in the United States. The red meat is not considered as edible tissue and is usually used as an ingredient in pet foods. Tuna must swim continuously, so they use ram ventilation of the gills to get oxygen from the water (Brown and Muir, 1970). The tuna's red (muscle) is used for swimming continuously, while the white/light muscle is used for vigorous, fast attack swimming in pursuit of prey (Graham, 1975). To maintain continuous swimming, heat must be conserved in the red muscle. This red muscle heat conservation has been documented for all tuna genera (*Allothunnus, Auxis, Euthynnus, Katsuwonus,* and *Thunnus*) (Sepulveda et al., 2008). Since they also must swim fast when needed, the tuna have thus adapted the two different muscle types (producing the red meat and white/light meat) to serve these different functions.

Graham et al. (1983) discuss the amounts of red meat in several species of tuna. This is important for tuna canning because the red meat must be separated from the white/light meat, and this amount of red meat affects the amount of edible meat recovered to be used for canning or human consumption. The amount of red meat in each species and fish size directly impacts the value of the raw fish and the labor needed to separate the red meat from the white/light meat. The percentage recovery of the white/light meat generally increases with fish size within a species, and the ease of skinning and separating the edible meat portions and the cleaning labor rates (time required to skin or clean the fish) decrease as the fish size increases (Correa-Gonzalez[6]).

Shelf-stable tuna products are produced in many forms: metal cans, glass jars, pouches, plastic cups, and other containers. The least expensive product per size is the canned tuna, and the most expensive is tuna packed in glass jars (DeBeer[4]). Tuna meat is traditionally packed with liquid media that include water, vegetable or fruit oils (soybean, cotton seed, sunflower, olive), and/or vegetable broths based on beans, celery, carrots, and onions added prior to sealing and retorting. Although the majority of canned or pouched tuna in the United States contains only tuna meat and liquid media, additional ingredients in the United States and other countries may include salt, chutneys, chilis, jalapenos, fruit juice flavoring (lemon), herbs, and spices. Canned tuna packs include solid, chunk, flake, or grated, which describe the size of the pieces of edible tuna meat and can be affected by the size of the can, the tuna piece size, the tuna meat composition, and the tuna meat color. Different regulations determine how canned tuna may be labeled for sale in the United States (FDA_SOI, 2001). Only edible white/light striated tuna loin muscle can be packed into canned tuna products, while other smooth muscle and parts like the heart are discarded or packed into pet food or processed into fish meal.

Only albacore can be labeled as white meat tuna and it must pass a special color test for whiteness. Edible tuna meat from the other allowable tuna species is packed as light meat tuna. Certain parts of the edible meat are too dark a color for the light meat packs, and they must be labeled as dark meat. Currently (2022), there are no national brands packing and selling dark meat for sale in the United States (DeBeer[4]), although, in some of the Pacific nations, dark meat tuna is canned in vegetable oil and sold.

Thawed tunas that have been previously sorted by size are butchered and prepared for precooking and cleaning in groups of similar size. This is to facilitate the scheduled precooking times and subsequent manual cleaning. As the fish is skinned and deboned, sections of usable meat get separated from the main loin portion and have to be cleaned separately from the tuna loins.

In most tuna operations, the maximum piece size available for canning is determined at the skinning and cleaning stage (DeBeer[4]; Colley[10]). As the red meat is removed, more chunks and smaller pieces of human grade meat get created. The removal of bruises or other quality defects from the tuna loins will create additional pieces and flakes (FDA_SOI, 2001). The manual cleaning of the precooked and cooled fish produces edible tuna meat: these pieces are called tuna loins, chunks, and flakes (DeBeer[4]; Colley[10]).

A single batch of similar sized fish, processed together, will yield solid, chunk, flake, and grated style edible tuna meat that can be processed and packed into cans, glass jars, pouches, or cups, or alternately, this tuna meat can be packed and frozen in sealed bags that will be shipped to other locations for further processing into retorted products. The red meat can be used to produce canned pet food products or are added to the bones and skin to produce fish meal, while the eyeballs can be harvested for highly refined fish oils. Modern processing factories now seek to process all the parts of the whole tuna and develop high-value markets for tuna processing by-products (DeBeer[4]).

[10]Colley, J. 2017. Personal commun. (email: javier.colley@thaiunion.com).

Regulatory Environment for Canned Tuna

The Pure Food and Drug Act (1906) and the Food, Drug, and Cosmetic Act (1938)

The production of canned tuna for U.S. markets is heavily regulated. The Pure Food and Drug Act of 1906 (PFDA[11]), was enacted to protect food safety and stated that adulterated foods (including fish) cannot cross state lines. The Food, Drug, and Cosmetic Act of 1938 (FDCA), (Cavers, 1939), replaced the PFDA. 21 U.S. Code 331(Prohibited Acts) prohibits the introduction into interstate commerce of any food, … that is adulterated or misbranded (U.S. Code 331). Sections 402 (a)(1) and (a)(3) of the FDCA state "If it (the food) bears or contains any poisonous or deleterious substance which may render it injurious to health or … that a food is deemed to be adulterated if it consists in whole or in part of any filthy, putrid, or decomposed substance or if it is otherwise unfit for food." These sections of the Act allow for the enforcement of the sensory analysis of tuna for decomposition and/or the presence of elevated levels of histamine (see next section). The presence of hydrocarbons or evidence of ammonia contamination of tuna are also considered adulteration. The FDCA (1938) also authorized the standardization of different types of packaged foods (Cavers, 1939).

California Cannery Inspection Act (1925)

The first law regulating time and temperature in the production of canned products, including canned tuna, was the 1925 California Cannery Inspection Act (CCIA). This regulation became the model for canning regulations around the world (Calif. Dep. Public Health[12]). The CCIA was a major piece of legislation for the regulation of all canned foods and was enacted after multiple deaths occurred from eating canned olives. Sanitary conditions were mandated in the canning factory, as well as standardized thermal processes for commercial sterility for canned foods.

Canned Tuna Standard of Identity (SOI) (1957)

Canned tuna is one of many U.S. foods that have a standardized identity. The Standard of Identity (SOI) detailed in 21CFR§161.190 specified the species of tuna (covered previously), style of pack (solid, chunk, flake, and grated), labeling, as well as ingredients (tuna, water, food oils, vegetable broth, flavorings, salt, and sodium acid pyrophosphate [SAPP]), (Federal Register, 1957; Federal Register, 1964; FDA_SOI, 2001). Vegetable broths (VB's) have been developed to add flavor and to maintain moisture in the fish muscle (DeBeer[4]). All the vegetables used in the manufacture of the VB for canned tuna must be listed in the SOI.

Canned tuna is a staple food in many developed countries and, as such, is regulated by many governments. Some of the regulations for the processing, structure, form, and ingredients of canned tuna are covered under:

a) The U.S. canned tuna standard of identity established in 1957, 21CFR§161.190 (Federal Register, 1957; FDA_SOI, 2001).
b) Codex Alimentarius for the European countries (CODEX, 1981).
c) The Canadian canned tuna standard (CFIA, 2018b).
d) Thailand Department of Fisheries[13] (DOF).

The SOI regulates the fill of container (FOC) which is the amount of tuna in the container. The original U.S. FOC law related to canned products was the Food Inspection Decision 144, 1912 (Callaway, 1947) which states "It should be as full of food as is practical for packing and processing without injuring the quality or appearance of the contents… Canned foods therefore will be deemed to be adulterated if they are found to contain water, brine… or similar substances in excess of the amount necessary for their proper preparation and sterilization." The liquid that is added for proper retorting and sterility cannot completely fill the container because canned tuna requires head space in the container to be able to maintain a vacuum after container closure. In the United States, the SOI was introduced in 1957 and required the pressed cake standard to be used for measuring the FOC (Federal Register, 1957; FDA_SOI, 2001). The U.S. pressed cake (weight) regulation for measuring the canned tuna fill of container is unique in the world, and the pressed cake target weight is based on the water capacity of the can (FDA, 2011b).

Companies manufacturing foods with standards of identity are allowed to deviate from an SOI with a temporary marketing permit (TMP). The three major brands of tuna in the U.S. petitioned the FDA to get a TMP to test market canned tuna using the drained weight of the tuna in the can as the standard for the FOC. This TMP was received in 2014 and extended indefinitely (evergreen) in 2016 (Federal Register, 2016). As part of the TMP the three major brands requested that the drained weight standard be exchanged with the press weight measurement for determining the FOC (Citizens Petition[14]). By early 2022 the evergreen drained weight TMP still exists (FDA, 2014c). The rest of the world uses drained weight as a standard method to measure the FOC, not the pressed weight method. In the EU, the drained weight standard requires that at least 70% of the net weight stated on the label of the product remain after container opening and draining for brine packs and at least 65% in oil packs (WELMEC, 2013). In Thailand, the drained weight standard requires at least 70%

[11]PFDA. 1906. Pure Food and Drug Act. Historical highlights (avail. at https://history.house.gov/Historical-Highlights/1901-1950/Pure-Food-and-Drug-Act/, accessed 19 Mar. 2020).

[12]Calif. Dep. Public Health. 2015. Significance and history of the cannery inspection program (avail. at https://www.cdph.ca.gov/Programs/CEH/DFDCS/CDPH%20Document%20Library/FDB/FoodSafetyProgram/Cannery/Significance-History.pdf).

[13]Department of Fisheries, Thailand (avail. at https://www4.fisheries.go.th/index.php/dof_en/view_role/7, accessed 1 July 2019).

[14]Citizens petition to amend the canned tuna standard of identity 21CFR§161.190. 3 Sept. 2015.

of the net weight (Thai Industrial Standard, 1987). In the U.S., in 2015 a proposal to change the SOI was submitted to use a minimum of 72% of the net weight, after draining, for both media styles, brine and oil (Citizens Petition[14]). The drained weight is reported as a percentage of the labeled net weight.

The drained weight procedure is very simple: the container is opened and emptied onto a number 8 mesh screen which is tilted to an angle of 17–20 degrees, and the product is drained for exactly 2 minutes and the product remaining on the screen is weighed (AOAC, 2011). The drained weight of tuna is the weight of the tuna meat remaining on a screen after the liquid has been drained off. The press cake method is much more complicated.

Good Manufacturing Practices (1968)

Good Manufacturing Practices (GMP's) are a large part of a quality assurance and regulatory system that ensures that foods for human consumption are produced and controlled by hygienic standards and practices. The rules are codified nationally in 21CFR§110 (1968) and 21CFR§117 (2011). These practices and procedures are designed to minimize food safety risks and hazards that cannot be controlled through final product inspection. The rules to enact GMP's for human food took effect in 1969. This was a major milestone to ensure a safe and sanitary food supply (Federal Register, 1986). There have been two major revisions since then in 1986 and 2011.

Low Acid Canned Foods Regulations (1973)

The U.S. regulations for producing a safe retorted food product are covered by the Low Acid Canned Food (LACF) regulations 21CFR§113 and 21CFR§108: these LACF regulations "were the first to utilize aspects of the Hazard Analysis and Critical Control Points (HACCP) approach to process control" (FDA, 2014a). The LACF regulations were implemented in 1973 and had a major revision in 1979 (Johnston, 1980). All canned tuna produced anywhere in the world for U.S. consumption must operate under the LACF regulations.

Nutritional Labeling and Education Act (1990)

The Nutritional Labeling and Education Act of 1990 provided for standardized nutritional labeling and a standard serving size of 2 oz for canned seafood, except for canned anchovies (Wartella et al., 2010). In 2016, the FDA published final rules on the new Nutrition Facts label for packaged goods. The major impact of that law was to revise some daily nutrient values, add some vitamins, and change the serving size for all canned seafood except anchovies from 2 to 3 oz (FDA, 2016). The larger 3-oz serving size for seafood became effective 1 Jan. 2020.

ASEAN-Canada Fisheries Post-Harvest Technology Project - Phase II (1992)

By the early 1990's, Thailand was the largest exporter of canned tuna in the world due to its unique position between two major fishing oceans. The quality and safety of the tuna and tuna products became a major concern of the Department of Fisheries, Thailand (DOF). From 1985 through the early 1990's, the Canadian Department of Fisheries and Oceans trained their personnel to improve the quality systems to address the quality, safety, inspection programs, and processing expertise for canned tuna products. This effort resulted in the development of the Canned Tuna Quality Management Manual (Suwanrangsi et al., 1995). This included a generic tuna HACCP plan (see next section) and a raw tuna sampling plan for histamine at receiving, which also provided a framework for organoleptic evaluations. Several time-and-temperature restrictions were determined, including a recommendation for precooking tuna to a 140°–150°F backbone temperature. The development of this Thai DOF manual was a significant improvement to the canned tuna safety knowledge base in Bangkok and other tuna processing factories in Thailand (Lord[1]).

Hazard Analysis and Critical Control Points—U.S. FDA (1997)

All seafood and fishery products processed for consumption within the United States are covered by the HACCP food safety system. The HACCP system uses Critical Control Points (CCP's) and Critical Limits (CL's) to control food processing risks. This science-based set of regulations to ensure seafood product safety was implemented by the FDA in 1997 through 21CFR§123 (Federal Register, 1995b). The first Fish and Fishery Products Hazards and Control Guide (Seafood HACCP Guidance or SHG) was issued in 1994 (FDA, 1994). However, by the early 1980's many tuna canneries were already testing for histamine levels using preliminary HACCP-like systems at the tuna-receiving step (Frank et al., 1981; Yoshinga and Frank, 1982; Burns, 1985; DeBeer[4]). More on histamine below.

The times and temperatures for the entire process cycle for tuna canning are covered in the latest FDA Seafood HACCP Guidance, 4th edition (FDA, 2011a; FDA, 2021a), subsequent amendments, or published scientific papers of validation of CCP's and CL's (Adams et al., 2018). Additionally, the FDA clarifies required CCP's or CL's to protect food safety via Warning Letters (WL) to individual processors. A summary of seafood HACCP warning letters is available from the Center for Food Safety and Applied Nutrition (FDA, 2017).

Food Safety Modernization Act (2011)

The U.S. Food Safety Modernization Act (FSMA) was enacted in 2011 (U.S. Public Law, 2011). The GMP regulation 21CFR§117 was introduced which applied a risk-based system to control food safety issues. Seafood processors are exempt from the HACCP portions of 21CFR§117 (FSMA), in general, because the existing seafood HACCP regulation based on 21CFR§123 has

Table 1.—Canned tuna food safety timeline.

No HACCP							HACCP -1		HACCP -2,3		HACCP 4th ed.	
1906	1925	1930	1938	1968	1973	1982	1994	1995	1998–2001	2004	2011	2020

1906 Pure Food and Drug Act : this would include smelling fish during butcher and packing as well as removing honeycomb during packing. No adulterated or decomposed fish in inter-state commerce.
1925 Calif Cannery Inspection Act - Process time and temp - retorting
1930 26L first published - National Canners Association Bulletin - National retorting standard
1938 Federal Food, Drug and Cosmetic Act
1968 GMPs 21CFR§110
1973 Low acid canned foods 21CFR§113
USDA 2 h or Calif - 3 h for tuna - pre retort lag time
1982 Defect action levels for histamine - 200 / 500 ppm
1994 Seafood HACCP Guidance - 21CFR§12
1995 ASEAN-Canada Manual
2004 Food Allergen Act
2011 FSMA

1906	PFDA.
1925	Calif. Dept. Public Health
1930	National Canners Association Bulletin L-26
1938	FFDCA
1968	Federal Register, 1968 - 21 CFR 110 GMPs
1973	Low Acid Canned Food Regs - 21 CFR 113
1982	Federal Register - 1982 - Defect action levels for histamine
1994	FDA - 1994 - HACCP Guidance 1st ed
1995	ASEAN – Canada Fisheries Post-Harvest Technology Project – Phase II
1998	FDA - 1998 / 2001 - HACCP Guidance 2nd & 3rd ed
2004	U. S. Public Law 108-282, Food Allergen … Act
2011	FDA -2011 - HACCP Guidance 4th ed
2011	U.S. Public Law, 111-353, Food Safety Moderization Act (FSMA)
2020	FDA -2020 - HACCP Guidance 4th ed, revised

protected seafood from safety hazards for about 20 years. The GMP regulation, 21CFR§110 is still in effect and enforced as well. Other required components and regulations of FSMA include the Foreign Supplier Verification Program, Accreditation of Third-Party Certification Bodies, Mitigation Strategies to Protect Food against Intentional Adulteration, and Sanitary Transportation of Human Foods (U.S. Public Law, 2011). Each non-U.S. supplier of food products is required to have a yearly audit by a qualified party to be certain that its food product processes comply with these regulations (Colley[10]). Table 1 summarizes the Food Safety regulations for canned tuna for the past century.

Biological Hazards and Control Measures for Histamine and *Staphylococcus aureus*

Scombroid Fish Poisoning (Histamine)

Fish of multiple genera and species that comprise the family *Scombridae,* including tuna species, can produce scombrotoxin (histamine) in their muscle tissue after death. Histamine, if ingested, can cause dangerous skin and intestinal toxic reactions in humans; however, histamine is rarely, if ever, deadly. However, scombroid fish poisoning (SFP) must always be considered a potential seafood hazard associated with tuna of which the prevention, using HACCP controls, is targeted.

Histamine can be produced in fish if, after they are captured, they are held without proper temperature control. Since wild-caught fish contain no histamine at the time of capture (Frank et al., 1981; Kim et al., 1999), histamine formation can be completely prevented by proper handling and temperature control (Hungerford, 2010).

Tuna and other Scombrids contain high levels of free histidine in their muscle tissue (Castellini and Somero, 1981; Abe, 1983; Biji et al., 2016). The free histidine acts as a buffer in the tuna muscle to counter the effect of the production of excess lactic acid occurring during their high energy activities of feeding, pursuit, or escape. When the tuna dies after capture and are not cooled quickly, histamine-forming bacteria (HFB) convert the free histidine in the tuna muscle to histamine by the histidine decarboxylation enzyme (HDC) (Hungerford, 2010; FAO, 2012). This decarboxylation reaction is energetically favorable for the HFB because they gain a proton of energy to use for pH control or metabolic energy (Molenaar et al., 1993; Konings et al., 1995; Ferrario, 2013). A clear explanation and schematic of the proton motive force generation by the decarboxylation and electrogenic antiporter is provided by Landete et al. (2008).

Histamine will form in the postmortem tuna that has not been chilled and stored properly (Burns, 1985; Hungerford, 2010). Histamine can also form in retorted canned tuna that has been opened, made into a tuna salad, tuna sandwich, or other foodstuffs, and left unchilled (McCarthy et al., 2015). Both food safety regulators and industry personnel make efforts to minimize histamine formation by controlling times and temperatures to limit its formation in the tuna on fishing boats, carriers, and canneries.

Histamine Regulations of Different Countries

The regulations or HACCP Guidance for maximum histamine levels for canned tuna vary throughout the world (DeBeer et al., 2021a). Some countries list maximum levels and others list maximum levels plus a sampling plan. Maximum levels by country range from 400 ppm in China to 50 ppm in Costa Rica (Costa Rica, 2004; Bingquan et al., 2017). The EU countries have a sampling plan of *n*=9, c=2, m=100 ppm, and M=200 ppm. This means two samples can exceed 100 ppm (m) but must be less than 200 ppm (M) in a sample size of 9 (Biji et al., 2016). In the United States in 2022 the new regulation enforcement limits are 35 ppm or more in 1 can in 30 indicating decomposition and 200 ppm or more indicating adulteration and subsequent legal action (FDA, 2021b). The limit for tuna received at a cannery will be 35 ppm or more with an *n*=18, c=0. The limit based on HACCP guidance recommended by the National Fisheries Institute (NFI) Tuna Council for acceptance into a tuna cannery for processing is 30 ppm (3 mg%) (NFI, 2014) for processed tuna destined for the U.S. markets. This recommendation is to provide for any delays in processing and thus is a safety allowance. Detailed sampling procedures for histamine are presented later in the section on Tuna Preparation Prior to Precooking.

Industrial tuna processing histamine control systems for the U.S. markets are separated into two components: the first is testing fish for existing histamine levels at the receiving canneries from catcher boats or carriers, and the second is suppressing the growth of HFB during processing with HACCP CCP's and CL's of time-and-temperature controls.

Histamine Action Levels and Testing at Cannery Receiving

Fish delivered for processing to a tuna factory packing products for the U.S. market must be first tested for histamine. The U.S. defect action level (DAL) for histamine in seafood is 35 ppm (3.5 mg%) or more (FDA, 2021b). Above that amount, the fish are considered adulterated, unacceptable for processing, and rejected. The action level (AL) is 200 ppm (20 mg%) or more which is based on toxicity and is the amount denoting a health hazard of food (FDA, 2021b). The 35 ppm DAL is determined by relatively small sample sizes using only a part of the fish, and, if higher, is viewed as evidence of mishandling of the fish during the harvest. This determination often suggests the possible presence of higher levels of histamine elsewhere (>200 ppm) within each individual fish or lot of fish (Staruszkiewicz et al., 2004).

Tuna Processing Time Guidance to Control Histamine Formation

The Seafood HACCP Guidance (FDA, 2011a) recommends a maximum processing time limit of 12 h for previously frozen tuna for histamine control if ambient temperatures exceed 21.1°C (70°F) at any point in the process, notably precooking. The time limit is designed to suppress the growth of HFB and thus curb histamine formation during processing. This time limit of 12 h includes all the process steps of thawing, butchering, precooking, cooling, cleaning, putting the loin meat in the can, seaming, and retorting until the center of the can reaches inhibitory temperatures for HFB of 60°C (140°F) (FDA, 2011a; FDA-WL, 2015) or the inhibitory temperature of 4°C for loin bags that are being frozen. Furthermore, the guideline of a 12 h limit (FDA, 2011a) for previously frozen tuna does not consider that the thermal treatment of the precooking step provides a clock re-setting heat treatment for histamine control and does not allow the 12 h time limit to restart after precooking. The 12 h guideline does not provide enough time to properly thaw, cook, cool, clean, and pack tuna, except for smaller fish (under 4 or 5 kg), without impacting (lowering) cooked meat recovery. Larger fish can take 12 h to thaw, so the time required for precooking, cooling, and cleaning will exceed the 12 h time limit (DeBeer[4]).

Precooking Temperature Guidance to Control Histamine Formation

Various studies indicate that precooking the tuna muscle to ≥60°C will provide a new starting time for histamine formation after cooling. Enache et al. (2013) developed thermal death time profiles for *Morganella morganii,* the most heat resistant HFB. Based on that work, Nolte et al. (2014) showed that a 60°C (140°F) core temperature of cooked tuna meat or an End Point Internal Product Temperature (EPIPT) was sufficient to reduce the *M. morganii* population by 5-logs. Each log is a factor of 10, so a 5-log reduction reduces HFB from 100,000 CFU/g to 1 CFU/g. A precooking validation study by Adams et al. (2018) concluded that the growth of HFB can be suppressed during precooking long enough to restart the clock and, hence, allow another 12 h to cool, clean, pack, seam the can, and get the center of the can of fish in the retort to 60°C (140°F). The 2021 Seafood HACCP Guidance recommends 12 h for fish that have been previously frozen or previously heat treated sufficiently to destroy HFB and are subsequently handled in a manner where there is an opportunity for recontamination with HFB (FDA, 2021a). This suggests the 12 h critical limit (CL) after precooking for histamine should start with first human touch, as it does for *S. aureus* (see below).

The information from Adams et al. (2018) validates that tuna processors can use precooking CL EPIPT of 60°C (140°F) as a Critical Control Point, thus extending the original 12 h limit by another 12 h of processing time after precooking stops, so in fact, allowing more than a 24 h span to process the tuna, depending on the precooking time.

The FDA recommendations for controlling histamine formation during this sequence of processing steps from a WL (FDA-WL, 2015) are

a) The time from when the first fish of a thaw batch is removed from the frozen antechamber until the last fish of the batch is within a precooker and the steam is turned on does not exceed 12 h.

b) Controls are in place to ensure that the precooker delivers sufficient heat to bring the cold spot of every fish in the precooker up to a minimum temperature of 60°C (in essence, to terminate histamine-forming microbial activity due to the previous exposure and to take advantage of a renewed exposure timeframe following the removal of the fish from the precooker); and

c) The time does not exceed 12 h from when the precooker doors are opened until the last fish product of the precooker batch is cooled, cleaned, packed, placed in a retort, and the cold spot of the containers (pouches, cans, etc) reaches 60°C or higher. This time-limit start time is different from the information in the Seafood HACCP Guidance (FDA, 2011a) which indicates the clocks starts with the first human touch after precooking and cooling.

Different Regulatory Scenarios for Tuna Processing in the Past Three Decades

There were four different tuna processing regulatory scenarios in the past decades (1990–2020).

Scenario 1

The 1994 Seafood HACCP Guidance (FDA, 1994) gave no guidance for restrictions for times and temperatures for tuna processing prior to retorting. Thus, there was no time-limit guidance from thawing through retorting except for a 2 h or 3 h time limit from the time the can was sealed until it was placed in the retort to prevent insipid spoilage (California Code of Regulations[15]; Cole[16]).

[15]California Code of Regulations, Title 17, Cannery Inspection Regulations, Section §12979 (avail. at https://www.cdph.ca.gov/Programs/CEH/DFDCS/).

[16]Cole, W. R. 2020b. In-plant sampling plans to address potential incipient or thermophilic spoilage. Tech. Bull. (avail. from TechniCAL, Metairie, Louisiana 70002).

Scenario 2

The guideline in the HACCP Guidance 2nd and 3rd editions (FDA, 1998, 2001) was a 12 h time limit from the start of thawing until the start of precooking.

Scenario 3

The 2011 Seafood HACCP Guidance and subsequent warning letters allowed 12 h from the start of thawing until inhibitory temperatures were reached (high or low) in the center of the retorted can or in bagged frozen loins (FDA-WL, 2008a; FDA-WL, 2008b; FDA-WL, 2010; FDA, 2011a; FDA-WL, 2016a). This 12 h limit is not enough time to process the tuna from the start of thawing until it reaches 60°C in the center of the can being retorted or 4°C in the center of the loin bag being frozen. This limitation allows only enough time for processing of small fish. Larger tunas require more time to properly process and to control histamine formation during the various processing steps of thawing, precooking, then cooling, cleaning, packing, canning, and the initial heating in the retort or chilling in the loin bag being frozen.

Scenario 4

Adams et al. (2018) showed that a safe process for controlling histamine during cannery processing includes a 12 h time period from the start of thawing until the steam is turned on in the precooker, the precooking temperature CL of 60°C (140°F) at the tuna core is reached, and a second 12 h time limit until inhibitory temperatures are reached in the retort or freezing chamber. With Scenario 4, larger fish can be processed than with Scenario 3 including thawing; however, the largest fish, for example, large albacore or yellowfin, still cannot be thawed properly within the initial 12 h period. To reduce the actual thawing time, tempering the frozen tuna to bring the temperature up from -20°C to -3°C, in chilled air, is an option. When the tempered tuna reaches -3°C, it can be brought into the water-thawing area, where thawing with water can start, and thus the thawing time will be shortened (DeBeer et al., 2021a).

Staphylococcus aureus Processing Guidelines

Staphylococcus aureus is a mesophilic bacterium that is commonly found on human skin (Kadariya et al., 2014). After high levels of growth, *S. aureus* can form a poisonous enterotoxin that is heat tolerant and is not destroyed by thermal processing in a retort (Schelin et al., 2011). Of the 9.4 million instances of foodborne illnesses due to major pathogens estimated annually in the United States, about 240,000 (2.6%) of them are estimated to be caused by *S. aureus* enterotoxin (Scallan et al., 2011), although the actual number is believed to be higher due to misdiagnosis, patients not seeking medical attention, lack of testing, or improper sample collection or testing (Scallan et al., 2011; Bennett et al., 2013; Kadariya et al., 2014).

S. aureus does not compete well with other bacteria, thus is not a risk to grow and produce this enterotoxin prior to precooking (FDA, 2011a). But after the other bacteria are destroyed by precooking, *S. aureus* growth and subsequent toxin formation may become an issue beginning with the potential problem for contamination of the precooked fish by human touch (FDA-WL, 2012).

As of 2022, there have been no documented cases of *S. aureus* enterotoxin in canned tuna, although the metal cans have been compromised with post-process contamination (Stersky et al., 1980). Since *S. aureus* growth only becomes a potential problem after the fish are touched and all the *S. aureus* bacteria are destroyed by the high temperatures during precooking and retorting, the guidelines are for a 3 h processing limit to prevent the formation of *S. aureus* enterotoxin (FDA, 2011a). This 3 h limit between the start of cleaning and retorting is required if ambient temperatures exceed 21.1°C (70°F) at any point in the process including precooking, waiting in front of the retorts, or in the retorts during retort loading.

The 3 h limitation ends when inhibitory temperatures of 50°C (122°F) are reached in the center of the pouch or can in the retort (FDA-WL, 2015) or 10°C (50°F) are reached in loins during the freezing process (FDA-WL, 2011). In a well-managed cannery, employees are trained not to touch the tuna fish after precooking, through cooling, and until cleaning starts. The cleaning-through-packing steps must be rapid to comply with this time limit. This compliance is most difficult when processing the larger can sizes and attaining inhibitory temperatures of 50°C (122°F) in the center of the can during retorting (FDA-WL, 2015).

The Seafood HACCP Guidance, 4th edition (FDA, 2011a), added multiple CL's of time-and-temperature for histamine and *S. aureus* control. Table 2 shows these various CL's for different process treatments.

Sampling Procedures for HACCP Controls

Tuna delivered for processing to a tuna cannery must be tested for salt (if brine-frozen) and histamine, and be evaluated for decomposition because of the variety of ways it was caught and preserved. The wild-caught tuna destined for canning are captured at sea using different types of vessels and with different methods of harvest and then preserved on board using a variety of methods including ice, refrigerated seawater, salt brine, and air-blast freezing. Chilling and freezing rates, as well as the frozen storage times, vary for different methods. Large purse seine vessels (seiners) and baitboats use saturated salt-brine freezing. Over time, salt can penetrate through the skin into the tuna flesh, and this added salt in the muscle will impact cannery processing and packing (DeBeer et al., 2019b). If the fish are not chilled and/or frozen rapidly or they spend long times in ice or refrigerated seawater (RSW), they may also be subject to decomposition from HFB and other means of spoilage.

The variation in salt (sodium chloride), and levels of decomposition or levels of histamine, require cannery testing for salt, histamine, and organoleptic screening for odors of decomposition. The tunas are screened organoleptically for decomposition after thawing at the butcher process. Fish internal temperatures are measured at receiving and also after precooking, if precooking is used as a CCP for histamine control.

The raw frozen tuna received into the factory are generally placed into large fish bins or totes of about 1 metric ton (t) each. The fish are separated into lots or batches for incoming quality evaluations (histamine and organoleptic). These incoming lots should be a maximum of 25 t based on the recommended histamine and sensory sample sizes (FDA-WL, 2016b). Generally, the lot numbers are assigned after the fish are sized at receiving. The samples for histamine (18 fish) and test lots for sensory evaluation (118 fish) are gathered from the incoming quality evaluation lots. After thawing and butchering and before precooking, these incoming quality lots are further assigned to precooking lots. They will be further assigned into production lots and seamer lots during packing and seaming. Preparation for retorting results in yet a further lot assignment. Then after retorting and cooling, the cans of fish are labeled and cased and placed on a pallet, which receives yet another case lot or pallet tag number.

In a modern tuna cannery with modern data processing systems, all of the canning day codes are assigned and printed permanently on the can lid or body and maintained to enable a recall or product withdrawal as needed at any stage of this process. All of the fish can be traced at any step of the way, back to the delivery and/or catcher vessel and ocean area of capture.

Tuna Spoilage

Tuna spoilage (adulterated fish) is caused by bacterial spoilage, chemical oxidation, proteolysis by endogenous proteases, and other enzymatic action. Some spoilage bacteria found on tunas produce off-odors, some produce histamine, and others produce both off-odors and histamine. Amino acid composition of fish species and differing populations and concentrations of these spoilage bacteria can produce decomposition profiles varying widely in the levels of spoilage odors and histamine. Incoming fish are tested for decomposition using different sampling plans for histamine (chemical testing) and persistent odors of decomposition using trained evaluators (FDA, 2011a).

For histamine sampling, the recommended sample size is 250 g of muscle to be removed from the lower anterior portion of the fish (FDA, 2011a), with the remainder of the fish used for processing. Organoleptic sampling is nondestructive and involves evaluation by smelling for persistent odors of spoilage for the skin, gills, and meat on the butchering cut (incision) into the stomach region and also visually for belly burn (proteolysis by endogenous digestive enzymes) of the stomach lining and other physical deterioration. For a guide to organoleptic evaluations of tuna, see the ASEAN-Canada Canned Tuna Quality Management Manual (Suwanrangsi et al., 1995).

Sampling for Histamine and Odors of Decomposition

Sampling of the incoming fish at receiving involves a multi-attribute sampling system and can be quite complex. One or more sampling plans are grouped and include a rectifying plan that can be used as needed (FDA, 2011a; Gomes, 2011). Attribute sampling plans can be described by operating characteristic curves (OCC) for each set of lot sizes (N), sample sizes (*n*), number of failures to accept (c) and number to fail (r), which is always one more than (c).

The multi-attribute sampling at receiving tests for two attributes: histamine levels and persistent of odors of decomposition by sensory evaluation. Rectification is possible depending on results from decomposition evaluation. It is critical that samples for histamine (18 samples) and sensory evaluation (118 samples) be collected from different individual fish, in order that reliability and confidence levels reported here hold true. Thus, a minimum

Table 2.—HACCP histamine control and *Staphylococcus aureus* processing guidelines.

Received tuna, frozen or unfrozen	Hazard	Process stage	Location	Critical control point or corrective action	Procedure	Sample size/location	Critical limit	Ref - comp and hyperlink tab
Never frozen	Histamine	Receiving	Wharf	Temperature collection	Backbone temperature	Min 12 fish, same species	< 4.4°C	FDA, 2011a:128
Never frozen	Histamine	Receiving	Wharf to factory	Transit	Cover with ice		Cover with ice	FDA, 2011a:137
Never frozen	Histamine	Receiving	Wharf to factory	Corrective action - lack of ice, temperature too high, fail sensory test	Chill with ice, test for histamine	60 fish, histamine, if fail, reject the lot, if pass, 100% sensory		FDA, 2011a:128
Never frozen	Histamine	Total process	Factory	No precooking CCP	Butcher through retorting		4 h	FDA, 2011a:142
Never frozen	*S. aureus*	Process time - *S. aureus*	Factory	*S. aureus* CCP, after first human touch	Post precooking to retorting or re-freezing (Inhibitory temps)		3 h	FDA, 2011a:12, FDA, 2011a:421
Never frozen	Histamine	Total process	Factory	Precooking CCP	Time from butcher to precooking		4 h	FDA, 2011a:142
Never frozen	Histamine	Total process	Factory	Precooking CCP	Precooking, time as needed	Min 24 fish, EPIPT	60°C	Adams et al., 2018; FDA_ WL, 2015
Never frozen	Histamine	Total process	Factory	Post-precooking CCP	Post precooking time, cooling, cleaning, packing		12 h or first chance of recontamination	SHG, p. 9, Adams et al., 2018; FDA_WL, 2015
Never frozen	Histamine	Process time - *S. aureus*	Factory	*S. aureus* CCP, after first human touch	Post precooking to retorting or re-freezing (inhibitory temp's)		3 h	FDA, 2011a:12; FDA, 2011a:421
Both	Histamine	Receiving	Factory	Collect histamine samples	Largest batch or lot size	25 m		FDA_WL, 2016
Both	Histamine	Receiving	Factory	Collect histamine samples	Single species per lot			FDA, 2011a:8
Both	Histamine	Receiving	Factory	Collect histamine samples	Collect uniformly throughout the lot	Min 18 fish, or entire lot	35 ppm	FDA, 2011a:133; FDA, 2021a
Both	Histamine	Receiving	Factory	Collect histamine samples	Sample location	Lower anterior portion, no belly flap		SHG, p. 9; FDA_WL, 2010
Both	Histamine	Receiving	Factory	Collect histamine samples	Sample size (wt)	250 g		FDA, 2011a:23; FDA_WL, 2010
Both	Decomp/ histamine	Receiving	Factory	Sensory	Thawed fish or if frozen used a piece of muscle collected with a drill bit	Min 118 fish, or entire lot	< 3 fish fail or 2.5%	FDA, 2011a:9
Both	Histamine	Receiving	Factory	Corrective action histamine	None, reject lot			FDA, 2011a:133
Both	Histamine	Receiving	Factory	Subdividing a lot for retesting	Not allowed			FDA, 2011a:9; FDA_WL, 2012
Both	Decomp/ histamine	Receiving	Factory	Corrective action, sensory	60 fish, histamine, if pass, 100% sensory of lot, if fail, destroy lot			FDA, 2011a:134
Frozen	Histamine	Thawing	Factory	Not U.S. HACCP, but Canada or Thailand	Max backbone temp at butcher		5°C	Suwanrangsi et al.,1995
Frozen	Histamine	Thawing	Factory	Thawing, water and air temperature	Need to monitor continuously			FDA_WL, 2008
Frozen	Histamine	Thawing	Factory	Water thawing	Need to monitor continuously water thawing below 4.4°C if it is a C.L.			FDA_WL, 2016a
Frozen	Histamine	Total process - histamine	Factory	No precooking CCP	Start of thawing to retorting or re-freezing (Inhibitory temps)		12 h	FDA, 2011a:142
Frozen	Histamine	Total process - histamine	Factory	Precooking CCP	Start of thawing thru butcher to steam on		12 h	Adams et al., 2018; FDA_ WL, 2015
Frozen	Histamine	Total process - histamine	Factory	Precooking CCP	Precooking, time as needed	Min 24 fish, EPIPT	60°C	Adams et al., 2018; FDA_ WL, 2015
Frozen	Histamine	Total process - histamine	Factory	Precooking CCP	Post precooking to retorting or re-freezing (Inhibitory temps)		12 h or first chance of recontamination	FDA, 2011a:9; Adams et al., 2018; FDA_ WL, 2015
Frozen	*S. aureus*	Process time: *S. aureus*	Factory	*S. aureus* CCP, after first human touch	Post precooking to retorting or re-freezing (Inhibitory temps)		3 h	FDA, 2011a:421

of 136 different fish must be randomly sampled from each lot to be evaluated.

1) Initial testing for histamine, *n*=18, c=0, DAL=35 ppm (FDA, 2021a). This test should be conducted first, when samples are collected from frozen fish for chemical testing of histamine. If one fish fails, the lot fails with no possibility of rectification. Note: As of 2011, the FDA does not allow the incoming quality evaluation lot to be sub-divided into smaller lots (sub-lotting) for retesting (FDA, 2011a).
2) Initial organoleptic testing for odors of decomposition, *n*=118, c=2. If only one or two fish fail, the lot passes and can be processed normally. This sampling is typically accomplished using a test lot system where a series of test lots, which are created from the larger delivery lot, are thawed and evaluated for odors of decomposition. If 3 of the 118 fish evaluated fail, that lot of tuna fails.
3) The 2011 Seafood HACCP Guidance (FDA, 2011a) allows for rectifying the lot that failed for sensory evaluation, after the initial histamine evaluation has passed, by resampling for histamine (*n*=60, c=0) followed by 100% rectification by evaluating each fish of the entire lot for odors of decomposition. This procedure also requires that the fish found to be decomposed during sensory evaluation are to be analyzed for histamine content. Note that during the rectification procedure, the NFI (2014) recommends that if 10% of the lot is rejected for odors of decomposition, the lot must be destroyed. Additionally, if 12 or more fish are rejected for off-odors during the first organoleptic testing of 118 fish, this will reach the recommended 10% levels. The co-authors recommend rejection of the lot at that time and do not incur the expense of testing 60 fish for histamine as required by the rectification process or plan. There must be 60 fish randomly sampled from the test lot tested for histamine, including each of the fish rejected for odors of decomposition. If one fish fails, *n*=60, c=0, the lot fails with no possibility of rectification. If all 60 fish pass histamine testing, the lot can be rectified with 100% of the fish organoleptically inspected, with the caveat of 10% rejection of the sample just mentioned. Any individual fish that has odors of decomposition is rejected. The rectification records should be maintained on a fish-by-fish basis, pass or fail.
4) All the individual fish in the rectification lot that have odors of decomposition must be rejected and recorded; however, the FDA has no limit on number of fish rejected for decomposition for failing or rejection of an entire lot. But, as previously stated, the NFI (2014) has recommended stopping organoleptic inspection and rejecting the lot if more than 10% of the fish in the lot fail for decomposition because the evaluators' noses will encounter nose fatigue: after multiple decomposed fish are smelled, the nose becomes desensitized to the off odors.

This sampling system supports the processing of smaller lots of marginal fish, meaning less than 25 t. If the factory is rectifying a lot of tuna that failed the test lot procedure, as described above, the delivery lot being rectified (RecLot) must not be processed with other fish. If the fish from the same RecLot are processed on separate days and if the RecLot fish processed on the first day passed, the canned products, pouches or other retorted containers must be held separately. If portions of the same RecLot fail on the following days, the fish that passed on the previous day will have to be rejected, so the factory must retrieve the already processed fish in cans, pouches, or bags and destroy them.

The multi-attribute sampling system with rectification has been evaluated for effectiveness. For food non-fatal illness hazards, 95% confidence of 95% reliability is recommended (DeBeer et al., 2017b). Reliability is defined as the percentage of acceptable units in a lot. Another common statistic, the average outgoing quality limit (AOQL), is also reported here. AOQL is calculated to be the highest average defect rate that would occur under a sampling plan where failure results in 100% rectification or 100% rejection of the lot. Table 3 summarizes the evaluation of the multi-attributes system. Histamine sampling alone provides only 60.3% confidence of 95.0% reliability and 2.0% AOQL.

Sensory sampling alone provides 93.8% confidence of 95.0% reliability and 1.2% AOQL. In combination, the two tests provide 97.5% confidence of 95.0% reliability and 0.85% AOQL. When rectification is applied, there is an additional probability a lot will pass. Overall, when initial sampling is performed, followed by rectification, there is 96.8% confidence of 95.0% reliability and 0.5% AOQL. However, with rectification, results of the initial sensory test have been additionally validated through histamine analysis (reject if any histamine levels greater than the DAL levels are found), and the lot must still undergo 100% sensory evaluation.

The rigor of this procedure is based not only on reliability, confidence levels, and AOQL, as reported here, but also on the correlation between the two different attributes analyzed, which is not considered in these calculations. Also note for initial histamine sampling, that the AOQL on its own appears to indicate an acceptable defect level. However, the AOQL reflects the maximum defect rate that could be expected over time, but it does not express a confidence level for individual lots. Reliability and confidence, therefore, provide a better measure of performance on a lot-by-lot basis. Since the histamine resample can contain up to 11 fish from initial sensory evaluation, additional sampling for new fish

Table 3.—Receiving sampling: A multi-attribute and rectifying system.

	Sample number	Testing procedure	N	n	c	Disposition	Confidence and reliability
Initial sampling	Initial, alone	Histamine	25 t	18	0	If fail, reject lot	Confidence: 60.3 Reliability: 95% AOQL: 2.0%
	Initial, alone	Decomposition	25 t	118	2	If fail, apply reconditioning, unless > 10% fail (11 fish), then reject	Confidence: 93.8% Reliability: 95% AOQL: 1.2%
	Multi-attribute	Histamine Decomposition	25 t	18 118	0 2		Confidence: 97.5% Reliability: 95% AOQL: 0.85%
Rectification	Three samples combined	Histamine Decomposition Histamine	25 t	18 118 60[1]	0 2 0	Pass Fail Pass	Confidence: 96.8% Reliability: 95% AOQL: 0.5%
	Rectify by 100% sorting	Decomposition	25 t	All fish		Stopping rule, if 10% fail, reject the lot, per the NFI	

[1]Confidence limits calculated with 49 independent samples because a maximum of 11 could have come from decomposed tuna, if one follows the NFI guidance.

could be as low as n=49. For this reason, n=49 is used in the evaluations reported here. This yields a conservative calculation of confidence, reliability, and AOQL.

The Operating Characteristic Curve (OCC) of the incoming multi-attribute sampling for evidence of biological adulteration (decomposition and histamine) and rectifying sampling are helpful curves for understanding the robustness of the sampling system. Figure 2 shows that the histamine sampling OCC with an n=18, and c=0, is not a particularly robust curve. The decomposition OCC with an n=118 and a c=2, is a bit more robust, but if we put them together, the OCC becomes even more robust. If the first sampling system passes for histamine levels and then fails for organoleptic evaluation, the lot may be rectified; a histamine sample with an n=60 and c=0 can be drawn and added to the previous sampling OCC (Fig. 3). This provides a confidence level of 96.8%, a reliability level of 95.0%, and an AOQL of 0.5%. Practical implementation of this rectifying option, which includes a second histamine sampling and organoleptic evaluation of every individual fish and rejection of the lot if this evaluation reaches 10% of the fish in the lot, has been noted by the co-authors to provide assurance that this is a good control for not processing decomposed tuna. Table 4 summarizes the history of the CCP's and CL's for histamine levels and decomposition control for sampling at receiving and processing time-and-temperature controls from 1982 until 2022. Some of the CL's are based on the HACCP guidance and others are from FDA warning letters already mentioned.

Temperature Sampling

Fish are collected and sampled for temperature readings at two locations during the tuna canning process: one location is at receiving for fresh fish, where a sample size of 12 fish is recommended by the Seafood HACCP Guidance (FDA, 2011a), and the other location is after the precookers to collect End Point Internal Product Temperatures (EPIPT's) when there is a precooking CCP. Even when there is no CCP required, processors generally collect EPIPT's (backbone temperatures) for process control. DeBeer et al. (2017b, c) report sample sizes for confidence limits and reliability levels, as well as data collection tools. Note that an attribute acceptance sampling plan for temperature collection will require more samples than a variable acceptance sampling plan.

Sampling for *S. aureus*

There is no sampling for *S. aureus* enterotoxin since there is no safe level. Controlling *S. aureus* growth and preventing any enterotoxin formation are determined by time-and-temperature alone and depends on the time at the ambient temperature per the Seafood HACCP guidance (FDA, 2011a).

Tuna Preparation Prior to Precooking

The typical processing steps during tuna cannery operations include receiving the frozen fish, sorting the tuna by species and weight, holding the fish in the cold storage, thawing, butchering, racking, precooking, initial water cooling (sidespray), chilling in a chiller room, removing the skin, deboning, removing the red meat and bruises, cleaning and polishing the cleaned loins, cleaning the tuna pieces, packing the tuna meat into containers, adding media, sealing the cans or the pouches, and retorting, cooling, labeling, and casing these containers. For a typical tuna canning process flow chart see DeBeer et al. (2017b), and the NFI (2014). An example of a factory layout is shown in Visvanathan et al. (2007).

Post Capture Processing at Sea

After capture the tuna is frozen at sea with little or no further processing (Burns, 1985). Sometimes the gills and internal organs from the larger fish that are caught by longlining are removed before chilling and/or freezing the fish. These fish are called "gilled and gutted" (G&G fish) (Royal Hawaiian Seafood[17]), while Price et al. (1992) refers to them as "dressed." Some troll-

[17]Royal Hawaiian Seafood. 2017. Seafood industrial terminology guide (avail. at http://sfrhs.com/phone/industrial-terminology-guide.html, accessed 19 Jan. 2017).

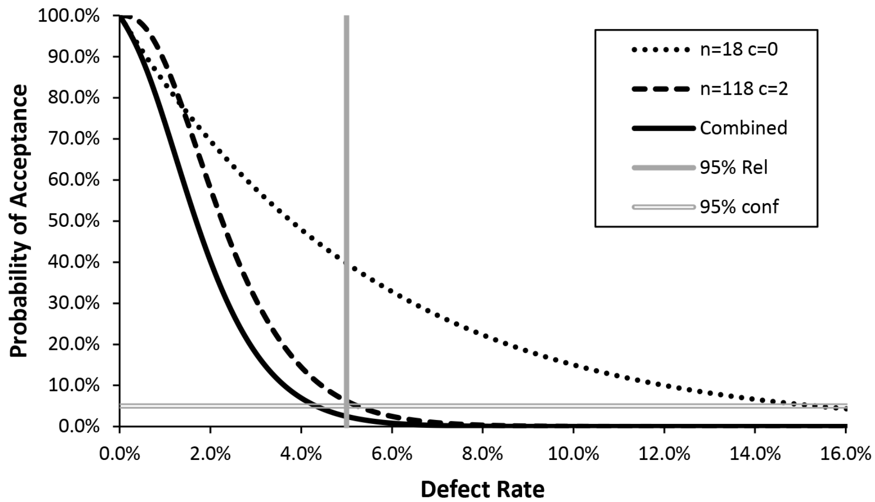

Figure 2.—OCC curves—Primary sampling for histamine—defect rate vs. probability of acceptance.

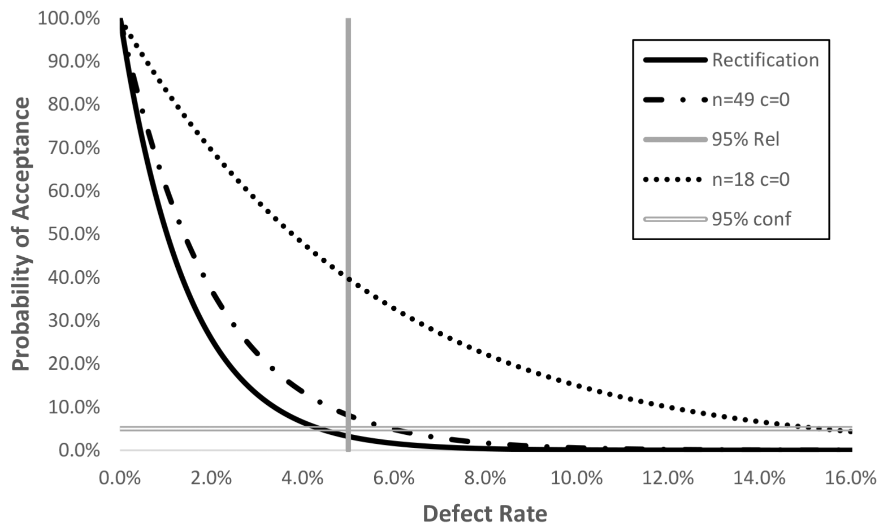

Figure 3.—OCC curves—Secondary sampling for histamine—defect rate vs. probability of acceptance.

caught albacore is bled immediately to improve the color, making it lighter (Hilderbrand, 2004).

Receiving, Testing, Sorting, and Grouping by Size

When the frozen tuna is received at the processing factory, it is unloaded and sorted by species and size prior to being weighed for payment, depending on the situation and facilities available to the unloaders. The tuna of different species and/or sizes have different values to the processors, and thus different prices are paid to the fishermen.

The frozen tuna are separated by size (weight) as they are passed across sorting tables and separated and grouped by size for storage and production scheduling. All these tunas should be sorted and separated by species and size for precooking to maintain or improve yield and recovery. The sized and sorted fish are placed in separate fish bins or totes for storage in freezer rooms (cold storages) for efficient access and removal from the cold storage for processing per HACCP guidelines. This process control step (sizing) is a particularly important component of tuna processing, with the goal of thawing, butchering, and precooking same-sized fish in an optimized, efficient manner.

As the frozen fish are received and sorted, they are divided into lots used for histamine and preliminary organoleptic evaluation. Receiving lot numbers are assigned, and histamine samples (18 raw fish minimum, per lot) are usually collected after sorting. Test lots are assembled for the organoleptic evaluation (118 raw fish minimum) (FDA, 2011a). The maximum receiving lot size for histamine and organoleptic controls should be 25 t (FDA-WL, 2016b). If the receiving lot size is larger than 25 t, then the sample size for histamine testing and organoleptic evaluations will increase in proportion (FDA-WL, 2014). As indicated in the Seafood HACCP Guidance (SHG), chapt. 7, 136 fish (18 + 118) should be the minimum sample size for histamine and organoleptic evaluation (FDA, 2011a).

After the frozen fish are thawed and butchered, they are placed into precooking baskets. At the sorting stations, the fish are separated into sizes that fit naturally into the fish baskets. The fish sizes are identified as Splits, 1-Lg, 1-Sm, 2s, ….. 10s, 12s, and 15s, referring to the number of fish loaded into a single basket, so a larger basket number means more fish in that basket. Each of these sizes will have different thawing and processing times, recovery standards, and cleaning rates per ton of round fish. An example of some process parameters for skipjack is shown in Table 5. These process parameters are very factory specific, depending on the equipment available (DeBeer[4]). The sorting of the fish by weight, species, and size is critical for better process control and better recovery of edible meat.

Table 4.—History of CCP and CL's for tuna processing histamine and S. aureus control.

	Year						
	1982	1994	1998	2001	2011	2015	2021
HACCP Guidance		1	2	3	4	4	4+
Histamine action level (raw)	500 ppm	500 ppm	500 ppm	500 ppm	500 ppm	500 ppm	200 ppm
Histamine defect action level (raw)	100 ppm[1]	50 ppm	50 ppm	50 ppm	50 ppm	50 ppm	35 ppm
Histamine defect action level (canned)	200 ppm	200 ppm	50 ppm	50 ppm	50 ppm	50 ppm	35 ppm
Canned Limit - DAL sample size	2/24 cn	2/24 cn	2/24 cn	2/24 cn	2/24 cn	2/24 cn	1/30 cn
Existing decomposition							
Chemistry - histamine							
N						25 t	25 t
n		5% of totes	1 or 2 fish/t	18	18	18	18
c		0	0	0	0	0	0
Smell - organoleptic							
N						25 t	25 t
n		All fish in lot	118	118	118	118	118
c		<=2.5%	<=3	<=3	<3	<3	<3
Confidence limits		95.0%					
On line inspection		50%					
Rectification/reconditioning							
Sublotting		Yes	Yes	Yes	No	No	No
Histamine		Analyze lots with > 2.5 % decomp for histamine	*n*=60,c=0, include any decomp fish from initial testing	*n*=60,c=0, include any decomp fish from initial testing	*n*=60,c=0, include any decomp fish from initial testing	*n*=60,c=0, include any decomp fish from initial testing	*n*=60,c=0, include any decomp fish from initial testing
Decomposition			Sort for decomp	Sort for decomp	Sort for decomp	Sort for decomp	Sort for decomp
On line inspection - organoleptic		100%	100%	100%	100%	100%	100%
Honey comb (precooked fish)			Reject	Reject	Reject	Reject	Reject
Preventing further decomposition							
Time and temperature limits							
Thawing to precooker			12 h	12 h	12 h	12 h	12 h
Precook CCP/CL (60°C at backbone)						60°C	60°C
Precook to retort (60°C at center can)						12 h	12 h
Staphylococcus aureus							
Precook to retort (60°C)					3 h	3 h	3 h

[1]Raw fish over 100 ppm, accompanied by organoleptic decomposition to be destroyed.

Table 5.—Basic cannery capacity data for skipjack.

Basket size	1Sm	2s	3s	4s	6s	8s	10s	12s	15s
Size range (kg) Min	9.1	6.8	5.0	3.6	2.7	2.0	1.4	0.9	0.5
Max	11.3	9.1	6.8	5.0	3.6	2.7	2.0	1.4	0.9
Avg size (kg)	10.2	7.9	5.7	4.3	3.2	2.4	1.7	1.1	0.8
Fish/metric ton (t)	98	126	176	232	315	420	588	882	1225
Est t/box	0.77	0.79	0.82	0.86	0.73	0.77	0.82	0.86	0.91
Thaw h/box	6	6	5	4	3	2	2	1	1
ThwBox h/t	8	8	6	5	4	3	2	1	1
Butcher spd- t/min h	5	5	4.5	4	3	1.8	1.25	1	0.8
Butcher h/t	0.20	0.20	0.22	0.25	0.33	0.56	0.80	1.00	1.25
Fish/basket	1	2	3	4	6	8	10	12	15
Basket/t	98	63	59	58	52	52	59	73	82
Baskets/rack	16	16	16	16	16	16	16	16	16
Racks/t	6.1	3.9	3.7	3.6	3.3	3.3	3.7	4.6	5.1
Racks/precooker	18	18	18	18	18	18	18	18	18
Mt/precooker	2.9	4.6	4.9	5.0	5.5	5.5	4.9	3.9	3.5
PreCooker time (h:m)	3:05	2:10	1:20	1:10	1:00	0:40	0:40	0:35	0:35
PreCooker h	3.08	2.17	1.33	1.17	1.00	0.67	0.67	0.58	0.58
SideSpray h	4.00	3.25	2.58	2.17	1.75	1.50	1.33	1.17	1.00
Chill room h	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.75
Min racked h after precooker	7.00	6.25	5.58	5.17	4.75	4.50	4.33	4.17	3.75
Min racked h	10.1	8.4	6.9	6.3	5.8	5.2	5.0	4.8	4.3

Production Planning

The production plan is based on many factors including species, size, percent recovery, thawing times, precooking and cooling times, cleaning and packing rates, and retort times by can size. These variables result in a complex production plan for a round fish tuna factory, and the plan is never the same from day to day because the fish sizes and species are never the same. When producing frozen loins for canning at another factory, both the frozen loin plant and the final cannery share this planning complexity. There must be extensive coordination between the frozen tuna loin supplier and the cannery to provide correctly-sized frozen loins as well as packaging coordination which includes the variables of correct species, proper flake content, moisture content, color sorting, overall quality, and HACCP compliance.

A production plan is created for every individual day of production to coordinate tuna processing, depending on the changes in fish availability and sales plans. This scheduling requires that the fish be packed by species and size into a specific can size for a specific label or stock keeping unit (SKU). Because the steps listed above should flow from one to the next without pileups, these requirements result in a detailed hour-by-hour production plan from the thawing phase through labeling and casing. For example, if the cleaned loins are packed into cans using a Luthi Solid Packer (SP) tuna filling machine[18], which runs at a very predictable speed, the cleaned tuna loins must be loaded into it in a uniform and consistent manner. A typical tuna canning/seaming line will have two Luthi SP machines feeding open cans filled with tuna into one seamer. A seamer machine cinches the lid to the can and closes the can. If each SP tuna filler runs at 180 cans per min (CPM), then the seamer must run faster than 360 CPM. If each can is filled with 100 g of cooked tuna meat, this canning line (SPs and seamer) requires (360 CPM *100 g/can) = 36,000 g per min (36 kg/min) or 2.16 t/h of cleaned loin meat to be available to load into the Luthi SP. Thus, the previous steps must be able to deliver 2.16 t of cleaned loin meat every single hour.

Recovery is measured by the weight of the cooked and cleaned meat as a percentage of the round tuna weight and thus is an important metric for the overall process. Figures 4 and 5 compare the recovery by size and the number of labor hours (skinners and cleaners) for yellowfin, skipjack, and albacore needed to provide 2.16 t of cleaned tuna meat for that hour. Skipjack (SJ) and yellowfin (YF) of the same size are considered to be equivalent for scheduling purposes, recovery, and labor rates by fish size. The raw tuna scheduled will have to be adjusted by the recovery by size so, for example, the required 2.16 t of loin meat will have to come from about 4.6 t of round YF/SJ if the expected recovery is 47% (2.16 t/0.47 recovery for 10 kg sized fish), or 3.8 t of round albacore with a higher recovery standard.

[18]Mention of trade names or commercial firms does not imply endorsement by the National Marine Fisheries Service, NOAA.

Thawing

Thawing the tuna properly is the key in preparation for the butchering and precooking processes. The tuna removed from the cold storage are most often thawed using circulating water in small or large bins or sometimes in open raceways with moving water. Prior to the 1960's, the fish delivered directly to the factory were tempered (explanation below) and thawed aboard the fishing vessels and then unloaded directly into the factory without sorting by size (DeBeer et al., 2019b; DeBeer[4]). However, at that time, cold storages, thawing bins, and thawing stations were also needed for imported frozen fish that were delivered by bulk carrier or shipping containers. The practice of shipping frozen round fish by bulk carrier began to take place in the 1950's (Sylvester[5]).

In the 1960's, the limits for methyl mercury (MeHg) levels for tunas (Peterson et al., 1973) precluded unloading thawed fish directly off the vessel into the cannery, instead requiring the addition of the now regular unloading, sorting, and thawing steps. The canned tuna SOI (FDA-SOI, 2001) allows for many species to be labeled as light meat and mixed in the same can. This facilitated blending of groups or lots of different species of light meat to reduce the levels of MeHg in the canned tuna. For the California canneries, especially, higher MeHg levels were primarily an issue with larger yellowfin from the Eastern Tropical Pacific Ocean until the regulatory level was increased (Peterson et al., 1973; DeBeer[4]). The MeHg action level was raised from 0.5 ppm to 1 ppm in 1995 (FDA, 2007).

At present (2022), tuna are processed separately by species, so there is not much blending of different species in the canned product. All the frozen tuna are now received into cold storage, allowing the tunas to be sorted and stored by species and size. The elimination of thawing the fish on the fishing vessel and direct delivery into the cannery for processing changed the basic practice of fish scheduling and daily production planning. It also made it possible to run the HACCP test lots prior to clearing and accepting frozen fish lots (DeBeer[4]).

Some canneries still process tuna that is delivered chilled, on ice, requiring either immediate processing or freezing of the fish on shore. The Seafood HACCP guidance (FDA, 2011a) set time limits for processing fresh, unfrozen fish to 4 h from the start of processing after the fish is no longer iced until inhibitory temperatures for histamine control are reached in the center of the can in the retort (FDA-WL, 2011). The inhibitory temperature for histamine in canned product in the center of the can is 60°C (140°F) (Adams et al., 2018). Four hours is not enough time to inspect, test, precook, cool, clean, can, and retort these fish to reach 60°C (140°F) in the center of the can, without an additional precooking CCP. Hongpattarakere et al. (2016) suggested that the factories freeze the iced fish first and then thaw them to utilize the 12 h time CL for previously frozen fish. Reportedly, freezing the tuna first before processing also results in firmer fish flesh after precooking (Lord[1]; Heroux[19]).

Processing frozen tuna gives the factories far more time flexibility than processing chilled raw fish. However, frozen fish must be thoroughly thawed for proper precooking. Different tuna factories utilize a variety of equipment and thawing methods, but they are generally simple variations of circulating water or air around and past the frozen fish contained in bins made of hot dipped galvanized metal plate or heavy

[19]Heroux, R. 2019. Personal commun. (email: rick.heroux@hotmail.com).

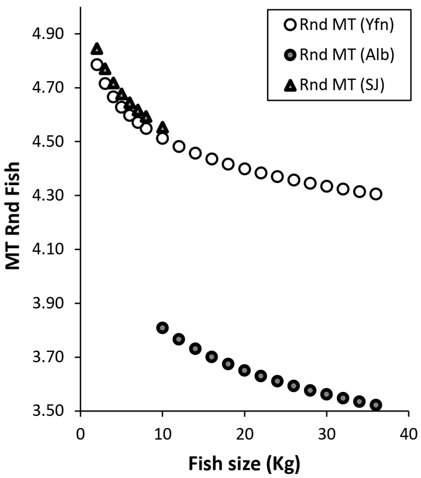

Figure 4.—Metric tons of round yellowfin tuna, skipjack tuna, and albacore to produce 2.16 t of loin meat to feed a Luthi solid packer for 1 h.

wire. The standard industry tuna storage and thawing bin or box is 1.12 m x 1.52 m x 1.07 m (44 in x 60 in x 42 in) LWH and holds about 1 t, depending on the fish size. These bins or totes hold the frozen tuna in the cold storage and are usually used for thawing as well.

The thawing bays are generally of two types. One type can be a large flat area for a single level of fish bins; the area is walled and has a slight slope which drains to a pit or pits for water collection and recirculation. The other type can be a smaller area with higher walls, where the fish bins can be stacked up to four bins high, draining to the water recirculation pit (Lord[1]; DeBeer[4]). In both cases the thawing water is pumped through overhead pipes that either spray water on the bins or use hoses to fills the bins with water. With the stacked bins, the water passes from the top box to the next bin down either through hoses, metal channeling devices, or simply through holes in the bottom of the bins. The water then is guided to a recycling pit to be reheated as needed and reused.

Heat transfer occurs through conduction (contact), convection (movement of air or water), and radiant heat. The rate of thawing depends on four variables: the size of fish (thickness), temperature of the frozen fish, temperature of the ambient water or air, and the flow rate of the thawing medium (water or air). The thickness of the fish is fixed, but the difference between the water/air temperature and the frozen fish temperature makes a difference in the thawing rate (time). A larger temperature difference between the frozen fish and the thawing medium will cause a faster thaw. The flow rate impacts the surface coefficient of heat transfer (ht) from either air or water on the tuna (Farkas et al., 2004). Farkas et al. (2004) suggests that uneven temperature gradients exist in the thawing bins resulting in uneven thawing rates and that increased circulation can reduce the amount of unevenness in thawing. Increasing "h" by increasing the thaw water flow rate over a given range reduces the thawing times and core temperature variation between fish (Bailey et al., 1974; James and Creed, 1980). But this benefit of increased water flow rate on "h" is not unlimited. Increasing the water circulation rate eventually has diminishing returns. At a certain point, there is no further effective increase in the thawing rate with increased water flow: increasing or decreasing the temperature of the thaw water generally shortens the thawing time more than changing the water flow (Bailey et al., 1974; James and Creed, 1980; DeBeer[4]).

Properly preparing the thawed fish for optimum precooking is a key goal. The entire precooker batch of fish should be of the same size group and have uniform initial temperatures (IT's) at the fish cores and no partially frozen fish. The challenge is to achieve the proper balance of water flow rate, water temperature, and thickness of the fish to properly prepare the fish for precooking and also comply with HACCP time-and-temperature guidelines for processing tuna.

Much of the industry understanding of proper thawing has accrued over time. Various patents (Anderson et al., 1960; Carruthers et al., 1964; Peterson, 1971, 1973) emphasize the importance of evenly thawing each of the individual tuna so that the precooking starts

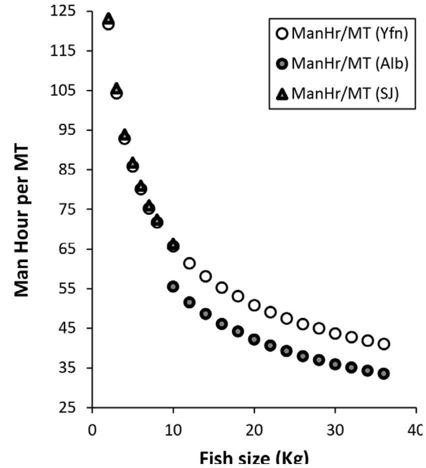

Figure 5.—Man hours by species to clean enough fish to produce 2.16 t of loin meat to feed a Luthi solid packer for 1 h.

with uniform core temperatures. Magnusson and Hartshorne (1952) found that 30 gal/min is a good water flow rate for thawing fish. A 32–35 U.S. gal (121–132 liters)/min thaw water flow has worked well for many years for the standard industry thawing bin (Nolte[3]; DeBeer[4]; Colley[10]).

Today many canneries use thawing bins with weirs constructed inside the bins at the corners. This improvement allows the thaw water to flow in from the top and then it is forced to sink to the bottom and flow upwards through the weirs in the corners for drainage. This technique improves the water circulation throughout the thaw bin. Delivering the thaw water by using hoses from the overhead water delivery pipes requires that the hoses have sufficient length to achieve the downward flow deep into the bin and induce circulation of the thaw water up, around, and through the stacked fish. Good circulation between all the fish is an all-important goal.

Properly thawing the fish is particularly important for properly precooking the fish beyond the concern presented by different fish sizes. Completely thawed fish and partially frozen fish have vastly different heating profiles and cooking rates. The result of incomplete thawing will be frozen meat at the center of the fish. The heat energy or enthalpy used during precooking is much higher to thaw the frozen muscle before it can be cooked as there is a lag time in the increase in the backbone temperature because of the initial frozen flesh at the center of the fish. In many instances, these differences in lag times can occur even with fish of similar size and with the same IT's because there was a different sized frozen mass at the core of some of the fish. Initial backbone temperatures equal to or below about -2°C (28°F) indicate that some part of the fish is still frozen, and this negatively impacts predicting precooking times because of the variation of lag times, resulting in overcooking of some of the fish.

This unevenness of precooking times when starting with fish frozen at the core must be addressed; the importance cannot be underestimated. Fish that have different dimensions of frozen material at the core can be the same internal temperature but will have very different enthalpy requirements (kilojoules) to get the frozen mass thawed. Additionally, as the fish thaws, the rate of thermal conductivity changes by a factor of 3 or 4. Frozen fish conducts heat much faster than unfrozen (thawed) fish (DeBeer et al., 2015). So, as the outer layers of the fish thaw, the resistance to the passage of heat through the tuna meat to the core increases. When fish remain partly frozen at the start of precooking, the final temperatures differences between fish in the same precooker will tend to diverge further apart. Completely thawed fish will tend to have temperature differences at the core (backbone) converge closer together by the end of precooking.

A key concern when thawing tuna in the large bins using moving water is that as the fish thaw, they change shape. As the outer surfaces thaw, the muscle softens, and the fish changes shape and collapses a bit. This collapse closes the spaces between fish, and there is less room for the thaw water to circulate and transfer the heat from the water to the fish. For larger individual fish such as albacore or yellowfin, this slight collapse is not so much of a problem. However, this is a problem for purse-seiner-caught skipjack which may become deformed. The center of the mass of skipjack or small yellowfin during thawing can collapse together and form a frozen block or ball in the center of the thawing bin. The thaw water will not then reach the interior of the mass while the outer fish can get quickly over-thawed (Lord[1]). The outside or even the core of the fish near the walls of the box may be 20°C, if that is what the thaw water is, and the fish in the center of the box are still frozen.

Table 6.—Enthalpy required to thaw 1 kg tuna from -20°C to +4°C.

Temp. range	Delta °C	Specific heat KJ/kg/ °C	Enthalpy KJ/kg	% total change in enthalpy	References
0°C to 4°C	4	3.3075	13.23	5%	DeBeer et al., 2015: Appendix A
0°C	0	234.9	234.90	83%	DeBeer et al., 2015: Appendix D
-20°C to 0°C	20	1.7165	34.33	12%	DeBeer et al., 2015: Appendix A
Total	24		282.46	100%	

As the frozen fish are thawing, the surrounding thaw water gets chilled (like ice cubes in iced tea). A traditional coastal-based cannery can use single-pass ocean water with a constant temperature for thawing so there is no issue with consistent water temperatures. If the thaw water is recirculated from a thawing pit, some form of heat may be needed to maintain the proper water temperature for fish thawing. Direct steam injection into the thaw water has worked. Some factories have used retort cooling water as makeup water. The retort cooling water generally needs to be cooled before disposal, so using the heat of the retort cooling water in the thawing pit water is an efficient way to thaw the fish and dissipate the retort water heat (Erickson, 1962).

Not adding heat to the water means thawing the fish with cooler water and lengthens the thawing times for the fish size because the heat transfer rate has been reduced. This approach will work with smaller fish, where longer thaw times will still fit into the 12 h process time window for histamine control. However, extended thawing times for larger-sized fish can be limiting for adherence to this HACCP 12 h control. Another way to increase circulation in the thawing bin and reduce thawing times is to use air injection into the thaw water either with a blower or an air compressor. However, using air compressors can result in the thaw water getting too warm compared to using an air blower (Heroux[19]).

Enthalpy (measured in kilojoules) is the amount of heat necessary to change the temperature of a mass at a constant pressure and volume. Enthalpy is measured from one temperature to another temperature and is relative. When thawing fish, enthalpy is used both to increase the overall fish temperature and to handle the phase change of the fish from frozen to unfrozen. To determine the enthalpy or heat needed for thawing fish, the temperature range of -20°C (-4°F) to 4°C (39°F) is used. For these calculations, the fish are considered to be thawed at 0°C (32°F). The data in Table 6 shows the amount of enthalpy required for this thawing and phase change in fish muscle. The data is only for illustration purposes as the phase change in fish actually occurs over quite a wide temperature range, but the enthalpy calculation results are essentially the same. The heat of fusion phase uses more than 80% of the energy when the temperature is changed by 24°C (ΔT from -20°C to 4°C) during thawing (Table 6).

Generally, tuna processed in tuna canneries throughout the world are thawed in a separate location than the precookers, although there are exceptions either by design or by other limitations. One example is the Cabinplant A/S precooking equipment that has both thawing and cooking cycles in the same chamber. This equipment starts with frozen fish and thaws, cooks, and cools in the same chamber. The purpose for the design of this Cabinplant for precooking is to save water in a location that has limited potable water resources (Lord[1]).

Another way to minimize thawing times, using water thawing, is to temper the fish in air prior to water thawing (DeBeer et al., 2021a). This method will help meet the HACCP Guidance for time and temperate exposure for histamine control. Tempering is defined as allowing the fish temperature to increase while the fish still stays frozen, without using water. Tempering provides the controlled increase of frozen fish temperatures by placing the fish in a chilled chamber that is just below freezing so the fish remain below or about -4°C to -3°C (24.8°F–26.6°F). The anteroom of the cold storage facility is a practical example. The temperatures of the tempering room must be recorded and keeping continuous recordings of the temperatures is advised (FDA-WL, 2016a; DeBeer et al., 2021a). These cold frozen temperatures prevent bacterial growth, but because enthalpy or heat has been added, the remaining thawing time using water will be reduced, and the HACCP requirements for histamine control can be met. Although there are HFB that can produce histamine at these low temperatures, the lengths of time required for this formation means that these HFB are not an issue (Dalgaard and Emborg, 2009; DeBeer et al., 2021a). The backbone temperature target for tempering (-4°C to -3°C) is well below the level for pathogenic bacterial growth and histamine formation (Behling and Taylor, 1982; Frank and Yoshinaga, 1987).

Butcher and Racking

After thawing, the fish are butchered to remove the entrails and then rinsed. The butchering process is the first time individual thawed fish are available for physical inspection and sensory evaluation. Tuna being packed under federal inspection in the United States must receive organoleptic evaluations carried out by trained factory workers for each fish, with the federal inspectors continuously auditing the process (Shanks[20]). The butchering process prior to precooking allows factory inspectors to inspect the thawed meat and to remove any physically damaged fish. Fish with odors of decomposition, belly burn, or other visual signs of abuse or decomposition are also removed.

Organoleptic evaluation of each individual fish at the butcher line makes economic sense (see below). Each individual thawed tuna is inspected, and the rejects of fish by type can be tracked for the causes: physical damage, belly burn, decomposition, ammonia, or hydrocarbon smells. Industrial practice limits the rejects from a lot on a percentage basis (maximum 10% for decomposition and other off odors), after which the entire lot should be rejected because of workers' nose fatigue and the danger of decomposed fish getting past the inspectors and getting into the commercial process. This practice requires defining manageable-sized lots at receiving for processing since the 2011 Seafood HACCP Guidance (FDA, 2011a) does not allow sublotting or subdividing the original lot into smaller lot sizes for histamine or organoleptic evaluation.

After butchering and evaluation, the fish are racked; the eviscerated tuna are put into fish baskets by common size (see above), and the baskets are loaded into wheeled fish racks holding up to 7 or 8 layers of baskets. When the racks are filled, they are rolled into the precooker. Tuna of similar size and thickness should always be racked and precooked together.

Larger fish are generally split or cut into smaller portions after evisceration and prior to racking to reduce the piece size, thickness, and precooking time while increasing factory capacity through faster precooker cycles. Fish are split depending on thickness and weight, and the split fish usually weigh 15 kg and greater (DeBeer[4]).

Larger fish greatly impact the scheduling of tuna cannery processing because of the different time requirements at different processing steps; there cannot be any storage, delays, or resting times for tuna once fish have been removed from frozen storage until retorting the cans or freezing the meat in a loin bag. Smaller fish can be precooked very quickly but require far more labor hours per ton to clean than larger fish (Fig. 4, 5). Longer times to clean smaller fish can lead to idle or down time at the packing machines, which operate at a fixed rate. Conversely, larger fish take longer to precook but can be cleaned very quickly. Shorter times to clean larger fish can overwhelm the packing machines with the cleaned loins and cause delays for filling the containers (cans, cups, pouches, or loin bags) (Lord[1]; DeBeer[4]).

Precooking

Usually, the fish are cooked twice in canned tuna processing. During the first cook the thawed and butchered fish are cooked with saturated steam to prepare them for the separation of the edible from the inedible parts, which is termed cleaning. The edible portions are filled into cans, cups, or pouches (hermetically sealed containers). The second cooking operation is called retorting. The hermetically-sealed containers of tuna meat are heated under pressure and elevated temperatures to produce commercially sterile shelf-stable products. Thus, the first cook of thawed fish is called precooking in the trade.

There are two methods of preparing tuna prior to separating the edible tuna meat and filling the meat into a container (can, pouch, or cup) to sterilize it. The first, and most common method, is to precook the tuna, after thawing and butchering them and prior to cooling and cleaning (DeBeer et al., 2015). The cooked and cleaned tuna loin meat is then either put directly into the cans, and the cans are hermetically sealed and retorted at the canning factory or the tuna meat is placed directly into plastic bags and frozen, for later canning at another canning factory (Lord[1]; Nolte[3]). These frozen bags of tuna meat are referred to as frozen loins in the trade.

The second method of preparing tuna for canning uses larger albacore and larger yellowfin processed into the so-called raw packs and as described earlier, is produced at lower volumes (Paulet[2]). Here there is only

[20]Shanks, L. 2020. Personal commun. (email: lenanah1@aol.com).

one heating phase. The edible meat in the raw tuna pack is separated from inedible meat while the thawed tuna is raw. The edible meat is filled directly into a container which is hermetically sealed just prior to retorting it. This is termed a "raw pack." The raw-packed tuna has a very different texture and flavor from the precooked tuna packs (Paulet[2]). The primary market for raw packed tuna in the last 50 years has been France, although by 2022 a small percentage has been introduced into the U.S. market (DeBeer[4]).

The art and science of precooking has been described in patents and numerous papers since before the 1940's. The proposed methods for precooking in these patents vary greatly and are summarized in Appendix A. More recent published papers on precooking and its effects on tuna for canning include Bell et al. (2001), DeBeer et al. (2015, 2019a), Perez-Martin et al. (1989), Ruilova-Duval (2009), Stagg et al. (2012), Webb (2003), and Zhang et al. (2002).

Historically, there are four primary reasons for precooking the tuna fish. The first is to firm up the edible muscle tissue for easier cleaning. Cleaning involves the separation of the edible meat from the skin, red meat, and bones, and then reducing the meat into smaller pieces to fill the cans. The second reason is to identify visual evidence of defects such as bruises or honeycomb (decomposition) (Frank et al., 1984) that are seen in the cooked tuna loins that were not evident in the raw fish (DeBeer[4]). The third reason is to drive off (remove) some of the fish oils and accompanying odors, and the fourth reason is to prevent white protein curd from forming in the can on top of the cake as happens during the retorting of the "raw packs" (Anderson and Stolting, 1952; Ruilova-Duval, 2009). In 2011, the HACCP CCP and CL of 12 h for the entire tuna processing cycle was added for the prevention of histamine growth (FDA, 2011a). A CCP for precooking and its CL of 60°C (140°F) backbone temperature was validated and added a few years later (Adams et al., 2018).

The terms precooking and cooking will be used interchangeably in this paper as different authors have used different terms to describe the same process. Bell et al. (2001) uses the term "atmospheric steam cooking," while Anderson and Stolting (1952), Perez-Martin et al. (1989), and Zhang et al. (2002) use the term "precooking." The second heating operation (retorting) is quite different and will be discussed later.

It is important to understand the different cooking temperature profiles of both the saturated steam and the fish backbone temperatures. Unless otherwise noted, whole eviscerated (butchered) tuna is the material used for the precooking profiles. For precooking trials and studies, the target for the initial core temperature (IT) is 0°C (32°F); however, in practice these may vary up or down.

The cooking practices for atmospheric precookers (APC's) have not changed much in 100 years, and the description in Anderson and Stolting (1952) is still fairly accurate today. Prior to 1952, there were no modern purse seiners or modern nylon nets capable of capturing the large quantities of tuna that are routinely captured today. Previously, most of the fish was captured by tuna clippers (pole-and-line boats) that used hooks, not nets. Then, ammonia refrigeration and brine freezing systems were widely introduced on tuna clippers in the decade just prior to World War II (Lassen and Rawlings, 1959), and, consequently, some of the tuna clippers were used as refrigerated supply ships during World War II (Felando and Medina, 2012).

In the 1950's, frozen fish were tempered or thawed in the wells aboard the tuna clippers and sent directly to the factories for precooking and further processing (Anderson and Stolting, 1952; Erickson and Loewe, 1960b). This practice of thawing the fish on the tuna clippers precluded sorting the fish by size for uniform thawing and processing. The practice of unloading the thawed fish from the tuna vessel directly to the butcher table in the factory onshore continued in San Diego into the early 1970's (DeBeer[4]). The fish were either manually sorted by size while the fish were being racked immediately prior to precooking, so that many precookers had to be open at the same time to accept the different sized fish being unloaded from the vessel, or multiple sizes were precooked together resulting in the smaller fish being overcooked or the larger fish being undercooked. Currently, in 2022, the still hard frozen fish are unloaded at an unloading dock and transported to the freezer or cold storage by insulated trucks or using forklifts for fish bins. The fish are sorted by size groups at or near the cold storage, and the sorted fish are stored frozen in fish bins in a cold storage before being transferred to the thawing area for processing (Lord[1]; DeBeer[4]).

Basic Precooking Concepts

There are three primary methods of precooking tuna, each using specialized equipment. These are a) Atmospheric Precookers (APC's) where the steam is vented naturally at atmospheric pressures (DeBeer et al., 2015), b) vacuum precookers (VPC's) where the ambient steam pressure and temperature can be increased or decreased by water sprays and vacuum pumps (DeBeer et al., 2019a), and c) heated water baths used primarily for precooking in Europe as previously described (Perez-Martin et al., 1989).

APC's use the condensation of saturated steam under atmospheric pressures to cook the thawed fish (DeBeer et al., 2015). Saturated steam means steam produced and transported under pressure. The ambient temperature inside the APC rapidly rises to 100°C while the APC is being vented. The APC can also be modified to cook in a stepped ambient temperature profile. There is no standard design or required equipment for precookers as is required for retorts so precooker designs vary throughout the world. Retort equipment design, however, must meet minimum U.S. standards per Federal Code 21CFR§113.40 or be approved by a process authority (FDA, 2014a).

Vacuum precookers (VPC's) use the heat from the condensation of saturated steam under a range of pressures and temperatures that can be selected. The pressure controls the temperatures in a fixed capacity container. The VPC's are manufactured by John Bean Technologies (JBT[21]) (formerly Food Manufacturing Corporation (FMC)) or Maconse[22]. They are designed to improve control of the precooking process by cooking the fish by using condensing steam at temperatures lower than 100°C (212°F), while also being able to cool the fish more rapidly than evaporative cooling at atmospheric pressure (Perez-Martin et al., 1989). Vacuum precooking and the stepped-down precooking operate at a lower ambient temperature, have longer heating cycles than APC's and thus result in slower heating at the core (DeBeer et al., 2019a).

Heated water or brine immersion cooking is used by some European tuna processors but on a limited basis. The target water temperature is about 100°C (212°F) at normal atmospheric pressure to cook the fish enough to firm up the muscle tissue for cleaning (Perez-Martin et al., 1989). Water immersion cooking involves lifting the trolleys holding the tuna into and out of the heated water, compared to simply rolling trolleys holding the tuna into and out of an APC or VPC. Perez-Martin et al. (1989) suggests that using water immersion cooking is limited because it requires time to heat up the cooking water. Water cooking also requires more space for the equipment, and the cooking cycle may be longer than APC's or VPC's (Lord[1]). Perez-Martin et al. (1989) state that the turbulence of injecting the steam to heat and the circulating water can disrupt the fish muscle structure as well. Because of these disadvantages of cooking in water, the two methods using steam to cook tuna (APC's and VPC's) are by far the most prevalent in the industry.

[21]JBT Food Tech (avail. at http://www.jbtfoodtech.com/en/Solutions/Equipment/Tuna-Pre-Cooker, accessed 24 Dec. 2016).

[22]Maconse (avail. at http://www.maconse.com/, accessed 24 Dec. 2016)

The tuna process using steam precookers begins with the sized, thawed, and butchered fish being placed into baskets which are then loaded onto wheeled trolleys. The tuna-laden trolleys are rolled into the precooker, and the doors are closed. After closing the precooker, the air is removed from the precooker by either venting with saturated steam (APC's) or with a vacuum pump (VPC's). After the air is removed in the APC's, the vents are partially closed, and the fish are steam cooked at ambient pressure for some period depending on the fish size and the target ending backbone temperatures.

The cooking process starts with the controlled flow of saturated steam into the precooker. The saturated steam condenses on the surfaces of the cooler fish transferring the latent heat of vaporization from the steam to the fish and then heating it. A steam controller replenishes the saturated steam as it condenses in order to maintain a constant pressure and temperature in the precooker. The condensed steam (water) falls from the fish being heated to the floor and drains from the precooker as part of the cookout juice, which contains fish oils, soluble proteins, and water. Although there are several variations of precooking techniques, the result is the same: the edible muscle tissue is coagulated enough to manually separate the bones, skin, and red meat from the edible meat after the cooked fish are cooled.

The target set point for the steam temperature in the APC has varied over the years. Lang (1950) and Anderson and Stolting (1952) mentioned 216°–220°F (102°–104°C); however, in recent years most operators use 100°C (212°F) as the set point for the steam temperature. The precooker construction varies quite a bit around the world, so temperature set points and controllers will vary as well.

Recovery and yield of cooked edible meat from the round fish is a key factor used to measure industrial tuna processing efficiency. The historical goal of precooking was to control tuna heating in order to get a minimum target backbone temperature. For many years, the target backbone temperature was 57.5°C (135°F) (Peterson, 1971, 1973); however, the current HACCP precooking guidance has increased the core target temperature by 2.5°C (5°F) to 60°C (140°F) (Adams et al., 2018).

The following is a description from Bell et al. (2001):

> "The process of steam cooking of tuna occurs in a saturated moisture environment. These conditions do not provide temperatures above boiling [>100°C] nor produce a moisture gradient at the ... surface to cause the evaporation that occurs in a dry cooking system. Thus, the use of saturated steam creates a cooking system where thermal denaturation of muscle proteins is the primary mechanism in moisture loss."

Current tuna precooking processes continue to try to both minimize this cooking moisture loss and reach the minimum backbone temperature to be able to separate the edible loin meat from the red meat and bones, and also to maximize the cooked recovery while now also meeting the HACCP Guidelines requirements for histamine control while precooking.

The amount of cook losses during precooking is measured by comparing fish weights before and after precooking. The losses during precooking are primarily water, soluble proteins, and fish oils. Percentage of total weight cook losses are higher for smaller tuna than for larger tunas (Lord et al., 2021; DeBeer[4]). In addition, the retorting of the edible meat in sealed containers later in the process causes further denaturation of the tuna muscle protein and moisture loss. Retorting is the most destructive and highest heat the tuna meat will encounter (Bell et al., 2002; Nolte[3]).

Atmospheric Precookers (APC's)

The majority of the precookers in the world in 2020 are APC's with vents and floor drains open to the atmosphere (Lord[1]; DeBeer[4]). The vents are used to remove the air from the precookers initially and then act as bleeders so steam can escape and provide for steam circulation. The drains allow condensed steam (water), fish juices, and oils to escape. The rate of conductive heat transfer into the fish interior depends on the thermal diffusivity of the fish and the changes of state of the meat as the fish is cooked from the surface to the backbone (Bell et al., 2001; DeBeer et al., 2015).

Temperature distribution tests must be conducted on each class of APC's or each precooker on a regular basis to assure that all the fish are evenly heated during an APC cooking cycle. These tests are also necessary after any equipment change such as replacing steam pipes or control valves. See Appendix 5 in the NFI Tuna HACCP Guide (NFI, 2014) or IFTPS guidelines (IFTPS[23]) for the correct procedures to conduct these temperature distribution tests for precookers.

The removal of cold spots and an even heat distribution throughout the precooker are critical to the precooking of all the fish of the same size to a similar target backbone or core temperature. The APC must be rigorously maintained and in good working order with all of the valves and steam piping intact to work as designed and maintain atmospheric pressure. It is especially important to check and maintain the steam pipes near the bottom of the precooker for soundness on a weekly basis, since hot water and salt from cooking liquids will promote corrosion of these pipes. Extensive corrosion of these steam pipes requires that they be immediately replaced as broken pipes and/or unintended steam leaks can commonly occur.

An ideal heating temperature profile for an APC shows the steam temperature increasing quickly to 100°C (212°F) during the venting cycle, holding constant during precooking, and then decreasing quickly after the steam stops (Fig. 6). The surface temperatures of the fish follow the saturated steam temperature profile. The backbone (core) or the geometric center of a split fish or whole fish experiences an initial lag in temperature increase. This temperature then increases at a rate of less than 2°C/min in a sigmoidal fashion or shape, depending on the fish size (thickness) (Bell et al., 2001; DeBeer et al., 2015). After the steam is turned off, the temperature at the backbone continues to increase for a time due to simple thermodynamics (Fig. 6) and before it starts to cool (DeBeer et al., 2015): simply put, the second law of thermodynamics states that heat moves from a warmer area to a cooler area. After the steam stops heating the surface of the piece of tuna, portions of the interior of the fish are still hotter than the core and the core temperature increases as the heat transfers to the cooler core of the fish. This time of continued heating of the core after the steam valves are closed is termed "overshoot" (Perez-Martin et al., 1989). This overshoot is to be expected and can be incorporated into the precooking time schedules.

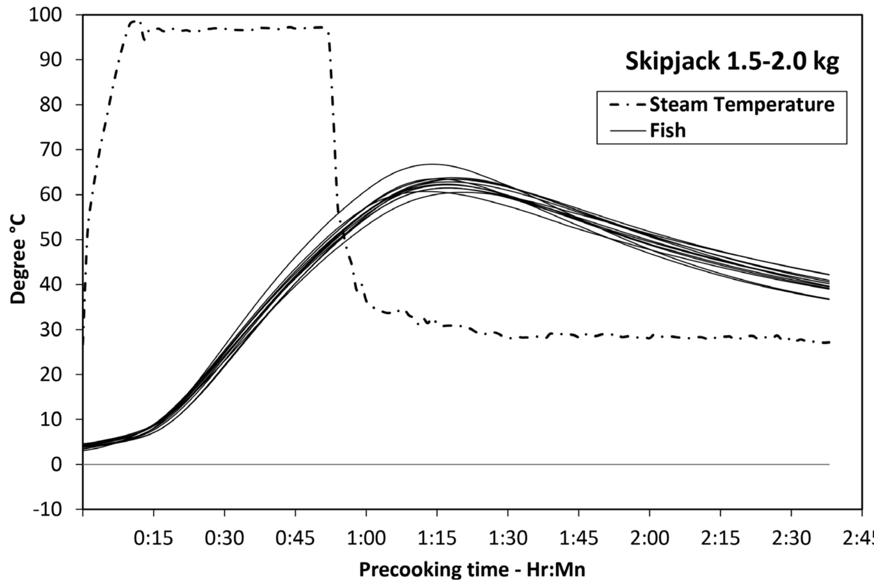

Figure 6.—Temperature profile of an atmospheric precooker.

Cooking times in APC's are quite uniform and predictable if the fish has been properly sized and thawed to a uniform core or backbone temperature. Zhang et al. (2002) estimated the rate of temperature increase at the backbone to be about 0.75°C/min for 3.5 to 4.6 kg skipjack, and Perez-Martin et al. (1989) estimated a range of 0.35°C/min to 0.96°C/min for 4–8 kg albacore. Larger fish (thicker pieces) experience slower heating rates. Nolte et al. (2014) used a 2°C/min increase of the core temperature which is considered attainable only on very small fish.

Historically, individual processors established their own backbone temperature targets and precooking times by fish size (Anderson and Stolting, 1952; DeBeer[4]). Elaborate proprietary tables of precooking times are established based on the existing equipment, fish size, species, and IT's (Lord[1]; DeBeer[4]). Operators measure the backbone (core) temperatures after the fish are removed from the precooker to ascertain if targets were met at the end of precooking: The fish must be returned to the precooker for further heating if the backbone temperature targets are not met. Measuring the backbone (core) temperature for these determinations is now called measuring the End-Point Internal Product Temperature (EPIPT) Frazier (2005). See Appendix 6 of the NFI Tuna HACCP Guide (NFI, 2014). DeBeer et al. (2017b, c)

[23]IFTPS. 2014. IFTPS Guidelines for Conducting Thermal Processing Studies. Chapt. 4. Conducting Temperature Distribution Studies (avail. at http://iftps.org/wp-content/uploads/2017/12/Retort-Processing-Guidelines-02-13-14.pdf, accessed 2 Oct. 2019).

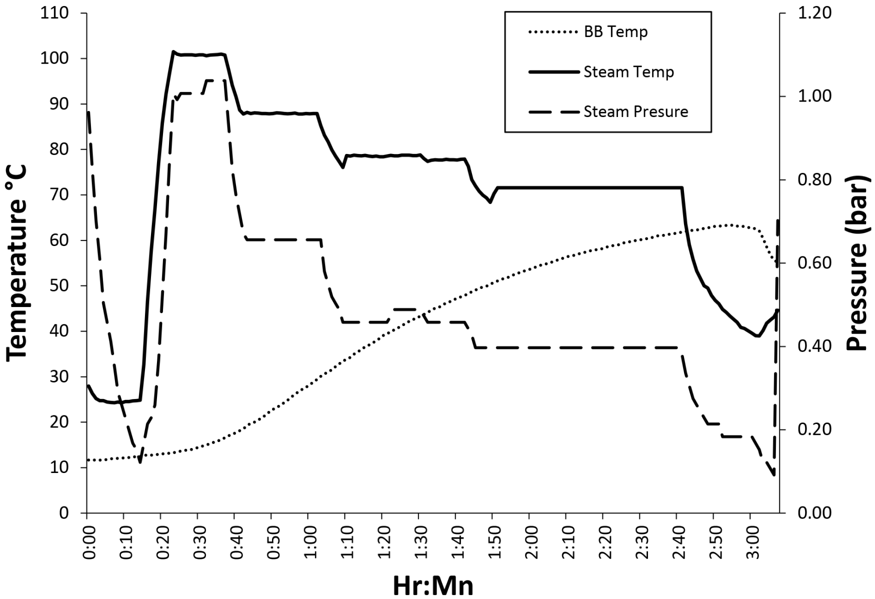

Figure 7.—Temperature profile of a vacuum precooker.

developed sampling plans and practical applications for collecting these core temperatures or EPIPT's and for making practical accept-or-reprocess decisions.

Many APC's are now equipped with temperature probes to help control cooking, measure EPIPT's, and determine completion times. However, relying on probes inside a precooker to determine EPIPT's has disadvantages because of the very rough environment. The fish can change shape during precooking and the probes can move out of place. The probes can often break or have bad readings even if multiple probes are in use, and most of the probes are located close to the precooker doors. Assuming that the coldest part of the precooker is near the doors is not always true, and validation using temperature distribution testing is required to use internal probe temperatures as the primary means of regulating precook or monitoring a precook CCP.

The EPIPT's need to be collected from individual fish throughout the precooker to verify the proper precooking CL's have been reached. Proper procedures include having backup plans and equipment (thermometers, recording paper, pencils) prepared in case the probes break down or fail in another way. Thus, an EPIPT control mechanism with physical measurements of backbone temperatures after precooking is generally needed (Nolte et al., 2014; DeBeer et al., 2017a, b, c).

To control the food safety hazard of histamine formation, the EPIPT at the fish backbone must reach 60°C for all the fish or corrective actions (CA's) of additional cooking must be taken. The times of the original and additional precooking cycles need to be included as parts of the 12 h total processing time requirement, from start of thaw until the end of precooking in this case because the CL of 60°C was not reached the first time (FDA-UTL, 2016). A further CA, including sampling for histamine, n=60, c=0, needs to be completed (FDA-WL, 2014) if the 12 h time requirement is exceeded.

Vacuum Precookers

A process for precooking and cooling tuna in a vacuum was patented by Erickson and Loewe (1960a, b); however, as later patents (Lassen, 1965; Peterson, 1971, 1973) noted that the fish which had been cooked and cooled in the early VPC's tended to explode if they were cooled too fast at a lower pressure. VPC's were not commercially feasible until Maconse[22] and FMC Corporation (Weng, 2000, 2003) developed vacuum precookers for commercial use, and, more importantly, used computers to control the pressure and temperature regulators. The outer shells of the current vacuum precookers are designed to withstand a vacuum. The first commercial VPC was developed in the 1970's, and FMC made its first VPC in 1985 (Dahl[24]). The precooking and cooling profiles are closely-guarded proprietary trade secrets within each company using vacuum precookers.

Tuna precooking using a VPC involves first loading the fish on trolleys into the precooker, closing and sealing the doors, and removing the air via a vacuum pump. Steam is then introduced for several minutes to fill the chamber to raise the chamber pressure and temperature to 100°C (212°F) and keep it there. For the temperature step-down, water is sprayed on the inside walls to cool the precooker chamber, condensing some of the steam and creating a vacuum. Chamber pressures and temperatures then follow a step-down profile through the use of steam, water spray, and a vacuum pump. At each step down, the lowered pressure lowers the temperature, and some steam condenses to water. The latent heat of vaporization for the phase change is still transferred to the tuna but at a lower ambient temperature. Figure 7 illustrates a typical VPC profile.

When the cook is completed, as measured by the tuna core or backbone temperatures, cooling is begun by spraying water on the fish, and a vacuum is created in the VPC with the vacuum pump. The combination of a water spray and a partial vacuum demonstrates controlled evaporative cooling. As the water evaporates from the tuna surface, a phase change occurs which is the opposite of steam condensing to water. Now the sprayed water is con-

[24]Dahl, J. 2020. email dated 7 Apr. 2020 (email: Jeff.Dahl@JBTC.com).

verted to vapor, and heat is removed from the fish. Controlling the vacuum is critical to preventing the fish from exploding (Lassen, 1965; Peterson, 1971, 1973).

Weng's patents (2000, 2003) provide charts with examples of the ambient temperature profiles. Perez-Martin et al. (1989) estimates that vacuum cooling is six times faster than conventional cooling while Wang and Sun (2001) reported even faster rates of vacuum cooling. Co-authors (Lord[1]; DeBeer[4]) have found that the cooling cycle of VPC's is even faster than what Perez-Martin et al. (1989) reports.

This cooling and pressure control issue (exploding fish) in the VPC's is a concern during retorting as well because the internal pressure within the container (cans, pouches, and cups) remains much higher than the outside chamber pressure during initial cooling of the container. When the outside of the flexible pouches, cups, or even cans are cooled too quickly after retorting, the pressure differential from inside (higher) to outside (lower) can cause pouches or cups to explode and cans to buckle. Compressed air is normally pumped into the retort (air over-pressure) during cooling to solve and prevent this issue. Modern retorts, VPC's and APC's use computer controls to manage the various steam, water, air valves, and vacuum pumps.

In Figure 7, the changes of internal pressure range from over 0.15 atmosphere (bar) to 1 atmosphere, and the ambient temperature stepped down three times from 100°C (212°F) to 70°C (158°F). It is this ability of a VPC to cook fish at lower temperatures with controlled pressure that provides the advantages of precooking fish in VPC's (DeBeer, 2019a). A well-maintained VPC can control the ambient temperature profile precisely (Weng, 2000, 2003; DeBeer[4]). This requires preventing leaks from occurring in the door gaskets or the vacuum pump, and the water spray nozzles must be clean and functional.

Steam pressure and temperatures can be substantially lower in a VPC than an APC. The initial lag in the backbone temperature increase at the beginning of the precooking is similar in both the VPC and the APC; however, the precooking cycle in a VPC will require longer times. Time is required to pull the vacuum, remove the air, and then introduce the steam for the VPC operation. Precooking using a VPC also takes longer than in an APC because the temperature difference (ΔT) between the lower ambient steam temperature of the VPC and fish backbone temperature gets much smaller towards the end of the heating cycle than in an APC at 100°C (DeBeer et al., 2019a), and it is the ΔT that drives the heat inward. Vacuum precooking can easily take twice as long as APC precooking, especially if the fish are frozen at the core at the start and must be thawed during precooking (DeBeer[4]).

Stepped Precooking with APC's

Stepped precooking procedures involve changing the steam temperature in the precooker chamber by various methods during the precooking cycle (Erickson and Loewe, 1960b). Stepped precooking is designed to heat the core of the tuna at the fastest possible rate while avoiding overcooking the tuna meat nearer the surface. Erickson and Loewe (1960b) also cite eliminating scorch and avoiding drying out the surface of the fish as reasons for using stepped precooking. Step-down processes are far more common (Lord[1]) and normally begin with venting to remove the air so the ambient steam temperature can reach 100°C (212°F) throughout the precooker. Subsequent steps are taken to lower the steam temperatures by creating a steam-air mixture. It is essential that adequate provisions are made to allow additional air to enter the APC as the temperature is stepped down to prevent the potential collapse of the precooker. A vacuum is formed as the steam condenses, and the outer shells of the APC's are not generally designed to withstand such a vacuum and may buckle. Vacuum breakers should be installed on the precookers which are used for step-down procedures.

The precooker chamber temperature step-down changes are accomplished by a controlled water spray against the inside of the precooker shell and not against the fish (Bichier[25]). As the precooker ambient temperature goes below 100°C (212°F), the APC will contain a steam-air mixture. Air is denser than steam and will naturally sink to the bottom of the precooker. The densities at 100°C (212°F) of dry air and steam are 0.947 kg/m^3 and 0.597 kg/m^3, respectively (ETB[26]). This steam-air mixture must be circulated to maintain an even-temperature distribution. Fans or water spray are employed intermittently thus resulting in momentary temperature increases or decreases. These temperature drops cause the steam control valve to open and introduce steam to recover the set point temperature. Control of stepped processes in APC's is best achieved using computerized controllers. EPIPT's must also be monitored upon the removal of the fish from the stepped precooking cycles in APC's (DeBeer et al., 2017a, b, c). The step-down cooking procedure is used to lessen the "cook value" of the tuna meat (DeBeer et al., 2019a). The term "cook value" is explained in detail by Awuah et al. (2007) and Holdsworth (1985). A step-down precooking temperature profile is shown in Figure 8.

Successful step-down precooking will reduce the temperature gradient in the tuna muscle from the surface to the core. However, step-down precooking is generally difficult to accomplish without good circulation of the steam-air mixture inside the precooker. Overshooting the target end of cook temperature at the center of the fish can occur quickly with standard precooking if the steam is not turned off at the right time (Fig. 6). Since step-down precooking takes longer, the danger of overcooking is lower.

Control mechanisms for achieving minimum tuna core temperatures

[25]Bichier, J. Personal commun. (email: Jacques.Bichier@JBTC.com).

[26]ETB (Engineering Tool Box). 2019. Engineering Tool Box (avail. at https://www.engineeringtoolbox.com/air-density-specific-weight-d_600.html, accessed 21 Oct. 2019).

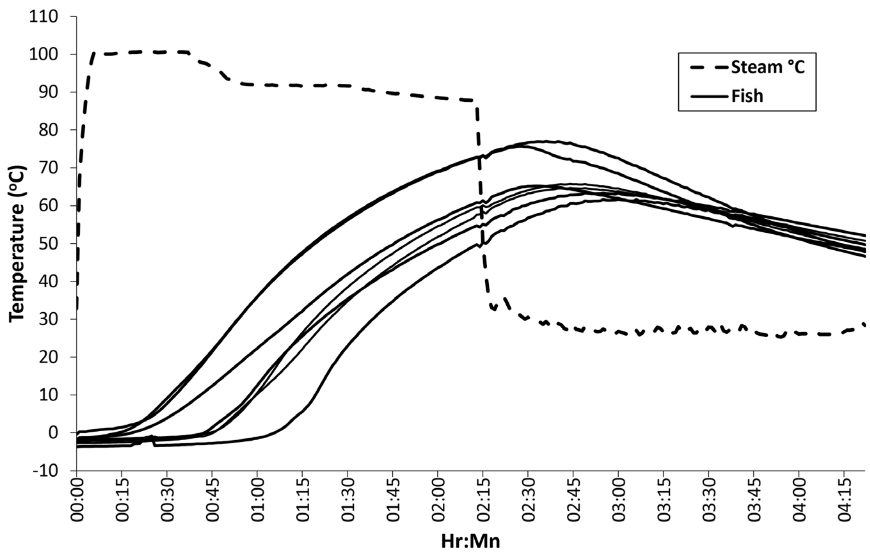

Figure 8.—Temperature profile of an atmospheric precooker—stepdown profile—6 kg skipjack tuna.

are required for all precooking processes in order to comply with HACCP guidelines. Tuna backbone or core temperatures will continue to increase after the steam is turned off. The rate of increase depends on the temperature difference (ΔT) between the ambient steam temperature (surface temperature of the fish) and the tuna backbone temperature at the time of steam-off (Perez-Martin et al., 1989; DeBeer et al., 2015). Since the tuna core temperature will continue to increase, the steam can be turned off before the core reaches the target temperature of 60°C. Determining this amount of time requires experience with individual precookers and different fish sizes (DeBeer et al., 2017a, b, c).

To determine the time of steam-off, start with overcooking the tuna first. Then precooking times can be backed off as need be. Do not approach this early steam-off process by undercooking first, because if resulting re-cooking is required, both precooking times will need to be totalled to calculate the 12 h process time requirement for thawing and butchering. Exceeding the 12 h process time will require corrective actions including re-cooking and an extensive histamine sampling program (FDA-WL, 2014; DeBeer et al., 2017a, b, c).

Critical Temperatures in Precooking Tuna

During precooking there are several temperature levels that impact the tuna muscle structure and firmness and the safety of the final canned product. The maximum peak for tuna muscle protein denaturation and coagulation occurs at 59°C (138°F) (Bell et al., 2001) while a 5-log reduction of *Morganella morganii* occurs at 60°C (140°F) (Nolte et al., 2014). Coincidentally, the collagen which attaches the muscle fiber bundles to the backbone, pin bones, and other bones is weakened at that temperature (59°–60°C). Cooking tuna to this final temperature facilitates easier separation of the edible meat from the skin, bones, and red meat. When the tuna has been cooked to a core temperature of 60°C at the thickest portion or center of the mass, the other or outer muscle has been cooked to higher temperatures, depending on the muscle portion's position in the loin and on the ambient steam temperature in the precooking chamber during precooking.

Peterson (1971, 1973) was the first to publish that a suitable ending backbone (core) temperature is 57.2°C (135°F), which is quite close to the current CCP CL EPIPT of 60°C (140°F) mentioned previously (Nolte et al., 2014; DeBeer et al., 2017a, b). Other earlier patents before the HACCP guidance suggested different precooking backbone temperatures for whole fish: Lang (1950) suggested 71°C to 77°C (160°F to 170°F), Erickson and Loewe (1960b) suggested 71°C to 82°C (160°F to 180°F), and Perez–Martin et al. (1989) suggested 70°C (158°F). Suwanrangsi et al. (1995), suggested a final backbone temperature range of 60°C (140°F) to 65.6°C (150°F).

Tuna Quality Changes that Can Occur During Precooking

Utilizing vacuum precookers has fish quality advantages for precooking high value tunas such as albacore or yellowfin. When the steam is shut off to the APC at the end of precooking, oxygen-laden air replaces steam around the hot fish. This air can cause oxidation and darkening in the fish flesh; however, precooking and cooling under vacuum maintains the steam environment and prevents darkening of the meat during cooling. Therefore, fish properly precooked and cooled in a VPC produces much lighter/whiter meat than fish cooked in an APC (DeBeer et al., 2019a). This is extremely important in premium canned albacore markets, such as those in the United States and Canada (Nolte[3]; DeBeer[4]).

Cathepsins and Calpains

Cathepsins and calpains are proteolytic enzymes in the fish that break down muscle structure after the death of the fish (Sriket, 2014). Calpains are most active at neutral pH while cathepsins are most active in acidic conditions near a pH of 5. Calpains are most active within 24 h of the death of the fish and can cause texture loss or mushiness in skipjack or other tunas if the tunas are not rapidly chilled after capture. Cathepsins are most active between 50°C and 60°C and less active at over 60°C (Ruilova-Duval, 2009; Stagg et al., 2012) and are thus active during precooking as the fish core reaches higher temperatures approaching the target precooking temperature of 60°C.

According to Stagg et al. (2012), Abusive holding, high temperatures, and resulting muscle degradation of raw skipjack tuna can additively adversely impact the textural quality of precooked fish. "Proper temperature control during thawing, handling, and thermal processing prior to precooking of skipjack tuna is crucial to the texture of the [cooked meat] going into the can, and likely also the canned product." Previous muscle degradation also affects the texture of the precooked tuna.

Ruilova-Duval (2009) reported on albacore and that: "muscle enzymes were activated during precooking and remained active during subsequent cooling at 30°C or higher…. Albacore tuna muscle precooked at 50°C was less firm in texture, … had greater grittiness and a more grainy mouthfeel… and had a lower cooked moisture content than meats precooked at 70°C. This weakening of albacore tuna texture and increased water loss is likely the result of [the activity of degradative muscle enzymes]".

Table 7 shows some critical temperatures for muscle enzymes, bacterial activity, and processing for precooking tuna. Precooking the tuna to backbone temperatures of over 60°C, then chilling the fish quickly, and processing it quickly is advantageous for recovery purposes. This will help minimize the risk of increased cathepsins activity and the resultant soft and mushy cooked tuna meat that has poor texture.

Table 7.—Critical temperatures for precooking tuna.

°F	°C	HACCP CL	Log lethality, 2 deg/min, *Morganella m.*	Histidine decarboxylase	Cathepsins	Peterson's patents
152.6	67					
150.8	66					
149.0	65			Complete Inactivation		
147.2	64					
145.4	63					
143.6	62		17.5			
141.8	61					
140.0	60	HACCP CL	5.7			
138.2	59					
136.4	58		1.8			
134.6	57					Recommended backbone temp
132.8	56		0.6	Optimal		
131.0	55				Most active	
129.2	54		0.2			
References		Adams et al., 2018	Enache et al., 2013; Nolte et al., 2014	Savany and Cronenberger, 1982	Stagg, et al., 2012; Ruilova-Duval, 2009	Peterson, 1971 and 1973

Tuna Processing, Cooling after Precooking Through Retorting

After the tuna are precooked, they need to be cooled before starting the manual cleaning process where the edible meat is separated from the skin, bones, and red meat. The cleaned edible meat is to be filled into containers and preserved (either retorted in hermetically sealed containers or frozen in loin bags). Fish cooling is an important and sensitive process and should provide properly set (gelled) proteins to prevent flaking during cleaning while not over-chilling and drying-out the cooked meat resulting in the skin sticking to the meat. These conditions will affect the cleaning process negatively. When the skin sticks to the loin meat, proper cleaning is difficult to achieve and thus results in reduced recoveries, because of defects remaining on the loins or the loss of loin meat removed with the skin. FDA Seafood HACCP safety controls and regulations impose time-and-temperature limits on these post-precooking cleaning and packing processes (FDA, 2011a).

Sidespray Cooling

After the fish is precooked to achieve the required minimum core temperature for inhibiting histamine formation (60°C), the steam to the precooker is turned off. By heating the tuna core to 60°C, the *Morganella morganii*, the most heat resistant HFB has at least a 5-log reduction in vegetative cells and the histidine decarboxylase enzyme is inactivated (Adams et al, 2018). The fish are then cooled as quickly as possible, using either vacuum-assisted water sprays inside the VPC, direct water sprays onto the fish in an APC or VPC, or more commonly water sprays, outside the precooker in a sidespray area. When cooling fish inside the precooker, the temperature probes must provide readings that are representative of the entire load of fish.

The traditional simple method of cooling the precooked tuna outside the precooker is natural convective cooling using ambient air. Another simple method uses forced air cooling, while a more complicated but more rapid and efficient method is sidespray cooling.

Sidespray cooling is an evaporative process using a series of pipes to spray water onto the fish (from the side, hence the name), along with air blown across the fish in a series of timed cycles (Peterson, 1971, 1973; Lord[1]). The heat from the fish evaporates the water, which removes the heat from the fish, and the blowing air moves the heat and water vapor away from the skin. Increased air movement increases the rate of cooling. The cooling action during the sidespray process provides the muscle protein time to set up or gel and improves the cleaning of the fish and reduces the flaking of the meat. When the core temperature of the fish has dropped to about 40°C–43°C (104°F–109°F), the fish are then moved into a chill room that should be kept cool with high humidity.

Chill Room

A chill room is a large, refrigerated room with very high humidity that acts as a staging area for the fish after the sidespray so the fish remain cool and moist prior to being cleaned. Fans are used to increase circulation to remove temperature gradients that may form in the room. The nature of the batch process operation of tuna canning requires a staging or waiting area between the cooling area of the sidespray and the area for skinning, deboning, and cleaning the loins. Peterson (1971, 1973) suggested that the chill room maintain a moist cool environment and chill the tuna to about 60°–85°F (about 15°–30°C).

Skinning, Deboning, and Cleaning

Modern tuna canneries employ one of two approaches to accomplish the tuna-cleaning process after cooling. One approach is performing all of the skinning, deboning, and cleaning steps at a single station. The second approach is to remove the head, gills, and skin at one station, and then pass the skinned fish body for deboning and cleaning to a separate station. This two-station operation makes for much cleaner work areas and keeps the loins cleaner. Regardless of the approach, each process step develops by-product streams of skin, bones, red meat, and small dark pieces. Properly precooking and cooling the tuna greatly improves the efficiency of the tuna meat cleaning process. For example, while skinning the fish, the skin should be able to be easily wiped off the loin with a gloved hand and not require the use of a knife (Lord[1]). First the skin is removed with gloved hands and a blunt knife (if needed), and then the four loin sections are separated from the backbone and each other.

The precooked loins of edible meat are manually cleaned by removing the red meat, blood veins, bruises, or portions of skin remaining on the loin. The cleaned loins should be checked for off odors or other evidence of adulteration or contamination using an established system to check and verify the previous organoleptic evaluation. This is the last chance to make certain the fish is wholesome before the meat is mechanically packed and processed.

Cleaning tuna fish loins is a developed skill which requires specific training and experience. An efficient processing factory must develop standard training methods for different sizes of fish to properly clean the loin meat and not waste effort or fish.

Loin cleaning can also be followed by a polishing step, which may be conducted at a separate designated location. To remove fine tuna bones, stainless steel mesh butchers' gloves can be used to further polish the tuna meat loins. Capture and handling methods on board the tuna vessel can produce and impact the amount of bruising that is present in the tuna muscle which can further impact the cleaners' grading and efficiency. The cleaned loins are often graded for color or size to meet the appearance and size requirements for certain markets.

Filling and Sealing the Container

After the loins are cleaned, the tuna meat is filled into either cans, cups, pouches, or loin freezer bags, a vacuum is drawn with a vacuum machine or a steam jet, and the container is then sealed with a double seam (for a can) or a heat sealer (for cups, pouches, or loin freezer bags). The majority of the tuna cans are mechanically filled using various tuna filling machines. Manufacturers include Luthi Machinery, JBT Food Tech, Carruthers, Herfraga, and Hermasa. These production machines are designed with a feed conveyor, a series of very sharp knives, forming shoes, and push pistons. Specific manual feeding techniques of the tuna meat are used to produce different pack styles for canned products. Pouches are filled by hand or machine and heat sealed in a vacuum sealer, cups are filled by hand and heat sealed in a cup machine using vacuum, and loin bags for freezing are generally filled manually and vacuum heat sealed before freezing.

Sealing or Seaming the Retortable Container

Seaming or sealing the containers is an important part of the Low Acid Canned Foods (LACF) regulations, 21CFR§113.60, Containers (FDA, 2019b) and is critical to the safety of the canned products. There are two styles of seamers for cans: one style spins the can under the chucks and rolls as the double seam is formed, and the other style holds the can in a fixed position and the seaming head moves around the can, which does not spin, and a double seam is formed as the seaming head circles the can. The can seamed in a fixed position, without spinning, will provide the best cake appearance. For the tuna cake appearance, the spinning head seamer cannot be run at too high a speed because the cake will be disturbed by centrifugal action of the spinning can. If the factory management desires cans of fish with the best top appearance when the can is opened, the cans should not spin too much but should be kept as flat (horizontal) as possible in the retorts and while being labeled. High-speed labelers will spin the cans but only for a couple of revolutions. The cans should be handled flat, if possible, on all conveyors and can tracks and use a can track with a cable conveyor rather than gravity delivery systems, which roll the cans and disturb the top appearance of the tuna cake.

Heat sealers are used when the final containers are plastic cups, pouches, or bags to heat weld and seal the plastic lid to the cup, or plastic pouch or heat weld the loin bag seam edges together. There are many variations of the heat sealers depending on the plastic composition and container form. Heat-sealed containers require a minimum 10-day incubation period after retorting to be sure there are no leaking seals (Arndt, 1992; USDA, 2013). The use of new processing procedures or products may require longer incubation times to be sure that the processing parameters, packing, and sealing are properly controlled so that safe products are produced.

Frozen Loin Bags

The cleaned loin meat can also be placed into high-oxygen barrier bags, sealed under vacuum, and then frozen for shipment to another cannery where the meat can be thawed and filled into cans. These barrier bags have a very low O_2 transmission rate (20 cc/m^2/24h at 1 atm and 23°C and 0% relative humidity), meeting the specifications for a high barrier bag **(**Flair[27]**)**. After the bags are filled manually, they are closed, the air is removed, and the bag is heat-sealed in the vacuum chamber. Many factories use forming machines before freezing the loin bags to shape them with flat sides for pallet stacking and shipping. The shape and dimensions of the bags of frozen loins can be designed to fit the feed conveyor of individual tuna packing machines at the receiving cannery, thus requiring close coordination between seller and buyer. After forming, the vacuum sealed bags filled with tuna meat then pass through a heat shrink tunnel using very hot water to shrink the plastic bag around the tuna loin meat. The bags of tuna meat are then rapidly frozen in a blast or plate freezer. The hard-frozen loins can be stacked like cordwood on a shipping pallet and then wrapped in plastic and cardboard for shipment and storage at the receiving cannery. The vacuum-sealed, bagged, and frozen loins can be stored for extended periods of time at temperatures of -20°C (-4°F) or below.

Retorting

The Code of Federal Regulations (21CFR§113) for retorting food products in hermetically-sealed, retortable containers requires that critical information be recorded to control the safety of these products (FDA, 2019b). Each can size and product type must have a process schedule approved by a recognized process authority. If the product is destined for the United States, each facility must have a unique Food Canning Establishment (FCE) registration number, and each product must have a unique "Process Filing" submitted to the FDA and must be assigned a unique "Submission Identifier" commonly called an SID number (Nolte[3]). The FCE and relevant SID numbers must accompany each shipment of retorted goods.

Each hermetically-sealed container of tuna, whether a can, cup, or pouch, must have a can code permanently affixed to the container surface 21CFR§113(c) (FDA, 2019b). This can code contains identifying information including the production factory, the product, the time of production, closing machine (seamer) line, and other details to facilitate ready and easy identification during the sale and distribution. This coding operation is done at the seaming machine or just after the seamer or heat sealer and before the sealed and coded cans are loaded into the retort basket. Each seaming/sealing machine must have a unique code as this is required for the can. After the cans, cups, or pouches are loaded into the retort, they are retorted until they are commercially sterile, 21CFR§113.83. The cans, cups, or pouches must be heated enough to kill all potential *Clostridium botulinum* spores with a 12-D cooking schedule to achieve a 12-log reduction in spores (Licciardello, 1983).

Incubation

Hermetically-sealed retorted products in containers closed with a heat seal (pouches, plastic cups, etc.) require incubation and 100% inspection after incubation to verify the integrity of the seal and absence of inclusions or channel leakers (CFIA, 2018a). Incubation times can range from 10 to 15 days at an incubation temperature of 32.2°C to 37.8°C (90°F to 100°F) (Arndt, 1992; USDA, 2013). This temperature is at the upper part of the growth range for mesophilic bacteria but below the thermophilic bacterial growth range. This incubation and inspection procedure is not conducted to confirm an adequate thermal process but rather to verify a proper heat seal was produced (Nolte[3]). Product containers sealed with double seams are rarely incubated for extensive periods of time since verifying the dimensions and efficacy of the double seams on a periodic basis (minimum every 30 min) is a requirement of the LACF regulations 21CFR§113.60, Containers (FDA, 2019b).

Label and Casing

After being retorted, the retorted containers should then be cooled rapidly and dried prior to affixing the labels and encasing multiple containers together in cardboard or plastic packaging for storage and shipping; this process is termed "label and casing." Metal cans should be cooled to an average temperature of 38°C (100°F) before casing (NFPA, 1982; Cole[16]), and metal cans must be dry to prevent rust from forming during storage. It is recommended that in humid conditions, the cans should be rapidly cooled to 49°C (120°F) and then allowed to dry as they cool naturally. Cans must cool to an average temperature no higher than 38°C (100°F) to avoid spoilage by thermophilic bacteria and heat damage to the quality of the product because of stack-burning (a change in color, taste or texture from slow cooling). Mechanical drying of the cans with air knives should be considered (NFPA, 1982). Air knives should be angled to move water away from the cans and provide proper removal of the water. Such an alignment should prevent water droplets from landing onto cans already dried. The cans, pouches, cups, or other containers will be ready for the labeling and casing operation after proper cooling and/or incubation and post-incubation inspections are completed. The cups and pouches must be manually inspected for soundness and absence of seam inclusions, seam damage, or leakage and then cased by hand.

Traditionally cans have used paper labels while now some cans are printed with Lithograph (Litho) technology. Paper labels offer more flexibility for labeling operations while Litho labels give the cans a more premium appearance. Paper labels are glued to the cans using mechanical labeling equipment, and then casing equipment can be set to produce case sizes that are required for the specific UPC/SKU which are then cased by automatic caser. The cans labeled using lithograph technology may be cased by hand or by au-

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[27]Flair Flexible Packaging Corporation. 2018. Avail. at http://www.flairpackaging.com/pages/gourmet_snacks_treats_flair_flexible_packaging/resources/packaging101_sustainable/Oxygen%20Transfer%20Rate%20(OTR)/2, accessed 13 Nov. 2018.

tomatic equipment. Cases of all these products are generally stacked and wrapped on shipping pallets and then loaded in shipping containers for transport to a distribution center or customer warehouse.

Cannery processors must rigorously document the labeling processes to prevent mislabeling of the product containers and avoid possible recalls for allergens. There are vision systems available that can verify each can code and compare it against the paper label applied, using high speed cameras for very high line speeds. These systems can also reject the wrong cans or stop the labeling equipment to prevent mislabeling (DeBeer[4]). Proper labeling can prevent allergen food safety hazards from occurring, as well as costly recalls due to the hazard. The HACCP plan should include allergen prevention with CCP(s) and CL(s). By 2013, recalls due to mislabeling and allergen risk were the most common of all FDA food recalls and the "use of the wrong package or label" was the most frequent problem leading to food allergen recalls (Gendel and Zhu, 2013).

Tuna Quality Changes from Raw to Cooked

After the precooking and during the cleaning steps, the cleaners must be alert to maintain quality in the final product by spotting and rejecting fish with odors of decomposition. The cleaners must also be alert for visual evidence of decomposition such as honeycomb (holes in the precooked tuna meat) (Frank et al., 1981, 1984: Burns, 1985) or post-precooker discoloration (ammonia burn) and this meat must also be rejected (DeBeer[4]). Ammonia burn can occur on the harvest vessel during brine-freezing of the fish when ammonia leaks from the cracked or leaking refrigeration coils into the salt brine and contaminates the tuna muscle. Ammonia burn is evident only after precooking when the tuna muscle turns quite red (Burns, 1985).

While cleaning the fish, the cleaners need to pay attention to their own itchy fingers, hands, or skin. Itchy fingers, hands, or skin can be an indication of histamine contamination in the tuna meat. The sensitivity between individuals varies quite a bit: some people are very sensitive (DeBeer[4]). Prior to wide scale histamine testing and screening of the raw tuna, it was something the cleaning room supervisors watched for diligently. Most of the skinners and cleaners in the world now wear gloves, and routine histamine testing screens out the lots of bad fish, so this phenomenon is not observed as often as it was 30 to 40 years ago (DeBeer[4]).

Canned Tuna Quality Changes During and After Retorting (Green Fish, Ph, and Struvite)

Some canned tuna markets favor different product characteristics than other markets. For example, those with more up-scale standards generally require larger chunks or piece sizes, lighter or more consistent color, and a smoother taste of the meat in the can (Nolte[3]). In many cases, these attributes reflect raw tuna characteristics. Albacore meat turns white after precooking, and the degree of whiteness can vary for different oceans and capture areas. Whiter coloration is considered to signify higher quality albacore by the consumer (Nolte[3]). For example, the Canadian market usually demands the white, clean albacore meat with no cleaning defects (Nolte[3]). The United Kingdom prefers the taste of skipjack (Lord[1]), while the Italian market favors yellowfin in olive oil (DeBeer[4]).

Sometimes albacore turns green in the can after retorting, thus impacting the white appearance (Naughton et al., 1957; Yamagata et al., 1969; Chaijan and Panpipat, 2011). Grosjean et al. (1969) reported that the green color is formed during retorting when the tuna myoglobin is denatured, a sulfhydryl group is exposed, and a disulfide bond is formed with cysteine. Fish from some catch areas have been noted to be more prone to produce green meat than from other areas (DeBeer[4]). This relationship suggests that there is a possible connection to what the fish eats but this has been difficult to prove. The green color is most noticeable immediately after canning the fish with a noticeable lessening of green color after several weeks due to absorption of the green color by the packing medium (broth or oil) (Nolte[3]).

The green color can be reversed by adding sodium sulfite to the can before retorting and the loin meat becomes much whiter. However, sulfites are an allergen not authorized by the canned tuna SOI. In 1996, there was an incident of unauthorized sulfites being added to an albacore vegetable broth to improve the whiteness of the meat in the can by a vegetable broth vendor without notifying the canners. The mislabeled cans on the store shelves were not recalled; however, all the cans in the warehouses around the country had to be labeled with an allergy warning (DeBeer[4]; AP News[28]). It was a massive, costly operation.

The pH of raw, frozen tuna is not routinely measured in a tuna factory because there are no action items that can be taken to change it; however, the pH of the precooked tuna meat is important to understanding struvite formation. The pH of the raw tuna meat is somewhat variable and is thought to depend on the method of death. The pH of longline albacore delivered to Van Camp Seafood in the 1960's ranged from 5.5 to 6.7 (Van Camp Seafood[29]). Skipjack directly captured in a purse seine net has a lower pH: John Kaneko[30] reported an average pH of 5.68, with a pH range of 5.65 to 5.79 for skipjack. His results were based on hundreds of samples. The lower pH of the skipjack is thought to depend on the struggle at death in the purse seine net or on a pole-and-line vessel (Van Camp Seafood[29]). Since the fish is chilled quickly, before the glycolysis cycle has completed, there is still lactic acid in the cells; perhaps this is why the pH is lower.

[28]AP News. 1997. FDA warns of sulfites in tuna (Avail. at https://www.apnews.com/fb904344f6717fcbe85217dcf497155f, accessed 29 Sept. 2019).

[29]Van Camp Seafood. 1966. Struvite control in canned tuna. Van Camp Seafood research lab. Doc. from J. DeBeer's personal library.

[30]Kaneko, J. Email dated 6 Sept. 2019 (email: jjohnkaneko@gmail.com).

Struvite is also a quality defect that can form in cans of albacore meat after retorting and is a colorless crystal that resembles glass. Although not a true safety defect, struvite is an appearance defect. It forms when the Mg++ ions in the cooked muscle combine with naturally occurring ammonium phosphate. Struvite doesn't form in tuna cans when the pH is below 6.1 (Van Camp Seafood[29]) or 6.2 (Miyauchi, 1950; Lampila, 2013). Sodium acid pyrophosphate (SAPP) can be added to the canning medium (liquid) to prevent struvite formation. The added SAPP keeps the free Mg++ in suspension (Kreidl and McFee, 1951). SAPP is an allowed ingredient according to the canned tuna SOI (FDA-SOI, 2001). Struvite is generally a concern only for albacore packs. Struvite has not been reported in skipjack packs, and this is generally attributed to the low pH of cooked skipjack meat thus preventing the formation of the crystal. Albacore are primarily captured by longliners. Skipjack and yellowfin are primarily captured by purse seiners, and this difference in capture methods may be a factor in the pH difference. Previously, the pH of cooked albacore loins was measured to select out the low-pH albacore to be filled into dietetic packs (DeBeer[4]), and SAPP would be added to the remaining albacore packs to prevent struvite.

Comparison of Precooking to Retorting

Precooking and retorting both involve thermal processing but have different goals. Precooking is heating uncooked fish with the objectives of denaturing the muscle protein, stabilizing the fish for cleaning, and stopping the growth of any HFB and histidine decarboxylase activity. Precooking does not achieve commercial sterilization. Retorting is heating sealed containers of cooked tuna meat with the objective of achieving commercial sterility. Both precooking and retorting destroy the vegetative cells of the HFB, other bacteria, *S. aureus,* and *Clostridium botulinum.* Retorting destroys the spores and/or neurotoxins of *C. botulinum.* Neither precooking nor retorting denature or destroy the histamine molecules that might be found in the tuna muscle and neither denatures *S. aureus* enterotoxins that might have formed.

The two processes are detailed and compared in Appendix B. Precooked tuna has a "shelf life" measured in hours per HACCP guidelines while retorted canned tuna containers are commercially sterile and have a shelf life that is measured in years. A successful retorting process requires very uniform or fixed dimensions for the cups, pouches, or cans. All cups, or cans must be of the same shape or size, and compression rollers are used to provide uniform thickness for pouches to be retorted and achieve commercial sterility (Afoakwa et al., 2013). If there are multiple sizes of containers in a retort batch, the scheduled retort process for the one that takes the longest time must be used to achieve commercial sterility. In contrast, the precooking process encounters fish actually changing dimensions and shape during precooking (DeBeer[4]; Colley[10]).

The target food safety organisms used to determine precooking or retorting thermal processes are very different, as well as the targeted log reduction numbers for these organisms. The target of the precooking process is a 5-log reduction of the HFB *M. morganii,* which is the most heat resistant HFB (Enache et al., 2013). This 5-log reduction of *M. morganii* can be reliably achieved by reaching a minimum temperature of 60°C (140°F) at the coldest spot in the fish (Nolte et al., 2014). In contrast, the required target of the retort process for commercial sterility is a minimum of a 12-log reduction of the spores of *Clostridium botulinum* to prevent the formation of the deadly botulinum neurotoxin under the anerobic conditions present within a retorted can of tuna.

Clostridium botulinum—12-D Cook

The minimum standard 12-D cook for *C. botulinum* spores is to maintain a temperature of 121.1°C (250°F) for 2.45 min (F_o=2.45) at the coldest spot in the can or container (Licciardello, 1983). However, for safety reasons the "minimum botulinum cook" is commonly considered as equal or equivalent to F_o=3.0 or 3 min at 121.1°C (250°F). The National Food Processors Association (NFPA) added to the level of safety and established a minimum F_o of 3.74 min for commercial canned tuna sterility in 1982 (NFPA, 1982; Cole[31]). FDA LACF authorities have been known to question tuna processors using an F_o below 4.0 min, while canned tuna buyers frequently demand an F_o of 5.0 or 6.0 min (Nolte[3]). Different times and temperatures can be used to achieve the 12-log reduction. When a lower retort temperature is used, a longer retorting time is required.

Canned tuna processing also addresses the concern of potential putrefaction and spoilage in cans after they have been retorted to a 12-D cook. To prevent spoilage during storage, retort processes are designed for the destruction of the spores of *C. sporogenes* which can cause spoilage (Licciardello, 1983). The spores of this pathogen are more heat resistant than *C. botulinum* so that such a retort process will provide a safety margin in addition to controlling spoilage after retorting (Brown et al, 2012).

Another concern for safety and *C. botulinum* control in retorted foods is the potential of human errors occurring in the application of the specified process to containers of food (Pflug, 2010). Many tuna factories use a higher F_o than 3.0 to address this potential of loss of control. Retorting to an F_o of > 3.0 can provide an added margin of safety if there is a human error in retort times and still produce the required F_o and safety of the canned product.

Energy Usage in a Tuna Factory

From "catch-to-can," the tuna industry is an energy intensive business. Thermal energy is required at every stage of the process. The frozen tuna destined for canning in a conventional tuna plant are thawed before under-

[31]Cole, W. R. 2020a. Email dated 3 Mar. 2020. Background data for 26-L-1982, Tuna Processes (email: BCole@tcal.com).

Table 8.—Thermal life of a kg of tuna from catch to can.

Activity	Back bone °C	Average temp °C	Heat removed /added	Delta deg °C, ave. temps	Specific heat Kj/Kg-°C	Latent heat of fusion Kj/Kg	Recovery %	KJ removed per Kg	KJ added per Kg	Basis %	Heat transfer medium
Swimming	30.0	30.0									
Chilled at sea	0.0	0.0	Removed	30	3.3		100%	100.5		6%	Seawater
Frozen at sea	-20.0	-20.0	Removed	20	1.7	422.9	100%	457.2		26%	Salt brine
Thawing	0.0	0.0	Added	20	1.7	422.9	100%		457.2	26%	Fresh water
Precooking	60.0	85.0	Added	85	3.3		85%		242.0	14%	Direct steam
Sidespray	43.3	37.8	Removed	47	3.3		85%	134.4		8%	Water and air
Chillroom	25.0	22.2	Removed	16	3.3		85%	44.3		3%	Water and air
Cleaning	25.0	22.2	Stable	0	3.3		50%	0.0		0%	Ambient air
Retorting	116.7	116.7	Added	94	3.3		50%		158.2	9%	Direct steam
Can cooling	37.8	37.8	Removed	79	3.3		50%	132.1		8%	Fresh water
Casing	26.7	26.7	Removed	11	3.3		50%	18.6		1%	Ambient air
						Total KJ's/Kg		887	857	100%	
								Change	1,745		

going two separate heat treatments prior to the labeling of the hermetically sealed and retorted containers. The retorted, sealed, and labeled tuna containers are then ready for long-term storage at ambient temperatures. Table 8 shows the heat gain and loss for a kilogram of tuna from the time it is swimming through capture, frozen preservation, further heat processing, and the label-and-case operation.

The total energy needed to change the heat phase state for a ton of tuna is the same for large and small fish, but the required energy rates per time period will differ markedly for different sizes of tuna. The minimum batch sizes for the equipment capacity during different tuna processing phases are shown in Tables 9–12. A 24-box thawing bay and an 18-rack precooker were used for the energy calculations: the tonnage processed per batch depends on fish size (Table 5). Both total kilojoules per batch and kilojoules per hour are shown. Inadequately sized boilers dealing with these changes in energy demand will result in steam supply problems in tuna canning factories due to the fact that the retorts always require priority over the precookers for full steam line pressure. The FDA requires a minimum of 90 psi for venting and retorting (FDA, 2014b). Steam boilers need to be sized to provide service to meet the maximum steam usage per hour for each fish size or can size for precookers and retorts. The venting procedure for the precookers and/or retorts has the highest instantaneous de-

Table 9.—Energy usage per hour in thawing tuna.

Fish/basket	Wt (kg)	Est. thaw h	Kg/box	Kg fish/ thaw bay	KJ thaw frozen fish	Kj phase change	Total Kj	Kj/h
12's	1	1	1,100	26,400	897,600	11,164,560	12,062,160	12,062,160
10's	2	1.5	1,000	24,000	816,000	10,149,600	10,965,600	7,310,400
8's	2.7	2	975	23,400	795,600	9,895,860	10,691,460	5,345,730
6's	3.5	2.5	975	23,400	795,600	9,895,860	10,691,460	4,276,584
4's	4	3	950	22,800	775,200	9,642,120	10,417,320	3,472,440
2's	8	4	925	22,200	754,800	9,388,380	10,143,180	2,535,795
1-Sm	10	5	925	22,200	754,800	9,388,380	10,143,180	2,028,636
1-Lg	13	6	850	20,400	693,600	8,627,160	9,320,760	1,553,460
Sm splits	16	7	850	20,400	693,600	8,627,160	9,320,760	1,331,537
XL splits	32	10	800	19,200	652,800	8,119,680	8,772,480	877,248
Jumbo splits	42	12	750	18,000	612,000	7,612,200	8,224,200	685,350

Table 10.—Energy usage per hour in precooking tuna from 0°C to 85°C average temperature.

Fish/basket	Mt/precooker	Precooker h	Kj/precooker batch	Kj/h
12's	3.90	0.58	1,020,771	1,759,949
10's	4.99	0.60	739,861	1,233,101
8's	5.44	0.67	1,424,331	2,125,867
6's	5.44	1.00	1,424,331	1,424,331
4's	4.99	1.17	1,305,637	1,115,929
2's	4.99	1.33	1,305,637	981,682
1's LG	4.54	2.17	1,186,943	546,978
Sm split	3.54	3.83	925,815	241,727
Med split	2.27	1.75	593,471	339,126
Lg split	2.63	1.92	688,427	358,556
Jumbo splits	1.81	2.17	474,777	218,791

Table 11.—Energy usage per hour in cooling tuna in sidespray from 85°C to 38°C average temperature.

Fish/basket	Mt/precooker	SideSpray h	Kj/precooker batch	Kj/h
12's	3.90	1.17	578,437	494,390
10's	4.99	1.50	739,861	493,241
8's	5.44	1.50	807,121	538,081
6's	5.44	1.75	807,121	461,212
4's	4.99	2.17	739,861	340,950
2's	4.99	2.58	739,861	286,768
1's LG	4.54	3.25	672,601	206,954
Sm split	3.54	4.75	524,629	110,448
Med split	2.27	3.33	336,300	100,991
Lg split	2.63	3.66	390,108	106,587
Jumbo splits	1.81	3.92	269,040	68,633

Table 12.—Energy usage per hour in cooling tuna in chill room from 38°C to 23°C average temperature.

Fish/basket	Mt/precooker	ChillRoom h	Kj/precooker batch	Kj/h
12's	3.90	3.00	183,739	61,246
10's	4.99	3.25	235,015	72,312
8's	5.44	3.50	256,380	73,251
6's	5.44	3.67	256,380	69,858
4's	4.99	4.00	235,015	58,754
2's	4.99	4.58	235,015	51,313
1's LG	4.54	5.83	213,650	36,647
Sm split	3.54	7.67	166,647	21,727
Med split	2.27	5.17	106,825	20,662
Lg split	2.63	6.33	123,917	19,576
Jumbo splits	1.81	8.00	85,460	10,682

mand for steam service (Cox[32]). Berteli et al (2012) suggest that venting can use up to 50% of the total steam consumed in the whole thermal process cycle of the retort. Although this has not been measured in precookers and published, it is likely that venting the precookers also uses a huge amount of steam (Lord et al., 2021).

Tuna processing is primarily a batch processing operation throughout the world, although many attempts to automate tuna processing have been made. The batch of frozen tuna that starts the thawing process will be broken up into smaller batches as the fish enters various processing steps. The thawing bay is generally spacious and can accommodate a large initial batch of fish. The precooking batch size or metric tons processed per precooker will be determined by the fish size and the capacity of each individual precooker. This precooker capacity is defined by the kilograms of fish per basket, the number of baskets per precooker rack, and the number of racks the precooker can hold. If sidespray lanes or zones are used, the capacity for this cooling step will have to be essentially double the precooker size because longer sidespray times than precooker times are required since the capacity for faster heat transfer of the condensing steam is greater in the precooker. The batch size for the chill-room step will be determined by the size of the room and how it can be utilized.

A chart of the maximum and minimum temperature for each process step is shown in Table 13. The critical limits for time-and-temperature for controlling histamine and *S. aureus* growth are shown in the right columns.

The overall capacity of a tuna factory is very difficult to model. If the fish sizes are generally uniform, it is much simpler, but if the fish sizes are mixed, it becomes more difficult. Each process step or area requires understanding the impacts of fish sizes on the requirements for both equipment and space. The space requirements for fish and retort baskets need to be planned for, and each piece of equipment in a process area needs to be matched in capacity with anything it receives from or feeds into. Fish must continually pass from one process step to another as time-managed inventory, and the tuna must be moved through the factory promptly and on time. So, every rack with fish, every cleaned loin container with meat, and every retort basket with unretorted cans must have an actual or virtual time stamp on it. These tuna process times for single or multiple steps have CL's and CCP's indicated in the Seafood HACCP Guidance (FDA, 2021a) and Adams et al. (2018).

Thus, designing a round fish tuna factory is very complex due to the times required for different process steps, requirements for space, and capacities needed for each fish and can size. Regardless of these complexities, a cannery must have a consistent daily stream of canned products to sell, and its capacity for processing these products should result in a consistent revenue stream. A brief outline of the approach to a tuna cannery design is provided in Appendix C (Cox[32]).

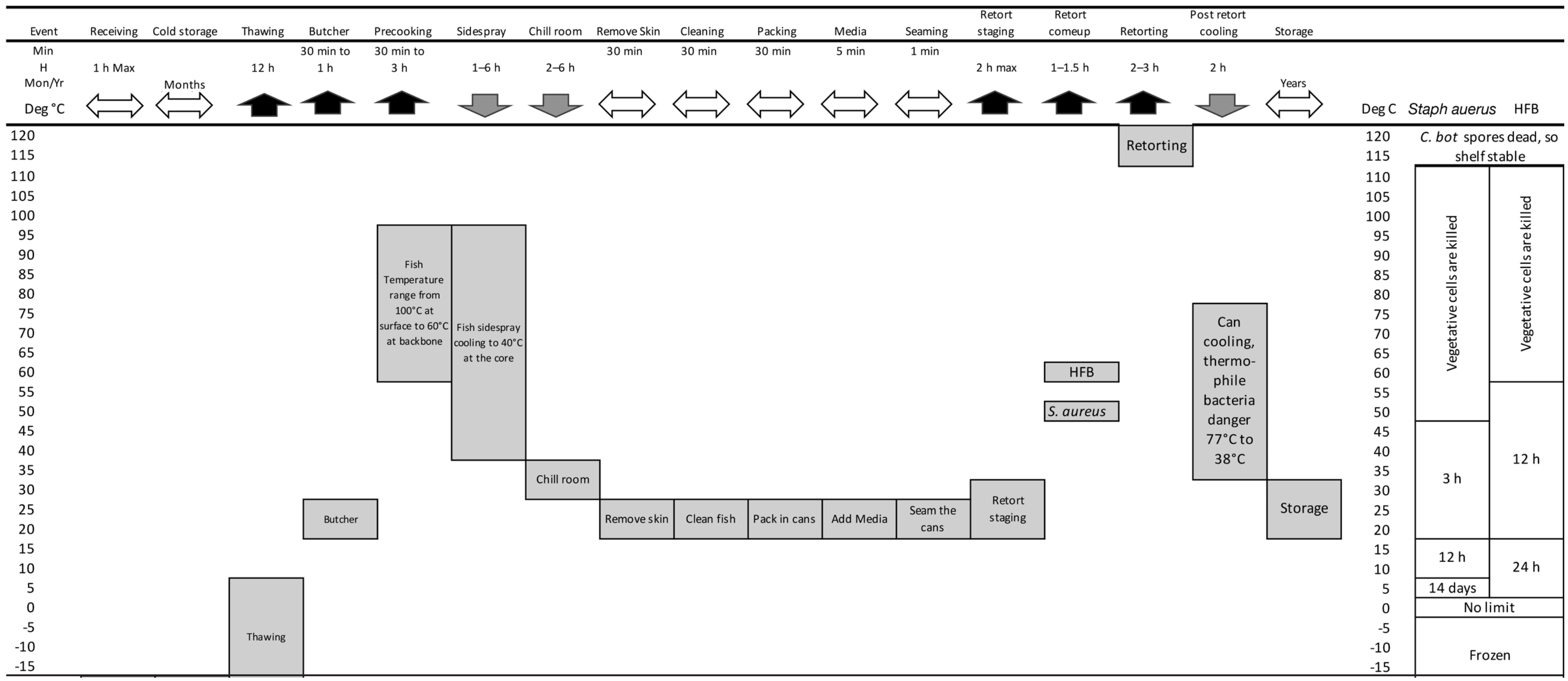
Sodium and Salt Control

The amounts of sodium (salt) in the U.S. diet and awareness of its public health impact has greatly increased in recent decades. The FDA has provided recommended sodium level claims that may be stated on the label retorted tuna containers (FDA, 2019a). These sodium claims must be declared per serving size, as are sodium claims for all processed and labeled food products that the FDA regulates. The specific sodium terms "no sodium," "very low sodium," and "low sodium" require < 5 mg, <35 mg, and <140 mg sodium per serving, respectively. Claims for reduced salt are based on previous sodium levels for that particular food product.

There are four sources of sodium common to commercial tuna packs; some packs may contain sodium from different sources. First, freshly-caught tuna has salt content of 0.1% to 0.2% (Karrick and Thurston, 1968), which equates to 33–67 mg sodium/3 oz serving. Second, tuna may absorb salt (sodium chloride or NaCl) during tuna preservation at sea (DeBeer et al., 2019b). To freeze the massive amounts of light meat species that can be caught in the tropical oceans, the use of cold salt brine is required. The tuna factories receiving this brine-frozen fish must have procedures to manage the salt content (sodium) from receiving through labeling. Fish with elevated salt levels require this management. Salt can easily be added to low salt fish to adjust the level but fish with higher salt levels must be blended with fish with lower salt levels to attain the desired sodium level for the final product. Some raw fish lots with high salt levels must be rejected outright. Third, canned albacore can also receive sodium during the addition of sodium acid pyrophosphate (SAPP). This sodium must also be accounted for: it is about 22% of the molecular weight of SAPP (DeBeer[4]). The maximum allowed addition of SAPP to a can of tuna is 0.5% (FDA-SOI, 2001). Fourth, salt can also be added directly to the can or with the canning media at can filling for low sodium fish. The preferred level of salt in

[32]Cox, J. 2019. Personal commun. (email: jim.cox67@yahoo.com).

Table 13.—Maximum and minimum temperatures for each stage in the tuna process.



tuna is between 0.8% and 1.2%, with the difference depending on whether the tuna is packed in water or oil. Tuna canned with olive oil may have up to 1.5% or more salt for taste enhancement (Bitting, 1937; DeBeer[4]).

Sampling for Salt (NaCl)

Sampling for salt levels is only needed for tuna that has been frozen in dense brine. Good sampling practices recommend sampling incoming frozen fish at the fish sorting step because salt content varies by fish size (DeBeer et al., 2019b). The sampling rate for salt testing for each fish size group should be at least 15 fish for individual fish weighing under 20 kg and 5 fish per group for fish over 20 kg (DeBeer[4]), depending on the variation of the salt content. Sampling for salt levels is variable sampling because average and maximum salt levels are used to make production decisions. There are tables of confidence levels and reliability for sample size for such variable acceptance sampling in DeBeer et al. (2017b).

Conclusions

Commercial tuna processing is a complex operation with many individual process steps and requirements. The raw material supply lines have long time periods, as the fish may travel long distances both for migrations while alive or dead with shipping, processing, and distribution. Tunas are harvested from all of the tropical and temperate oceans, depending on the species. The harvesting, onboard handling, and freezing equipment determine how the fish are frozen on the fishing vessel. The factory then determines how it is thawed, processed, and packaged in the tuna cannery. These handling and processing procedures have strict HACCP guidelines and controls for incoming testing and time-and-temperature processing scenarios. The commercial tuna processing business is very competitive, and profitability benefits from the economies of scale (DeBeer[4]). Manufacturing efficiencies and benefits are facilitated with big modern factories. Although bigger is better, cannery size does have limits, since as the cannery gets larger, the processing complexities and processing controls resulting from different processing times required for different sized fish will eventually overwhelm the factory management (Lord[1]; Correa-Gonzalez[6]).

The United Nations defined tunas and billfishes as "Highly Migratory Species" because of the vast distances these fishes travel in either temperate or tropical seas while passing in and out of the coastal zones of various countries (Joseph et al., 1988). Some tuna swims up and down the coasts seasonally with the oceanic currents, while some make trans-oceanic migrations. Successful commercial tuna canneries require on-going tuna deliveries for processing, while successful commercial tuna fishing boats require canneries to receive their tuna deliveries. Prior to the development of onboard refrigeration for freezing fish, the tuna-processing industry was locally-focused and restricted by the distances that fishing boats could fish and return to port in a reasonable amount of time with the fish preserved on ice. The amount of catch and types of species processed depended on what was available to the fishing vessels. Once these boats had the ability to freeze the fish, transshipment became feasible and has become a common commercial practice (Sylvester[5]). Refrigerated carrier vessels containing frozen raw tuna could move freely to canneries around the world, limited only by the transshipping costs, enabling commercial tuna canning to become an international business. For example, albacore is transshipped from Cape Town, South Africa, to a tuna cannery in American Samoa for processing, and then the cans are shipped to and sold in New York (DeBeer[4]). This harvested and frozen fish and resulting canned product traveled globally more than halfway around the world, west to east, and 74 degrees south to north, and passed through the Eastern, Western, Southern, and Northern Hemispheres. The canned tuna business is truly a global business.

Although there are many complexities, a tuna cannery is a relatively easy factory to build using off-the-shelf and used equipment. However, the supply lines for cans and ingredients, the availability of skilled seamer mechanics and technicians, and other mechanical trades mean that tuna canneries are often difficult to operate and manage efficiently and profitably (Cox[32]). Keeping fast-moving equipment such as seamers and labelers with very tight tolerances operating and maintained can be especially difficult, when only local tradesmen are available. Scheduling many different sizes of fish for processing through a cannery on a time sensitive, or restricted basis can make for a very challenging work environment (DeBeer[4]).

Maintaining absolute food safety practices while recovering the highest value from each fish is a requirement for a successful commercial tuna cannery. The recovery or yield of white or light edible meat from the purchased round tuna must be maximized into saleable products while controlling food safety and complying with HACCP regulatory requirements. Profitably using by-product streams such as fish meal, fish oil, and red meat for pet food is also a part of the challenge.

Recommendations for Improving or Maintaining High Recoveries

1) When the fish are not being processed, keep them as cold as possible and the colder, the better. Fish that have had salt penetration during freezing can suffer from drip loss during frozen storage.

2) Sort the fish by species and size at receiving and unloading. Store the same species and sizes together in the freezer for easy access and removal. Process the same-sized fish together to minimize overcooking and the unnecessary energy wastage.

3) Thaw the fish to a consistent backbone temperature. Schedule and thaw the fish properly, by size, so that they arrive at the butchering table properly thawed. Avoid thawing the tuna in the precooker.

4) Thawing the fish to a uniform

temperature facilitates proper precooking of whole fish and split pieces. Improperly thawed fish will result in overcooking the outside before the fish core thaws and heating begins. This situation will certainly lower recoveries.

5) Split the large fish into the pieces of the same thickness or precook different sizes in separate precookers.

6) Cook the tails from the same lot of fish separately if they are not the same thickness as the other split pieces. Tails can present difficulties during cleaning because of the high number of tendons. The tail meat can get very sticky to clean and needs to be cooled and treated properly: keep it moist.

7) Cook all of the fish to 60°C (140°F) or over at the core or backbone to meet the HACCP guidelines and minimize the cooling time to avoid the muscle breakdown due to the cathepsin enzymes.

8) Train the fish skinning and cleaning personnel to use consistent methods.

9) Clean the precooked tuna meat using two-stage cleaning. Keep the skinning and deboning tables separate from the cleaning tables. Maintain the fish cleaning area in a neat and clean condition. Do not mix the cleaned white or light edible meat with red meat or bone fragments.

10) Fill the cleaned edible meat into cans, pouches, or freezer bags as soon as cleaning is completed. Oxidation can occur and moisture is lost resulting in reduced recovery for every minute the meat is exposed after cleaning.

11) Loading the precooked loins and meat properly into the tuna filling machine conveyor can greatly improve the canned product appearance. Filling machine knives must be kept sharp. The correct filling machine formats must be used for the desired fill weights. Work with the filling machinery suppliers to optimize the loin feeding and resulting canned product appearance.

12) Be as consistent as possible. A consistent operating team can adjust times and temperatures as needed. Without this consistency, the outcomes of the needed changes cannot be accurately predicted.

Critical Issues that Confront the Tuna Processing Industry

1) Food safety: The first duty of the tuna cannery management is to produce a safe seafood product with no elevated levels of histamine, decomposition, *S. aureus* enterotoxin, leaking cans, and especially no viable *C. botulinum* spores or botulinum toxin. Everything else is secondary.

2) Sustainability: Access to fish of the usable commercial species and sizes will be a constant problem as the cost of capture and costs of processing change and fishing areas are opened and closed.

3) Scheduling: Optimal scheduling of the variety of sizes of wild-caught tuna is a never-ending, ever-changing challenge. The processing times and capacity parameters for each step of production need to be coordinated by fish size, all this while in compliance with HACCP requirements of CCP's and CL's for time-and-temperature is required for every processing shift. Linear programming software is available to develop a useful scheduling program. Such a program will require applying all of the inherent complexities to successfully schedule tuna through a processing factory in an optimal fashion.

4) Thawing: The critical problem is to successfully thaw smaller fish in conventional fish bins without forming an ice ball in the center of the box, as the fish softens and collapses on itself. This issue is still an unsolved problem in 2022.

5) Final thoughts: The fish is swimming in the ocean, someone will harvest it, someone will process it, someone will sell it, and people will purchase it to use as a high-quality source of protein. The authors hope this manuscript helps the tuna business in some small way.

Acknowledgments

The authors thank Mona Baumgartel for editorial help. The authors thank all of their mentors over the years for teaching them the "tuna processing business." The authors thank the journal reviewers for helpful suggestions to clarify ideas and improve the manuscript. The authors declare no conflict of interest. Any mention of any commercial brands of equipment is incidental. They are the brands of equipment the authors have worked with in the past. No endorsements are given or implied.

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Appendix A.—United States precooking and retorting patents.

Year	Patent number	Authors	Title or brief synopsis
1874	149,256	Shriver	Improvement in apparatus for preserving oysters and other product, in sealed cans – Original patent for a steam retort
1915	1,143,087	Stafford	Steaming or cooking the fish before separating the white meat from the dark meat
1938	2,110,801	Hopkinson	Cooking eviscerated or non-eviscerated tuna on the catcher boats or shore-side factories and refrigerating the cooked fish or loins until they could be delivered to a cannery for canning and retorting
1945	2,373,988	Wuori and Wuori	Packing uncooked loin meat into a can and retorting (raw pack)
1946	2,411,188	Borg	Cooking cleaned raw tuna meat in a can in a hot water bath before removing the liquid and then adding vegetable oil before sealing the can and retorting
1950	2,493,586	Lang	Cooking tuna to a backbone temperature of 160°F to 170°F (71.1°C – 76.6°C) while spraying the cooking fish with precooker juice, cooling by storing racks of whole precooked tuna in cold humidified room, and possibly storing for these precooked fish for several days
1953	2,635,050	Stevenson and Hodges	Cooking partially cleaned raw tuna loins before final cleaning and canning
1960	2,919,987	Erickson and Loewe	Vacuum cooling of precooked tuna
1960	2,919,988	Erickson and Loewe	Precooking raw, eviscerated fish at reduced steam temperatures (vacuum precooking)
1960	2,954,298	Anderson et al.	Injecting steam into the bone lines to separate the fish into quarters for further standard steam precooking
1962	3,024,114	McConville	Cooking raw, eviscerated tuna in plastic wrap to prevent discoloration
1962	3,050,403	Erickson	Thawing fish for precooking using heat from the retort water condensate
1964	3,152,912	Carruthers et al.	Injecting steam directly into the eviscerated tuna fish to precook them, the fish need to be thawed thoroughly first
1965	3,180,738	Lassen	Cooling the precooked tuna in an anaerobic sterile environment with inert gases including carbon dioxide, nitrogen, or argon
1970	3,547,657	Otsuka and Osada	Cooking the tuna with electricity in water to prevent struvite formation
1971	3,593,370	Lapeyre	Automate tuna butchering method
1971	3,594,191	Lapeyre	Mechanical method of processing tuna
1971	3,594,196	Peterson	Method of precooking and using evaporative cooling at normal atmospheric pressure. Precooking to a minimum of 135°F (57.3°C)
1973	3,709,142	Peterson	Properly thawing tuna to a uniform temperature, continuation of 3,594,196
1974	3,800,363	Lapeyre	Automated tuna butchering method
1974	3,806,616	Mencacci et al.	Using a caustic solution to clean fish
1988	4,738,004	Lapeyre	Automated tuna butchering method
1993	5,184,973	Orlando, Franco	Descaling tuna
2000	6,099,884	Manfre	Precooking with high pressure and high temperature
2000	6,153,860	Weng	Vacuum precooking and vacuum cooling
2001	6,210,262 B1	Burch, R. H. et al.	Method and apparatus for processing tuna for canning
2003	6,518,550	Weng	Vacuum precooking and vacuum cooling
2015	9,095,151	Simon	Method of making a tuna salad – precooking and pasteurizing tuna
2019	US2019/0090497 A1	Kasemsuwan et al.	Automated a portion of the raw tuna is processed with an automated skinner and steam tunnel precooker

Appendix B.—Comparison of the APC precooking and retort processes.

	Comparison of the APC Processes	
	Precooking	Retorting
Purpose	The primary purpose to bring about chemical and physical changes which coagulate the meat and facilitate separation of the red meat from the white meat, while minimizing loss of quality and yield. Histamine formation was also controlled, but this was studied and confirmed as a HACCP critical control point only from 2013 onwards.	The primary purpose is to sterilize the product in containers sufficiently for safe long- term shelf stable food preservation, also known as commercial sterility, while minimizing loss of quality and yield from physical and chemical changes to the meat.
Target organism and lethality	*Morganella morganii* vegetative cells, the most histominogenic of the histamine forming bacteria. Reference lethal temperature=60ºC, D_{60}=0.26 min, z=4.1ºC. A minimum 5 $\log_{10}$ reduction is recommended to prevent histamine formation after precooking	*Clostridium botulinum* spores. Reference lethal temperature 121.1ºC, $D_{121.1}$=0.2 min, z=10ºC. A minimum 12 $\log_{10}$ reduction is required. Further, to ensure destruction of all other non-pathogenic spoilage organisms which might prevent commercial sterility, a log10 reduction of 18.75 or greater (F_0=3.74) is used.
Toxin	Histamine	Botulinum toxin
Toxin heat stable	Yes	No
Hazard	Allergic reaction and symptoms	Severe illness and death
Process filing	No filing required. A safe precooking process is verified EPIPT.	FDA process filing (SID) required to establish and record a safe process.
Process equipment	The precookers must be well maintained, including calibration of all the instruments. Temperature distribution within the vessel must be validated by implementing temperature distribution testing.	Processors are required to ensure that retorts are well maintained, instruments calibrated, and temperature distribution within the retort is validated, either by using an approved retort design and vent schedule or by temperature distribution testing.
Process development	Processors develop their own process times by utilizing different method including heat penetration testing, computer modeling and experience.	Processors employ a Process Authority to establish new processes or validate existing processes. Processes are based on Heat Penetration, testing of products and procedures.
How bacterial pathogen destruction is delivered	EPIPT is used to control cooking to reach fish core temperatures in the range of 50–60°C and optimize processing characteristics, quality, and yield. *Morganella morganii* lethality begins to occur within this same temperature range and is more than 100x slower at 50°C than at 60°C. The EPIPT target of 60°C is more than adequate to achieve a 5-log reduction of *M. morganii* (Nolte et al., 2014).	Time-and-temperature controls of steam retorts are used to achieve the required reduction of *Clostridium botulinum* spores. Temperatures are monitored within the retort environment rather than of product inside the can or pouch of tuna. Retort temperatures typically range between 110–121°C (230-250°F). With a product temperature of 121°C, a log10 reduction of 18.75 would be achieved in 0.748 min (45 sec), but at 110°C the time required would be 74.8 min (100x more time). In practice, a can of tuna retorted at 121°C typically reaches commercial sterility before the contents reach 121°C, due to accumulating lethality while the retort heats up. However, a can of tuna processing at 110°C would reach 110°C well before commercial sterility was achieved, so measuring the tempera ture of the canned product is not useful to ensure commercial sterility during retorting.
Process monitoring	Times and temperatures are used to monitor the functions of the precookers. Process safety is monitored by measuring EPIPT utilizing a valid sampling plan.	Venting, come-up, cook, and cooling phases of the retort process are monitored by recording times, temperatures, and pressure to meet or exceed minimum requirements as recommended by the Process Authority, and as approved by FDA.
Unit size	Variable fish to fish and batch to batch. Fish sizes fall into cohort class and since they grow continuously, batches (for example) will not always be the same exact size.	Sealed and seamed product container have extremely regular dimensions, +/- .001 in. during retorting.
Unit weight	Determined by natural processes, cannot be controlled, and cannot be sorted to an extent that would allow process control by schedule alone, without complicating process to the point of creating a new safety hazard.	Extremely regular, determined by manufacturing process, and is controlled as a critical factor.
Conclusion	Proper precooking and the control of food safety hazards cannot be assured by an exact process schedule. Tuna temperature measurement by EPIPT is necessary to assure control and meet requirements.	The process schedule, controlling the process time-and-temperature and temperature validation of the retort environment, assure control of food safety hazards without the temperature measurement of the product itself. Seafood HACCP Guidance, Chapt. 16:319.

Appendix C.—Tuna Cannery and Canning Equipment Design.

The design of a tuna cannery process and its equipment requires knowing how much fish is needed to optimize the canning output, in terms of tons of tuna processed per day and per hour, pounds of cleaned meat per minute, ounces/grams of meat per can, sealed cans per minute, and the times for each operation. This review will focus on matching equipment capacities to fish volumes at each process step. Can sizes are critical to processing rates of the canning operation. In the United States the typical can sizes are 211 diameter (2 11/16 in) which has an 85 g (3 oz) net weight capacity, 307 diameter (3 7/16 in) which has a 142 g (5 oz) net weight capacity, 401 diameter (4 1/16 in) which has a 338 g (12 oz) net weight capacity, and 603 diameter (6 3/16 in) which has a 1.88 kg (66.5 oz) net weight capacity.

A critical element in cannery design is the fish fill weights and the net weight (fish plus canning media) for each can size. For example, a standard 142 g (5 oz) net weight, with a 113 g (4 oz) fill weight of tuna meat filled on a Luthi tuna packing machine at a rate of 180 cans per minute (cpm) requires 20.3 kg of edible tuna meat per minute. The efficiency factor of the packing machine and line must also be determined to obtain the actual amount of output of filled cans. Assuming a line will operate at 85% efficiency, due to unforeseen delays, the actual output will be 157 cpm instead of 180 cpm.

The following is an example for determining the line speed and necessary fish meat volumes using Luthi fillers and the most popular 307 diameter can. Assumptions include a 142 g net weight and 10 h shift (600 min of operation) using an average 314 cpm packing line speed (2 Luthi fillers running at 157 cpm each). Most U.S. canneries operate with two fillers per meat packing line to match to the output of a typical medium speed seamer at the end of the packing line. Using these parameters, the packing line using two filling machines and one seamer would use up 21,385 kg or 21.385 t of fish in a shift.

Empty can distribution and delivery to the filling machines is a major consideration in the design of the canning room area or space. Most empty cans are supplied to the cannery on a pallet that is approximately 1.42 m x 1.07 m. The empty cans are layered on the pallet so that cans are swept off one layer at a time, working down through the layers until the pallet is empty. This removal of the empty cans by layer can be accomplished manually or by a machine called a de-palletizer (automatic can feeding) to reduce labor. Most of these machines remove cans at a rate of 600 cans/min or higher. Empty cans must be conveyed to the canning line at a high elevation, and they are conveyed to the filler by gravity. These conveyors, or can runs, are made of round stainless-steel rods welded together with collars to hold the cans in a configuration which facilitate the conveyance of the cans by gravity to the vertical entrance of the tuna filling machine.

The filling machines must also be elevated so that the filled cans will travel by gravity down to another conveyor which moves them to a fill weight control station. A simple explanation of a filling machine is that it has a preset diameter to match the fish cake to the inside can diameter. In a filling machine, a series of pistons and knives cut the tuna meat cake to fit the inside diameter of the can and meet the target fill weight. Automated checkweigher devices are available that weigh the can for accuracy of the fill weight control. However, in most canneries, fill weight control is accomplished manually where sampling is conducted by removing the filled cans and weighing them to ensure the filler is performing to specifications.

Liquid condiments such as broth and water or oil, or other media are then added as necessary on top of the tuna meat cake to reach the prescribed net weight. Traditional condiment addition systems are a series of conveyors switching back and forth to pass the cans under the liquid flow long enough to get the correct amount of liquid while trying to minimize the meat disturbance on the surface of the cake. These are known as switchback conveyors. Net weight control, similar to fill weight control, is performed manually to obtain a statistical sampling to ensure that the proper net weight is being achieved.

After the addition of the canning liquids, the filled cans are conveyed to the seamer. Can lids are loaded into the seaming machine and positioned precisely over the entering full can. During the seaming process, steam is injected to heat the space between the lid and the filled can, to form a vacuum in the sealed can after the can and steam cools. A series of rollers compress the lid and can edges to form a rolled double seam and provide a hermetic seal as the cans revolve around a turret and then exit from the seamer.

The filled and seamed cans are conveyed to the retort baskets. These are large round or square baskets on wheels that can be rolled into the retort. One method to fill the retort baskets with cans is called a jumble loader, which allows the cans to fall into the retort basket, loosely load jumbled, forming random sized spaces between the cans. However, this method may create minor dents on the cans, and it also requires a method to unscramble and orient the cans for labeling after retorting. A superior method is to layer the cans into the retort basket after seaming while keeping the cans oriented either lid up or down. The machines that load by layers were originally called "Busse" loading systems and are now known as retort basket loaders. Sheets of metal or plastic with regularly spaced holes are placed between the layers of cans in the retort baskets. This layer of sheets must be designed to have the correct hole sizes and patterns to allow the proper steam flow during retorting. The design and hole dimensions are critical to proper retorting and achieving commercial sterility and are part of the FDA retort schedule approval process.

Designing a cannery is both an art and practical engineering, and all the steps and timings need to be coordinated with every other step. There are no real unlimited time resting stops for fish in a modern tuna cannery, except before processing when the fish are still frozen in the cold storage and then after the cans have been retorted, labeled, and the canned tuna process is completed.