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6200 Aurora Ave., Suite 200W, Des Moines, IA 50322-2864

John DeBeer,[1*] Fred Nolte[2] and Christopher W. Lord[3]

[1]*Chicken of the Sea International, Suite 500, 9330 Scranton Road, San Diego, CA 92121, USA;
[2]Fred Nolte Consulting, Vancouver, Canada; [3]Pro-Tech International Consultants Co. Ltd., Bangkok, Thailand

Precooking Tuna: A Study of the Factors Impacting the Time Required for Precooking

ABSTRACT

Precooking tuna is an essential part of the process of manufacturing traditional canned tuna. This paper briefly describes the manufacturing processes for precooking tuna in a conventional atmospheric precooker. Fish thickness and weights were measured to determine thickness variation by fish size. A finite difference simulation model was used to study the impact of three factors (fish size, initial backbone temperatures, and ambient steam temperatures) on precooking times. Results obtained with the simulation model indicate that the factors affecting precooking times are, in decreasing order, fish thickness, initial temperatures, and ambient steam temperatures. A multiple regression analysis indicates that the combination of fish size (thickness) and initial backbone (core) temperatures can account for 95% of the variation in predicted precooking time, with most of the variation based on fish thickness. Suggestions are offered for optimizing recovery of precooked fish and using the End Point Internal Product Temperatures (EPIPT) to control precooking results.

INTRODUCTION

The purpose of this paper is to describe the precooking cycle in a conventional atmospheric precooker and to study the impact of (1) fish size (thickness), (2) initial backbone temperatures, and (3) ambient steam temperatures on the estimated time of the precooking cycle in these precookers. Each of these parameters has an effect on estimating precooking times to achieve a desired backbone temperature. The audiences for this paper are tuna cannery management, tuna cannery quality control management, third-party quality assurance/control inspectors, and regulatory personnel.

"Precook" means to heat or cook the tuna in such a manner that the muscle tissue can be easily separated from the skin, red meat, and bones before the cleaned tuna muscle is canned, followed by the final sterilization or retort step. Thus, the precooked and retorted tuna are subjected to two heat treatments. Bell et al. (*1*) provide a detailed description of the changes to tuna muscle during these processes. In

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*Corresponding author: Phone: +1 858.597.4211; Fax: +1 858.362.9211; E-mail: jdebeer@cosintl.com this paper, the terms precooking and cooking will be used interchangeably, but the retort process will not be discussed. The three factors already listed that impact the precooking times were modeled mathematically and described in detail to determine their relative importance. Frozen tuna were weighed and measured to determine the variation of thickness of fish in different, sorted weight categories.

The entire United States (U.S.) seafood catching and processing sector is regulated by a system called Hazard Analysis Critical Control Points (HACCP), a science-based set of regulations was instituted by the Food and Drug Administration (FDA) *(6)* in 1997 to ensure seafood product safety. Scombroid fish (histamine) poisoning is one of the specific seafood hazards associated with tuna that HACCP attempts to prevent. When fish are harvested and die, certain types of bacteria can convert free histidine to histamine in a single step catalyzed by the enzyme histidine decarboxylase *(7)*. In the U.S., the limit for histamine is 50 ppm *(20)*.

In 2011, the FDA published the 4th edition of "Fish and Fishery Products Hazards and Controls Guidance" *(20)*. This document specifies a maximum processing time of 12 hours if ambient temperatures exceed 21°C at any point in the process. The time limit is designed to curb histamine formation during processing. The current recommended 12-hour time limit includes all of the processes, from start of thawing through cleaning, including precooking and the start of the retort process. It assumes that the precooking step does not constitute a clock re-setting heat treatment for histamine control.

The twelve-hour HACCP guideline mentioned earlier does not allow enough time to thaw, cook, cool, clean, and pack any fish except smaller ones (under 4 or 5 kilograms) *(4)*. However, a study by Vogl et al. *(21)* concluded that the growth of histamine-forming bacteria can be suppressed during precooking long enough to restart the clock and allow another 12 hours to cool and clean the fish. Enache et al. *(5)* developed thermal death time profiles for *Morganella morganii*, the most heat-resistant histamine-forming bacterium. Based on the work of Enache et al. *(5)*, Nolte et al. *(14)* developed a technique they used to prove that a 60°C (140°F) 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 100,000 CFU/g to 1 CFU/g. With the information from these studies, tuna processors are able to use precooking, with the proper heating temperatures and times, as a critical control point (CCP), thus extending the original 12-hour limitation and adding another 12 hours of processing time. Precooking tuna targets a 5-log reduction of *M. morganii*, a prolific scombrotoxin, or histamine former *(5)*. The 5-log reduction can be achieved reliably by reaching a minimum temperature of 60°C (140°F) at the cold spot *(14)*.

In summary, the historical purpose of precooking tuna was to stabilize the edible portions of the tuna flesh for further processing. In 2011, a second purpose, that of preventing histamine growth during tuna processing, was added.

Basic precooking concepts

There are three basic methods of precooking tuna, each with specialized equipment *(4, 9)*: (1) conventional atmospheric precookers (CAPs), with the steam vented naturally; (2) vacuum precookers (VPCs), in which the ambient steam temperature can be controlled up or down by water sprays and vacuum pumps; and (3) heated water baths, used primarily in Europe. The first two methods are by far the most prevalent. In addition, the step-up/step-down process, a technique of adjusting the ambient temperature during the cooking cycle, is used with both atmospheric precookers and vacuum precookers.

Conventional atmospheric precookers use condensing steam at 100°C (212°F) to cook the fish *(15)*. There is no standard design for precookers or required equipment, as there is for retorts. Therefore, numerous variations of precookers are available throughout the world. Precooking in a conventional atmospheric precooker is as follows: the thawed and butchered fish are loaded into the precooker in trolleys, the doors are closed, and the steam is let into the precooker through the steam spreaders and the air pushed out through the vent valves. After the vent cycle, the vents are partially closed, and the fish are steam-cooked for some period of time, depending on size and desired backbone temperatures. As a result, the edible muscle tissue is coagulated well enough to separate the bones, skin, and red meat from the edible meats.

After completion of the precooking cycle in a conventional atmospheric precooker, the fish are cooled either inside or, more commonly, outside the precooker, by a variety of methods. The oldest and simplest method is natural convective or air cooling; the second and next simplest method is with forced air cooling; and the third and most complicated, but fastest and most efficient, is a procedure called sidespray cooling. Sidespray cooling is a natural evaporative cooling process that uses water sprayed on the fish (from the side, hence the name) and air blown across the fish in a series of timed cycles *(9, 15)*. The heat from the fish evaporates the water, thus removing the heat from the fish, and the air moves the heat and water vapor away from the skin.

Recovery and yield from the round fish is all important for a factory's commercial survival. The historical goal of precooking was to cook the tuna to the target backbone temperature and no more. Per Bell et al. *(1)*: "The process of steam cooking of tuna occurs in a saturated moisture environment. These conditions do not provide temperatures above boiling nor produce a moisture gradient at the fillet 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." Every tuna processor is trying to minimize this cooking moisture loss, which explains why it is desirable to precook just to the required backbone temperature for ease of separation of the loins from the red meat and bones and to maximize the recovery, while meeting HACCP guidelines.

The amount of recovery loss during cooking is measured as the difference between weight of the fish before and after precooking. The losses during cooking are primarily due to evaporation of water, loss of soluble proteins, and fish oils. Smaller fish lose proportionally more weight than do larger fish *(4)*. The larger fish can be split or cut into smaller portions to reduce the piece size, reducing precooking time and increasing factory capacity, but also increasing potential losses during precooking. Usually, fish of 15 kg or larger are split, but this process depends on their thickness and length *(4)*.

Conventional atmospheric precookers (CAPs)

The vast majority of the precookers in the world have vents and floor drains open to the atmosphere *(4)*. The vents act as bleeders to allow air and some steam to escape and provide for steam circulation, while the drains allow condensed steam (water), fish juices, soluble proteins, and fish oils to escape. The heat is transferred from the steam vapor to the fish as steam condenses on the surface of the colder fish, and the latent heat of vaporization is released into the fish. 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 towards the backbone *(1)*. The thermal diffusivity depends on the thermal conductivity, specific heat, and density *(3, 11)*.

The ideal cooking temperature profile for an atmospheric precooker shows the ambient temperature inside the precooker increasing quickly to 100°C (212°F) during the venting cycle, held constant during precooking, and then decreasing relatively quickly when the steam stops. The surface temperature of the fish follows the ambient temperature profile. There is a general lag in the increase of the backbone temperature at the start of precooking, since the heat moves towards the midpoint of the fish or piece, after which the temperature moves up at a fairly uniform rate, depending on fish size (thickness) and chamber temperature. After the steam is turned off, the temperature at the backbone continues to increase for a time through simple thermodynamics, until it reaches equilibrium, or starts to cool *(Fig. 1)*. Cooking times in atmospheric precookers are quite uniform and somewhat predictable if the team starts with properly sized fish that have been properly thawed to a uniform temperature. Experience has shown that properly sorting fish by size and proper uniform thawing are very important processes for providing consistency in precooking to a uniform end point temperature, with a minimum of variation.

Historically, each company has established backbone temperature targets and precooking times by fish size *(4)*. All successful tuna factories have elaborate tables of precooking times based on the existing equipment, fish size, species, and initial temperature (IT) *(9)*. At the end of precooking, the operators measure the backbone temperatures to ascertain if the targets were met. If the temperature targets have not been met, the fish are returned to the precooker for further heating. This step, formerly called "measuring the backbone temperature," now is called "measuring the End Point Internal Product Temperature" (EPIPT). See Appendix 6 of the NFI Tuna HACCP Guide *(13)* for detailed EPIPT procedures.

Many atmospheric precookers are equipped with temperature probes to help control cooking and determine completion times. The disadvantages of using probes in a precooker are that, because of the very harsh environment, the probes often break or give inaccurate readings, even if multiple probes are used, and most of the probes are located quite close to the doors. Thus, an EPIPT control mechanism with physical measurements of backbone temperatures after cooking is needed to confirm that the fish has reached the proper EPIPTs at different locations throughout the precooker.

Modeling heat transfer during precooking

The rate of heat transfer during precooking, from the surface to the backbone or geometric center of the tuna, depends on the thickness, thermal conductivity, thermal diffusivity, and specific heat of either raw or frozen tuna flesh *(1)*. The following authors all measured the specific heat, thermal conductivity, and density to determine the thermal diffusivity of different species of tuna fish: Perez-Martin et al. *(17)* measured these variables in small albacore (*Thunnus alalunga*), Radhakrishnan *(18)* measured them in yellowfin (*Thunnus albacares*), and Zhang et al. *(25)* measured them in skipjack (*Katsuwonus pelamis*). These reference values for specific heat, density of the tuna, and thermal conductivity have been gathered in the Appendices. Appendix A lists the specific heat of different tuna species and different temperatures; Appendix B lists the density of tuna meats; Appendix C lists the thermal conductivity of different tuna species at different temperatures; Appendix D lists the latent heat of fusion for tuna, and Appendix E lists the latent heat of vaporization for water. It is apparent that there are substantial differences in thermal conductivity between species and at different temperatures. For example, in skipjack, the thermal conductivity is about three times higher in frozen flesh than in thawed flesh.

It is very difficult to model heat penetration in partially frozen fish; therefore, unless otherwise noted, whole eviscerated (butchered) tuna, completely thawed to a uniform temperature of 0°C (32°F), i.e., skin, meat, and backbone with an IT of 0°C (32°F), was used for modeling.

An important job of the fish preparation team is to determine the precooking times to achieve a certain

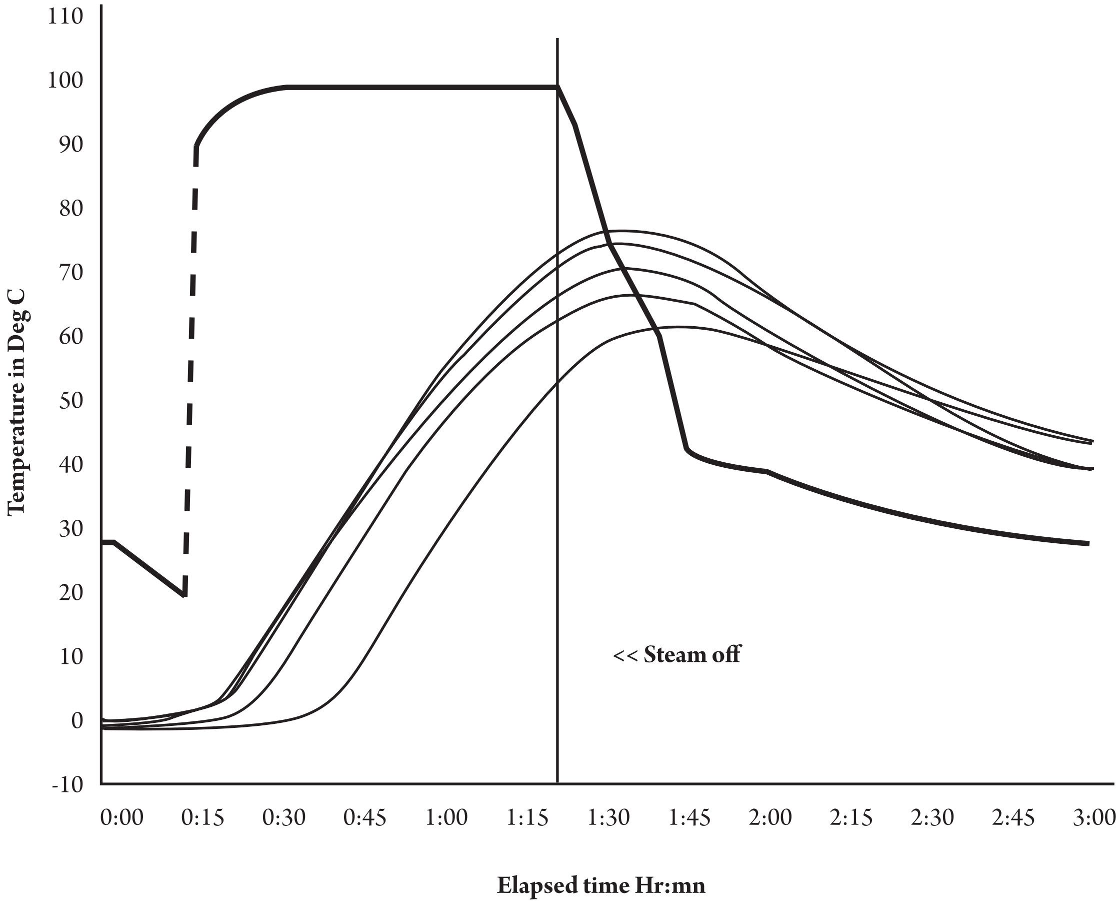

Figure 1. Temperature profile of a conventional atmospheric precooker (CAP). Broken line is ambient steam temperature and solid lines represent the backbone temperature of actual 1.8 to 2.7 kg tuna. Heavy vertical line indicates when steam is turned off

backbone temperature for each species and size range, based on the minimum measured IT. The precooking time depends on a number of factors, including:

1. Fish size (thickness) – minimum dimension of the cross section of the center portion of the fish.
2. Initial temperature of the fish (IT).
3. Ambient steam temperature.
4. Difference in temperature between the backbone and surface of the fish (ΔT).
5. Racking techniques (loading the fish into baskets) i.e., closeness packing.
6. Thermal diffusivity of the fish (i.e., thermal conductivity, specific heat, density).

Some of these factors are manageable during processing, but others are simply intrinsic to the individual fish. The first five items listed can be measured, managed, and/or changed over time; the sixth item is far more difficult to measure, model, or use in real time.

The backbone heating profile of tuna during precooking can be simulated by use of various modeling techniques, using some of the factors listed above. The simplest is called the finite difference analysis, using methods developed by Schmidt (1926; In German) and cited and demonstrated by McAdams *(11)* and Charm *(3)*. Essentially, the new temperature at a point or in a small area is calculated as an average of two adjacent points from the previous time period. After a certain time period passes, the heat moves from the hotter area to the colder area, and the temperatures are recalculated. This process is then repeated many, many times as the time period changes and the distance from the surface changes. The process can be recorded in a table and charted at various time intervals. As heat or cold is applied to the surface, the heat enters the fish and moves toward the colder center, exits the fish if the outside is cooler, or, if there is no difference in temperature (ΔT), remains static.

Zhang et al. *(26)* built a simulation model for precooking skipjack of a single size, using a finite element method, and Perez-Martin et al. *(16)* built a simulation model for precooking albacore by use of an explicit finite difference method. Both of these papers provided valuable ideas for this modeling project but did not vary the parameters, as done in the research reported in this paper.

Tuna fish delivered to the cannery are "ocean run" sizing; there is essentially no sorting by size on the catcher vessel or carrier vessel. At receiving, the fish are sampled for size groups for payment purposes *(4)*. Until the 1960s, many loads of fish were thawed aboard the catcher vessels and were sorted just prior to precooking. When the fish were mixed sizes at unloading, they would be sorted, just after butchering, into the different basket sizes and precooked separately, so as not to over-cook the smaller fish. This process involved multiple precookers being open at once to handle the different sizes, causing scheduling difficulties and delays in processing, and an actual loss in recovery because of the delays.

In modern tuna processing factories, the fish sorting for size is done at the receiving area of the factory cold storage after unloading from the fishing vessel or refrigerated carrier. The sorted fish are placed into fish bins so they can be thawed together and precooked in the same batch. The sorted fish of the same size group are generally stored together in the cold storage for operational efficiency.

The limitations on the range of weights (thickness) within a size group are a mix of historical precedence, sizing for payment, and sizing for processing. In the author's experience *(4, 9)*, sizing for processing purposes was so important that procedures are set up at many factories to weigh samples of the fish lots at the butcher station to provide the sorting station personnel with the feedback that they need to reduce sizing variation.

The purpose of the sizing data collection exercise for this paper was to determine the range of actual sizes within a sorted size group in one factory, so that thawing and precooking times could be estimated properly. It is important for the cannery management and the internal study to know the range of sizes in each size group. In fact, the weight of the fish serves as a proxy for the fish thickness, which impacts the precooking times.

To understand the influence of fish thickness on precooking based on fish weight, we conducted a study with these objectives:

1. To measure a representative sample of fish from various size or weight groups to determine the within-group and between-group variations of fish thickness.
2. To determine which of the controllable factors intrinsic to precooking have the most influence on reaching the desired backbone temperature within a predictable time period:
   a. Thickness variation: intrinsic and not controllable within a size or weight group; IT of the fish; controllable in general but uncontrollable if some of the fish are even partially frozen.
   b. Ambient steam temperature: variation controllable with engineering help.

MATERIALS & METHODS

Frozen albacore and skipjack were measured prior to thawing to determine the variation within size groups by weight and the extent of overlap between these groups. There were 13 fish in each group. The weight, length, girth, and thickness (the shortest distance to the center of the thickest portion of the fish) were measured in kg, cm, cm, and cm, respectively. The size groups ranged from about 1 kg to about 28 kg. Only the weight, length, and thickness parameters are included in the data reported in this paper. The girth measurements were not needed for the analysis and so were not included in the reported data. Length was included for completeness so readers can get an idea of the length and weight of the frozen fish measured. The data is reported in Table 1.

A finite difference model as described earlier was developed in Microsoft Excel-2010 and was used to model the heat penetration to the backbone and the temperature increase at the backbone over time. A simple one-dimensional model was developed, based on the thickness. The model used a fixed number of uniform-sized segments through the fish (surface to backbone), so as the fish got larger, the segments got wider and the time intervals between temperature measurements increased. Values of the thermal conductivity, density, and specific heat were estimated from the literature:

Cp — Specific Heat: Kjoule/°C = 3.3670 – Appendix A – estimated from yellowfin

p — Density: Kg/m^3 = 1080 – Appendix B – estimated from yellowfin

K — Thermal conductivity: W/(m*°C) = 0.5000 – Appendix C – estimated from yellowfin

In the model the only parameters that were changed are the:
(1) Size (thickness).
(2) ITs.
(3) Ambient steam temperature.

Thirty-two simulation models were run, 16 with a fixed IT of 0°C, while fish thicknesses and ambient steam temperatures were varied, and, with fixed ambient steam temperatures, while ITs and fish thicknesses were varied. The general procedure was to model:

1. venting the precooker for 10 minutes by starting at 50°C (122°F) and increasing the temperature linearly for 10 minutes to reach ~100°C (212°F),
2. fixing the IT at the start for whatever scenario we were modeling,
3. varying the ambient steam temperature as needed for the test,
4. stopping of steam at a time that would allow the backbone temperature to reach 60°C (140°F), and
5. stopping of heating by simulating rapid cooling with -40°C (-40°F) ambient temperature. The target cooling temperature of -40°C (-40°F) was used as a way to stop the heating cycle as rapidly as possible in the model. Using exaggerated temperatures is one way to trick the simulation model to cool the fish very fast, simulating evaporative cooling.

The parameters for *Table 2* (constant IT, varied fish sizes and ambient steam temperatures) were as follows:

1. All models were carried out with the IT at 0°C.
2. Four fish thicknesses, 8.5 cm (~2.1 kg), 10.5 cm (~3.2 kg), 11.8 cm (~3.8 kg), and 13.1 cm (~4.3 kg), were studied.
3. Steam venting was held to 10 min.
4. Four variations of ambient steam temperature after the 10 min vent period were used: 100°C (212°F), 98°C (208.4°F), 96°C (204.8°F), 94°C (201.2°F).
5. Steam was stopped at a time that would allow the backbone temperature to reach 60°C (140°F); then began a rapid cooling using -40°C (-40°F) ambient temperature.
6. Modeled cooking times to reach an EPIPT of 60°C (140°F) were recorded.

The parameters for *Table 3* maintaining a constant ambient steam and varying the IT and the fish thickness were as follows:

1. The IT was varied from 0°C to 20°C in 5°C increments (32°F to 68°F in 9°F increments) for each simulation for each fish size.
2. Fish sizes (thickness) were varied as before.
3. Steam venting was held to 10 min.
4. Ambient steam temperature was held at 100°C (212°F) after the 10 min vent period.
5. Steam was stopped at a time that would allow the backbone temperature to reach 60°C (140°F) and then a rapid cooling was started, using -40°C (-40°F) outside air temperature.
6. The modeled cooking times to reach to an EPIPT of 60°C (140°F) were recorded.

The results of the heating simulation model were analyzed with multiple-linear regression models, using an on-line software service *(24)*. The variables were as follows:

Y: Predicted precooking minutes to reach an EPIPT of 60°C based on the X variables,
X1: Fish size (Thickness),
X2: IT, and
X3: Ambient steam temperature.

Table 1. Average length, average weight, and average, minimum, maximum measurement at the thickest portion of skipjack and albacore tuna in various weight groupings

Fish Size Group	Average Length (cm)	Average Weight (kg)	Minimum Thickness (cm)	Average Thickness (cm)	Maximum Thickness (cm)
SKJ 01	41	1.2	6.5	6.7	7.0
SKJ 02	44	1.7	8.0	8.6	9.0
SKJ 61	48	2.1	7.5	8.5	9.5
SKJ 62	52	2.6	9.5	10.2	11.0
SKJ 63	53.5	3.2	10.0	10.6	11.5
SKJ 64	57	3.8	10.5	11.2	12.0
SKJ 65	60.5	4.3	11.5	13.2	14.0
SKJ 66	61	4.7	11.0	12.0	13.0
SKJ 67	61	5.4	11.5	12.6	13.5
SKJ C3	67	6.1	13.0	13.9	15.0
SKJ C4	70	7.6	14.5	15.2	16.0
SKJ C5	70.5	8.5	14.5	15.4	16.0
SKJ C6	73.5	9.5	13.5	15.0	17.0
ALB 70	77	11.0	17.0	17.9	20.0
ALB 71	83	13.5	16.5	17.5	18.5
ALB 72	93	16.2	16.5	18.6	20.0
ALB 73	97.5	18.4	19.0	20.7	22.0
ALB 74	100.5	21.0	20.0	21.4	23.0
ALB 75	99	23.1	21.0	21.8	23.5
ALB 76	109	25.5	21.0	22.7	23.5
ALB 77	107.5	28.3	22.0	22.7	23.5

Table 2. Simulated precooking times (h:mn) to reach EPIPT of 60°C by size and ambient steam temperature, holding initial backbone temperature constant

degrees C	IT°C	1.1 kg	1.7 kg	2.4 kg	3.2 kg
100	0	0:40	0:53	1:08	1:22
98	0	0:41	0:55	1:08	1:22
96	0	0:41	0:55	1:11	1:24
94	0	0:42	0:56	1:11	1:26

Table 3. Simulated precooking times (h:min) to reach EPIPT of 60°C by size and initial backbone temperatures, holding ambient steam temperature constant

degrees C	IT°C	1.1 kg	1.7 kg	2.4 kg	3.2 kg
100	0	0:40	0:53	1:08	1:22
100	5	0:40	0:53	1:05	1:18
100	10	0:39	0:53	1:04	1:17
100	15	0:37	0:49	1:03	1:14
100	20	0:35	0:48	0:59	1:11

RESULTS

For the small fish (below 4 kg), the thickness variation within a size group was a maximum of 2 cm, and for the larger (> 4 kg) fish, a maximum of 3.5 cm. This approach was for fish sorted by weight. The data are reported in *Table 1* and plotted as thickness versus individual weights in *Fig. 2*, and thickness versus weight groups in *Fig. 3*. It is very apparent that there is thickness variation within a single size group, but there is also considerable overlap of thicknesses between size groups. For example, the greatest thickness in a group is larger than the smallest thickness in the next higher group by weight. In other words, fish that weigh the same may have different size dimensions.

The results of simulation of precooking times of different sizes, ITs, and ambient steam temperatures are shown in *Tables 2 and 3*. The results of the final multiple regression analysis are presented in *Table 4*. A stepwise multiple regression analysis was used to evaluate whether fish size, ITs, and ambient steam temperatures, or a combination of these, were necessary to predict precooking times. At step 1 of the analysis, fish size was entered into the regression equation and was found to be significantly related to precooking time F (1, 34) = 462, *P* < .000. The adjusted R-squared was 93%, indicating that approximately 93% of the variance of the predicted precooking time could be accounted for by fish size. At step 2, the fish IT was entered into the regression equation and was found to be significantly related to precooking time F (2, 33) = 361, *P* < .000. The adjusted R-squared was > 95%, indicating that approximately 95% of the variance of the predicted precooking time could be accounted for by fish size and IT. At step 3, when the ambient steam temperature was entered into the regression model, the adjusted R-squared remained at 95%, indicating that no change in variance of the predicted precooking time could be accounted for by the ambient steam temperature in the ranges tested.

DISCUSSION

The results of the measurements of fish dimensions indicate a range of thicknesses within a weight size group and an overlap of thickness from one size group to the next. The operators know this approach and have to adjust when scheduling precooking times and checking the EPIPTs. The operators need to select the thickest pieces from each lot to collect the ITs and the EPIPTs.

This simple single-dimensional finite difference model can easily assess the relative impacts on precooking times of the three items just mentioned: size, ITs, and ambient steam temperatures. The model can measure broad trends but cannot be used for exact prediction of precooking times, simply because of the variations of fish sizes within groups and the thermal conductivity and density changes with temperature and species. The results of the simulation model indicate that size (thickness) has by far the largest impact on precooking time; the IT has the next highest impact; and the ambient steam temperature, over a given small temperature range, has the least impact. In a vacuum precooker with poorly performing valves, leaking gaskets, or leaking vacuum

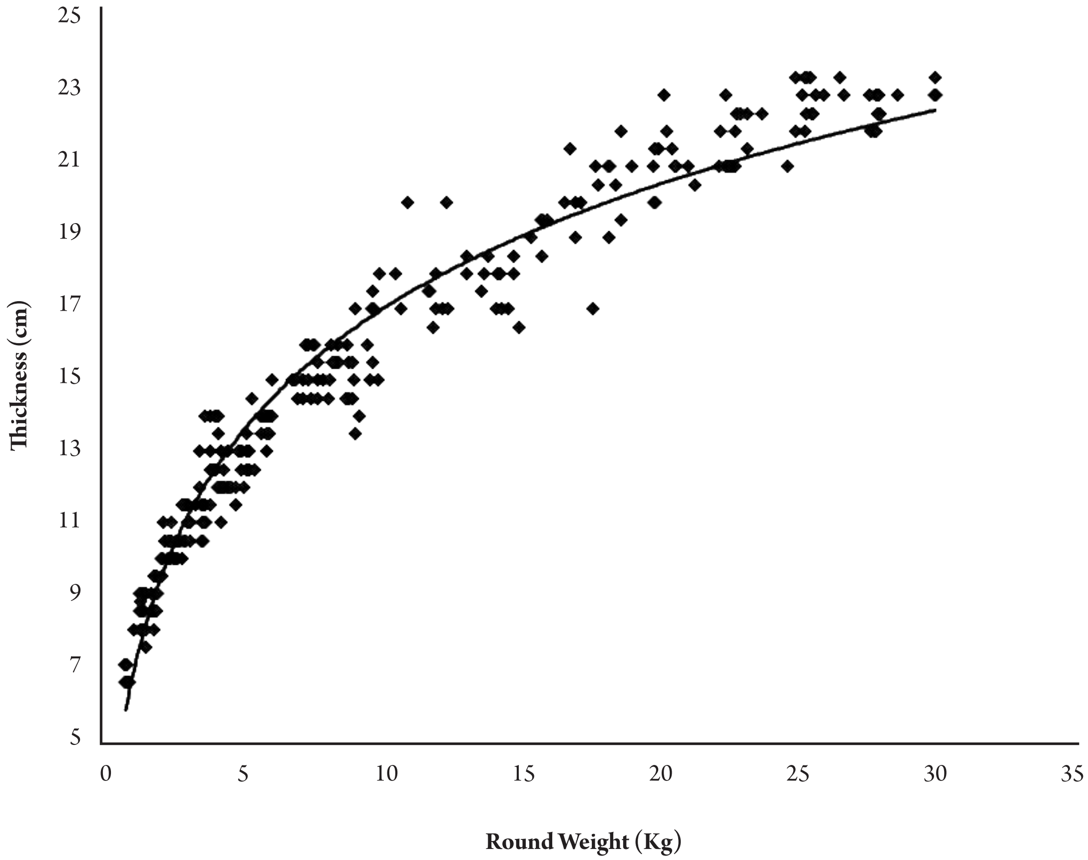

Figure 2. Thickness (cm) versus weight (kg) of skipjack and albacore, as a logarithmic trend line

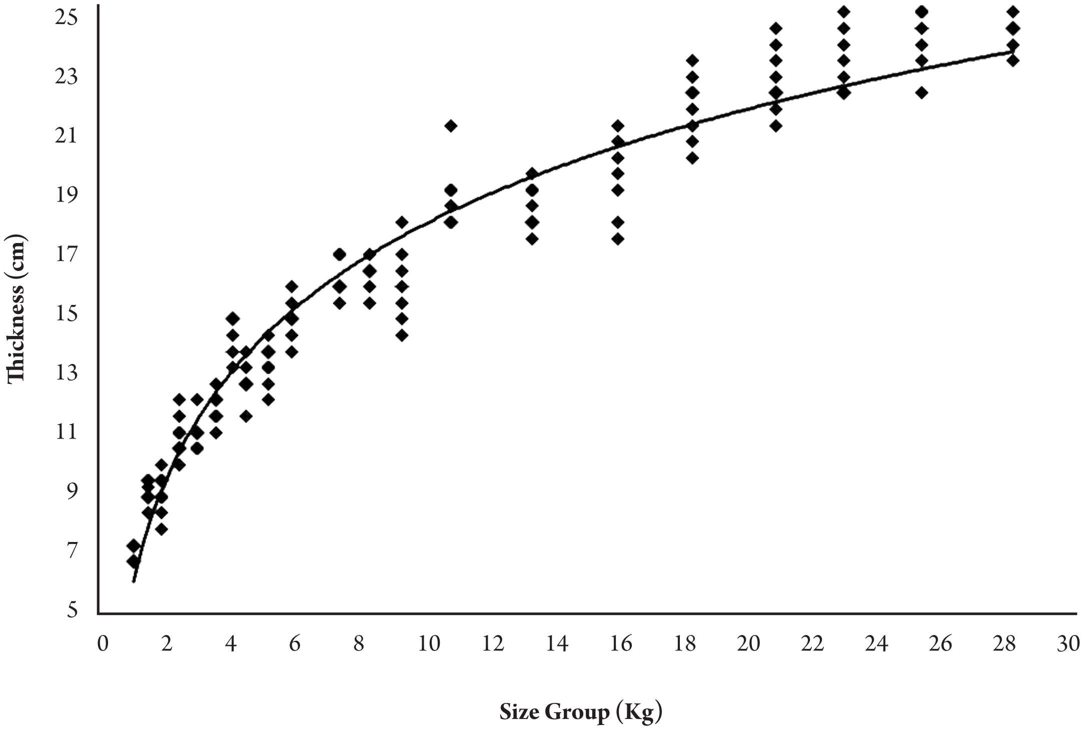

Figure 3. Thickness (cm) versus size group (kg) of skipjack and albacore, as a logarithmic trend line

Table 4. Multi-regression analysis of precooking simulation study

Variable	Coefficient	Standard Error Coefficient	T-value	*P*-value
Constant	24.26	1.49	16.25	0.000
Fish Size (kg)	17.06	.643	26.52	0.000
IT (°C)	-0.3009	.0696	-4.32	0.000

R-Sq	R-Sq(adj)	F	Deg Freedom
95.63%	95.36%	361	2, 33

Regression Equation
Minutes = 24.26 + 17.06 *Kg – 0.3009 * IT

pumps, steam air mixtures, and thus heat transfer, will vary. This phenomenon is equivalent to the transient cold spots of a couple of degrees one might see in an atmospheric precooker. Hence, it is far more important to size the fish properly and uniformly and to adjust for the coldest IT than it is to worry about a precooker that varies a couple of degrees from its set point in the temperature ranges tested.

This is not to say that having a uniform precooking ambient temperature is not important for uniformity in precooking results, because it is. When the precooker operator is sampling the backbone temperature (EPIPT) after the precooking heating cycle has been completed, he/she will want to be certain to test fish from all areas of the precooker, especially if persistent cold spots are known to exist.

Predicting a precooking time cannot be an exact science for an entire batch of fish in a precooker because of the amount of variation in fish sizes (within a weight size group) and differences in species, thermal conductivity, and fish density. Therefore, empirical testing must always be done. The steam portion of the precooking cycle can be stopped when the time target has been achieved, after which the backbone temperature can be measured. If the backbone temperature is not at target but is quite close, the operator can wait for a few minutes and measure again, because the backbone temperature will continue to rise and reach the desired EPIPT.

CONCLUSIONS & RECOMMENDATIONS

The results of the multiple regression analysis indicate that fish size is by far the most important predictor of precooking time. The effect of fish size was far more significant than that of the ITs, and the ambient steam temperature at the temperatures tested was not significant at all.

The universal characteristics of a standard precook profile (atmospheric precooker) are as follows:

1. The ambient steam temperature remains at 100°C (212°F) throughout the cycle.
2. An initial lag of the increase in the backbone temperature occurs at the start of precooking as heat is transferred from the surface to the center of the mass.
3. A fairly uniform heating rate is seen after the initial lag time as the fish is cooking depending on the thickness and ΔT.
4. A continuing "overshoot" occurs at the backbone or geometric center of the fish for some time after the steam is turned off.
5. If some of the fish are frozen at the core, the initial lag time will be longer.
    a. Fish that are frozen at the core require much more heat to thaw, so the "cooking time" of the rest of the tuna mass increases substantially. An increase in accumulated cooking time will lower the recovery, as the outer layers of the fish are cooked to higher temperatures for longer periods than necessary, losing extra moisture and oils.
    b. If some of the fish are still partially frozen and some are thawed completely, precooking times will vary significantly and the process cannot be reliably predicted or modeled.

The steps for a generic precooking and EPIPT control for an atmospheric precooker precooking cycle plan would be as follows:

1. Thaw fish properly to a uniform backbone temperature between -1°C and 4°C (~30°F and ~39°F).
2. Transfer the fish from the thaw box onto the butcher belt.
3. Eviscerate and inspect fish.
4. Rack or pan the fish of the same weight group and size in each pan or fish basket; do not mix different size groups in the same trolley.

5. Note the target or target sizes.
6. Collect and record multiple backbone temperatures for IT-based decisions.
7. Plan the precook cycle time recipe for the precooker load based on the largest size or coldest fish.
8. Load trolleys into precooker.
9. Plan to have steam off when the temperature of the coldest or largest fish exceeds 55°C (131°F).
10. Open the discharge door when it is safe to do so.
11. Remove the first trolley and test a minimum of 8 of the largest fish with the lowest IT, using a fast-acting thermometer.
12. If the EPIPT of any fish is below 55°C (131°F), push the trolley back into the precooker and precook for enough time for the fish to reach the required temperature.
13. If all the fish are above 55°C (131°F), note the time and EPIPT (backbone) temperature and check it again in 5 min. If the temperature is below 58°C (136.4°F), recook the fish; if the fish is above 58°C (136.4°F), wait another 5 min and recheck, to make certain the minimum measured EPIPT has reached the target of 60°C (140°F).
14. Collect EPIPT records from a minimum of 24 fish per precooker cycle.
15. Repeat steps 13 & 14.

The cooking operations area in a tuna factory is, by its very nature, a sweaty, steamy, and hot place to work, especially at the discharge side of the precooker. When the steam is turned off and the doors are opened, the heat and steam escape to the cooler area. The precookers have heavy doors, heavy trolleys, hot metal, and plenty of hot fat and protein to avoid. Personnel safety is paramount because of slick floors, a hot chamber, hot trolleys and hot fish; thus, the measurement of the backbone temperatures is sometimes delayed.

Optimal precooking practices depend on the following:

1. Sizing the fish to a uniform size within a processing lot – thickness and packing density do matter.
2. Thawing the fish properly and uniformly.
3. Ensuring that fish is not frozen at the core, as it will not precook in a predictable fashion because:
    a. In a production environment, it is impossible to know the amount of ice at the center of the fish mass and therefore the amount of heat necessary to satisfy the latent heat of fusion.
    b. The conductivity of the fish flesh changes as the frozen or thawed state of the fish flesh changes.
4. Recognizing that if some fish are frozen and some are completely thawed and they are precooked in the same cycle, the fish that starts frozen will have to be cooked far longer than the fish that starts thawed; thus, the fish that starts thawed will be overcooked, with a subsequent loss of recovery. The outer surface of the fish that starts frozen will be overcooked as well, costing recovery.
5. Thawing the fish properly in the thaw bays rather than in a precooker, as thawing in the bays is far more efficient and effective.

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Appendix A
Examples of Specific Heat

Heat required to raise a specified mass by one unit of a specified temperature, expressed as BTU/lb/°F or Cal/g/°C; compared to water as reference

Substance	BTU/lb/°F or Cal/g/°C	kiloJoule/kg/°C	Source
Water @ 15°C (59°F)	1.0	4.1868	*(12)*
Ice @ -3°C (26.6°F)	0.5	2.0934	ibid
Frozen raw tuna	0.41	1.7165	*(2)*
Yellowfin @ 10°C (50°F)	0.797	3.337	*(18)*
Yellowfin @ 20°C (68°F)	0.804	3.367	ibid
Yellowfin @ 30°C (86°F)	0.802	3.357	ibid
Albacore @ 25°C (77°F)	0.738	3.09	*(17)*
Albacore @ 51°C (123.8°F)	0.762	3.19	ibid
Albacore @ 83°C (181.4°F)	0.795	3.33	ibid
Albacore @ 108°C (226.4°F)	0.81	3.39	ibid
Skipjack @ 25°C (77°F)	0.807	3.377	*(25)*
Skipjack @ 50°C (122°F)	0.856	3.584	ibid
Skipjack @ 85°C (185°F)	0.866	3.626	ibid
Skipjack @ 105°C (221°F)	0.884	3.699	ibid
Unfrozen raw tuna	0.79	3.3075	*(2)*

Appendix B
Density of Tuna Fish

The weight in gm/cm^3 compared to sea water as the reference.

Substance	Size (kg)	Oz per cubic in	Gm per cubic cm	Source
Seawater		0.5925	1.025	*(23)*
Thunnus alalunga (Albacore)		0.6242	1.080	*(17)*
Katsuwonus pelamis (Skipjack)		0.6057	1.048	*(25)*
Katsuwonus pelamis (Skipjack)	0–2	0.6260	1.083	*(10)*
Katsuwonus pelamis (Skipjack)	0–2	0.6335	1.096	ibid
Katsuwonus pelamis (Skipjack)	2–4	0.6277	1.086	ibid
Katsuwonus pelamis (Skipjack)	2–4	0.6323	1.094	ibid
Katsuwonus pelamis (Skipjack)	4–6	0.6318	1.093	ibid
Katsuwonus pelamis (Skipjack)	4–6	0.6329	1.095	ibid
Katsuwonus pelamis (Skipjack)	6–8	0.6341	1.097	ibid
Katsuwonus pelamis (Skipjack)	6–8	0.6341	1.097	ibid
Katsuwonus pelamis (Skipjack)	8–10	0.6318	1.093	ibid
Katsuwonus pelamis (Skipjack)	8–10	0.6335	1.096	ibid
Katsuwonus pelamis (Skipjack)	> 10	0.6289	1.088	ibid
Katsuwonus pelamis (Skipjack)	> 10	0.6352	1.099	ibid
Thunnus obesus (Bigeye)	2–4	0.5930	1.026	ibid
Thunnus obesus (Bigeye)	2–4	0.6150	1.064	ibid
Thunnus albacares (Yellowfin)	1–2	0.6253	1.082	ibid
Thunnus albacares (Yellowfin)	1–2	0.6289	1.088	ibid
Thunnus albacares (Yellowfin)	2–4	0.6248	1.081	ibid
Thunnus albacares (Yellowfin)	2–4	0.6300	1.090	ibid
Thunnus albacares (Yellowfin)	4–6	0.6121	1.059	ibid
Thunnus albacares (Yellowfin)	4–6	0.6242	1.080	ibid
Thunnus albacares (Yellowfin)	6–8	0.6081	1.052	ibid
Thunnus albacares (Yellowfin)	6–8	0.6156	1.065	ibid
Thunnus albacares (Yellowfin)	8–10	0.6081	1.052	ibid
Thunnus albacares (Yellowfin)	8–10	0.6156	1.065	ibid
Thunnus albacares (Yellowfin)		0.6346	1.098	*(19)*

Appendix C
Thermal Conductivity

The property of a material that describes the rate at which heat will be conducted through a unit area of material for a given driving force measured as BTU/ (hr*ft*°F) or kcal/ (hr*m*°C) or Watts/ (m*°K). It is dependent on the material and upon its temperature.

Substance	BTU/ (hr*ft*°F)	kcal/ (hr*m*°C)	W/ (m*°K)	Source
Water @ 27°C (80.6°F)	0.35	0.5159	0.6	*(8)*
Yellowfin @ 5°C (41°F)	0.2582	0.3842	0.44680	*(18)*
Yellowfin @ 10°C (50°F)	0.2797	0.4612	0.48405	ibid
Yellowfin @ 15°C (59°F)	0.2842	0.4229	0.49187	ibid
Yellowfin @ 20°C (68°F)	0.2784	0.4143	0.48186	ibid
Yellowfin @ 25°C (77°F)	0.2665	0.3966	0.46121	ibid
Yellowfin @ 30°C (86°F)	0.2585	0.3847	0.44742	ibid
Albacore @ 15–20°C (59°F – 68°F)	0.2849	0.4239	0.493	*(17)*
Albacore @ 15–20°C (59°F – 68°F)	0.3276	0.4875	0.567	ibid
Skipjack @ -20°C (-4°F)	1.0689	1.5907	1.85	ibid
Skipjack @ -15°C (5°F)	1.0400	1.5477	1.80	ibid
Skipjack @ -10°C (14°F)	1.0169	1.5133	1.76	ibid
Skipjack @ -5°C (23°F)	0.9880	1.4703	1.71	ibid
Skipjack @ 0°C (32°F)	0.3062	0.4557	0.53	ibid
Skipjack @ 24°C (75.2°F)	0.3293	0.4901	0.57	ibid
Skipjack @ 53°C (127.4°F)	0.3293	0.4901	0.57	ibid
Skipjack @ 75°C (167°F)	0.3409	0.5073	0.59	ibid
Skipjack @ 85°C (185°F)	0.3582	0.5331	0.62	ibid
Skipjack @ 92°C (197.6 °F)	0.3813	0.5675	0.66	ibid

Appendix D
Latent Heat of Fusion

Substance	BTU/lb	Cal/gm	kiloJoule/kg	Source
Water @ 0°C (32°F)	144	79.71	333.7	*(22)*
Frozen Raw Tuna	101	56.1	234.9	*(2)*
Precooked Tuna	80.72	44.85	187.8	*(25)*

Appendix E
Latent Heat of Vaporization

Substance	BTU/lb	Cal/gm	kiloJoule/kg	Source
Water @ 100°C (212°F)	972	539.55	2259	*(22)*