PEER-REVIEWED ARTICLE

Food Protection Trends, Vol 35, No. 3, p.150–160

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

Paola Willmore,[1] Mark Etzel,[1] Elizabeth Andress[2] and Barbara Ingham[1*]

[1]Dept. of Food Science, University of Wisconsin-Madison,
1605 Linden Drive, Madison, WI 53706, USA

[2]Dept. of Foods and Nutrition, National Center for Home
Food Processing and Preservation, University of Georgia,
208 Hoke Smith Annex, Athens, GA 30602, USA

Home Processing of Acid Foods in Atmospheric Steam and Boiling Water Canners

ABSTRACT

Home canning is increasingly popular. We determined the efficacy of a boiling water canner (BWC) versus an atmospheric steam canner (ASC) in home canning of various acid foods. Research-tested recipes were followed, and temperature was tracked every 1 min with thermocouples placed at the experimentally determined cold spot for each product and in the heating medium. Time-temperature curves were plotted for at least three runs for each product in each canner, with 12 thermocouple tracings per product, through heating and air-cooling until internal temperature reached 130°F (54°C). Heat penetration rates during heating (f_h) and cooling (f_{cl}) were calculated. Total integrated lethality, $F_{180°F\ (82.2°C)}$, and lethality during heating (F_h) and cooling (F_{cl}) were calculated. Across all food products, f_h < fcl. F_{cl} was the majority contributor to $F_{180°F}$, ranging from 48% to 95%, for chocolate raspberry sauce and applesauce, respectively. Canner type did not significantly impact lethality ($P > 0.05$) in the canning of applesauce, tomato juice, and cranberries. $F_{180°F}$ for chocolate raspberry sauce was greater in a BWC than in an ASC ($P < 0.05$), but this was the result of differences in the initial food temperature, not in the canner type. Regardless of canner type or food product, calculated lethality, $F_{180°F}$, was far in excess of the required 5 log reduction for spores in tomato juice and for vegetative cells in other products. Our research suggests that there is a wide margin of safety for approved home canning processes for high-acid foods processed in either a BWC or an ASC. An ASC can be safely used for home canning foods that have a pH < 4.6, with the following stipulations: a current recipe research tested for a BWC must be followed with processing time in the ASC beginning as soon as the measured temperature inside the dome reaches the boiling point of pure steam (~212°F), and jars must be allowed to air-cool unimpeded on the countertop to ensure lethality.

INTRODUCTION

A revival of interest in home canning is evident *(5, 11)*. However, studies by the National Center for Home Food Preservation *(1)* suggest that consumers engaged in home

Corresponding Author: Phone: +1 608.263.7383; Fax: +1 608.262.6872; Email: bhingham@wisc.edu

canning may not be following up-to-date, tested recipes, potentially putting the health of these consumers and their families at risk. A survey of consumers processing foods at home indicated that 58% of 103 respondents who canned acid foods such as fruits and tomatoes used a boiling water canner, 15.5% a pressure canner, and 18% a pressure cooker. A rather high percentage (21%) used the "open-kettle" method (no processing after filling), and almost 4% reported using the oven-canning method *(1)*. The United States Department of Agriculture recommends the boiling water canner (BWC) for home processing of high-acid foods *(20)*. The time involved in heating a boiling water canner first to the pre-heat temperature and then, once jars are added, to the processing temperature, can be lengthy. This may discourage consumers from following proper canning methods. Consumers who fail to follow a research tested, up-to-date recipe completely when home canning may put the health of their families at risk.

An atmospheric steam canner (ASC) has been suggested as a time- and energy-efficient alternative to a boiling water canner, enabling consumers to adopt safe food preservation practices *(15, 16)*. Research done in the 1980s found that the process lethality achieved in the ASC when canning tomato juice, tomatoes, or applesauce was less than the process lethality achieved in a BWC, and suggested that more research was needed to determine how to modify BWC recipes so that they could be safely used with the ASC *(15)*. In 2005, researchers in California concluded that both the ASC and BWC could be used to safely can high-acid foods *(16)*. However, these researchers failed to follow recommended home-canning procedures, thus leaving unanswered the question as to the efficacy of the ASC for home preservation of high acid foods.

The goal of this research was to compare the safety of home canning of acid foods using an ASC and a BWC. Factors considered in evaluating safety included canner operation, heat penetration rates within foods, and integrated lethality ($F_{180°F\ (82°C)}$). A variety of acid foods — tomato juice, applesauce, cranberries in heavy syrup, and chocolate raspberry sauce — were canned in order to evaluate a range of processing variables.

MATERIALS AND METHODS

Equipment

An atmospheric steam canner (ASC) (Back to Basics Model 400A; Focus Electrics LLC, West Bend, WI) and a boiling water canner (BWC) (Victorio VKP1055; Victorio Kitchen Products, Orem, Utah) were used in this study. Each canner was equipped with a rack. Canners were designed to hold a maximum of 7 one-quart (QT, 946 ml), 8 one-pint (PT, 473 ml), and 8 half-pint (HP, 237 ml) home-canning jars. The ASC was filled with 2 liters of water at the start of each experimental trial, enough water to fill the bottom of the canner without submerging the metal rack; the BWC was filled with a maximum of 10 liters of water depending on jar size in use. In each case, the level of water in the BWC was at least 1 inch (2.54 cm) above the top of the jars after they were placed in the canner.

In preliminary experiments to evaluate the heating pattern in each canner type, the lid of each canner was fitted with stuffing boxes (C-24; Ecklund-Harrison Technologies Inc., Ft. Myers, FL) to allow the attachment of thermocouples (TC), which measured the temperature of the heating medium (steam in ASC and boiling water in BWC) *(Fig. 1)*. In the BWC, Type-T thermocouples (Ecklund-Harrison) were affixed at a depth of 7.6, 15.2, and 22.9 cm within the water column *(Fig. 1A)*. In the ASC *(Fig. 1B)*, a TC was affixed directly adjacent to each of the two vent ports (14.5 cm), a third TC was placed in the headspace of the canner, extending 1.27 cm into the dome, and a fourth TC was

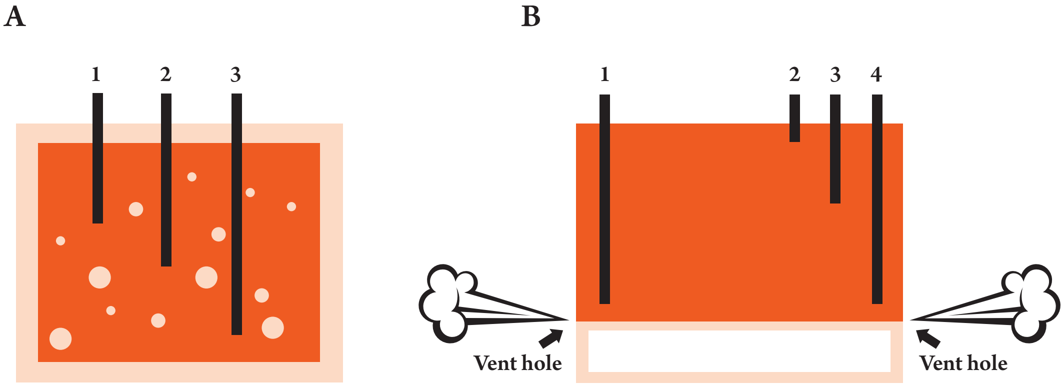

Figure 1. Thermocouple position within the BWC (A) and the ASC (B) during preliminary experiments to determine heating patterns within each canner

placed in the center of the canner at a depth of 7.0 cm such that, when the canner was operated full, jars were clustered around the probe in all directions (the presumed cold spot in the canner). All TCs were attached to an industrial datalogger (TechniCAL; New Orleans, LA) equipped with Cal Soft 32 software (TechniCal), which facilitated recording of temperature (°F) at 1-min intervals, per industry standards *(7)*. Both the BWC and the ASC were operated with the lid closed as instructed.

In lethality experiments with food products inside jars, one TC measured the temperature of the heating medium, projecting 1.27 cm into the dome of the ASC or 7.6 cm into the water column of the BWC, and three jars were equipped with a TC that measured the temperature at the theoretical cold spot of the food product, using CNS needle type-T thermocouples (Ecklund) attached to the datalogger (TechniCAL). Experimental conditions are described later. For experimental consistency, canners were cooled to room temperature (75 ± 5°F, 24°C) between each run. In all experiments, glass jars designed for home canning were used (Ball Canning Corporation, Muncie, IN). Standard home canning two-piece metal lids were used to seal jars in all experiments (Ball). Temperature measurements were made in replicate trials and jars, to have a total of 12 replicate measurements over at least three trials for each food product in each canner type.

Heating pattern in each canner

Before any lethality experiments were conducted, the heating pattern in each canner was evaluated. Hot jars (180°F, 82°C) were filled with commercially prepared tomato juice that was at room temperature (75°F, 24°C) or that had been heated to 180°F (82°C), and sealed with two-piece lids. Thermocouples measured the temperature of the heating medium in three (BWC) or four (ASC) locations (*Fig. 1*). Immediately after being filled, jars were placed in a BWC containing water pre-heated to 180°F ± 5°F (82°C), and the time that it took for the canner water to heat from 180°F (82°C) to a full rolling boil (210° ± 1°F; 99°C) was recorded. The process was repeated in the ASC, except that hot jars filled with tomato juice (75°F, 24°C; or 180°F, 82°C) were placed on the rack in the canner above room temperature water (75°F, 24°C), and the time that it took for the steam in the canner dome to heat to a consistent 210° ± 1°F (99°C) was recorded. Both canners were operated full (7 QT, 8 PT, 8 HP jars), half-full (3 QT, 4 PT, 4 HP jars), or containing only one jar (n = 3 trials per combination). Temperature from each TC was recorded in °F every 1 min until the temperature of the heating medium held at a consistent 210 ± 1°F (99°C).

Determination of theoretical 'cold spot' for each food product

Before lethality experiments were performed, the 'cold spot' (slowest heating spot) for each type of product was determined, using a BWC. Food products (tomato juice, cranberries in heavy syrup, applesauce) were prepared according to recommended methods (see below) and transferred to hot PT jars. Each jar in the canner (8 total, full capacity) was fitted with a TC set at either the geometric center of the jar (7.5 cm from the bottom) or in increments (~0.5 cm) to a height of 1.5 cm from the bottom of the jar *(6)*. Jars were processed in a BWC for the recommended processing time and cooled, with temperature being recorded at 1 min intervals. Three trials were conducted for each product. The rate of heat penetration during heating (f_h) and cooling (f_{cl}), and the lethality during heating (F_h), during cooling (F_{cl}), and overall ($F_{180°F\ (82°C)}$) were calculated for each product at each TC location.

Food processing

Each food product was processed following a current and approved home canning recipe *(9, 20)*. All foods were high in acid, with average pH values of 3.60, 3.72, 4.09, and 3.13 for applesauce, tomato juice, cranberries in syrup, and chocolate raspberry sauce, respectively. Filled jars were placed in a BWC preheated to 180°F ± 5°F (82°C), or in an ASC with room temperature water (75°F, 24°C) in the base. Processing time started when the TC in the dome of the ASC or within the water column of the BWC registered, 210 ± 1°F (99°C) and stayed at that level for at least 1 min. The elevation of the laboratory, in Madison, WI, is 935 ft (285 m) above sea level, and thus no adjustment in processing time is needed in order to use a tested recipe. At the end of the processing time, jars were removed from the canner and placed on a lab bench to cool until the average internal temperature of each jar reached 130°F (54°C). Each canner was operated at full capacity, 8 PT or HP jars, as appropriate for the recipe.

pH (Accumet AB15 Basic, Fisher Scientific, Waltham, MA) and water activity (3TE Aqualab, Decagon Devices, Inc., Pullman, WA) were measured for each food product. The amount of vacuum (psi) developed by canning was recorded on cooled jars from each trial not affixed with a TC, by use of a hand-operated vacuum tester (Nelson Jameson Inc., Marshfield, WI).

Tomato juice

Tomato juice was prepared according to a tested recipe *(20)* from raw fresh tomatoes that were washed, peeled, quartered, crushed, heated and passed through a Foley food mill (Mirro; Manitowoc, WI) Fresh juice was used within 24 h of preparation. Freshly prepared tomato juice was heated to 180°F ± 2°F (82°C) and packed into hot (180°F; 82°C) PT jars with added citric acid (Ball). Headspace was adjusted to ½ inch (1.27 cm) and the weight of each jar was recorded. Target fill weight for jars was 452 g. Jars were processed for 35 min in either canner type.

Cranberries in heavy syrup

Cranberries in heavy syrup were prepared according to a tested recipe *(20)*. Raw fresh cranberries were packed into hot (180°F; 82°C) PT jars with a target fill weight of 220 grams. Heavy syrup (40% w/v sucrose), heated to 180°F (82°C), was poured over cranberries in jars to a target total fill weight of 450 g. Headspace was adjusted to ½ inch (1.27 cm) before lids were applied. Jars were processed for 15 min in either canner type.

Applesauce

Prepared applesauce (Motts LLP, Plano, TX) was supplied by the manufacturer. Commercial applesauce is prepared from a blend of apples chosen to produce a product with standard pH, texture, color and flavor. Apples (whole) are heated and sieved to a standardized consistency prior to being packed hot (200°F; 93°C) into containers; there is no applied heat treatment after hot filling *(13)*. In order to process a product with uniform consistency and composition, a pre-prepared commercial product was obtained from the manufacturer and the process was completed according to a recommended home-canning method *(20)*. Applesauce was heated to 180°F ± 2°F (82°C) and packed into clean, hot (180°F; 82°C) PT jars, leaving ½ inch (1.27 cm) headspace, with a target fill weight of 460 g. Jars were processed for 15 min in either canner type.

Chocolate raspberry sauce

Chocolate raspberry sauce was made from raspberries, cocoa powder, pectin, lemon juice, and granulated sugar according to a standard recipe *(9)*. Hot product (200°F, 93°C) was filled into hot HP jars leaving ¼ inch (0.64 cm) headspace. Target fill weight was 270 g. Jars were processed for 10 min in either canner type.

Data handling

Time/temperature data were collected for all experiments at 1-min intervals. The Ball equation (Equation 1) *(17)* was used to calculate the rate of heating and cooling, f_h, and f_{cl}, for the heating and cooling portions of the curve, respectively.

Equation 1. $\log(u) = -t/f + \log(j)$

where $u = (T-T_a) / (T_0-T_a)$ and T = temperature at the cold spot (°F); T_a = heating medium temperature (°F); T_0 = temperature at the start of the heating or cooling process; f = time for a one log reduction in u (-1/slope of the linear portion of the semi-logarithmic plot); and j = lag factor for heat penetration to the point of temperature measurement.

Integrated process lethality was calculated for the heating (F_h) and cooling (F_{cl}) portions of the curve and overall ($F_{180°F}$) by finding the area under the time/temperature curve according to Equation 2 *(18)*, assuming *Escherichia coli* O157:H7 as the target pathogen.

Equation 2. $F = \int_0^t 10^{(T-T_R)/z}\, dt.$

where T = product temperature, °F; T_R = reference temperature, °F, or 180°F; t = time, min; z = temperature increase required to effect a ten-fold decrease in D_T, 10°F for *E. coli* O157:H7 *(10)*; and D_T = decimal reduction time, min.

Variables f_h, f_{cl}, F_h, F_{cl}, $F_{180°F}$, and canner type were compared using Analysis of Variance (ANOVA; SAS version 9.2, SAS Institute Inc., Cary, N. Car.) with significance level set to $P = 0.05$. The proc glm function was used to determine difference in lethality and in heat penetration rate across canner type, with temperature (°F) measured as the dependent variable and canner type, trial, and thermocouple as independent variables.

RESULTS AND DISCUSSION

The time required for traditional home canning of high-acid foods in a boiling water canner can be divided into four stages: (1) time to bring the heating medium (water) up to a pre-heat temperature, if any; (2) time required to bring the heating medium up to the boiling point once jars are added to the canner (come-up time); (3) process time (from a research-tested recipe); and (4) time for jars to air-cool prior to assessment of seal integrity. To avoid jar breakage due to thermal shock, approved canning guidelines recommend that the water in a BWC be preheated to either 140°F (60°C) or 180°F (82°C), for raw-packed and hot-packed foods, respectively, prior to placement of filled jars into the canner *(20)*. The ASC does not require preheating.

To establish operating parameters for the BWC and the ASC, we conducted preliminary experiments with commercially canned tomato juice. Tomato juice was either heated to 180°F (82°C) as recommended, or packed into jars at 75°F (24°C), representing a 'worst case' scenario. Hot QT, PT or HP jars were filled with juice and placed into preheated 180°F water (BWC) or on a rack over 75°F water (ASC). Each canner was operated full (7 QT, 8 PT, 8 HP jars), half-full (3 QT, 4 PT, 4 HP jars), or with only one jar (n = 3 trials per combination). The temperature in °F of the heating medium was monitored at 1 min intervals with strategically placed TCs *(Fig. 1)*, until the temperature of the heating medium held at a consistent 210 ± 1°F (99°C) for about 5 min. For the BWC, it took, on average, 22 min (n = 54 trials, range 18 to 36 min) for the water, ranging from 8 liters when processing HP jars to 10 liters when processing QT jars, to be preheated from 75°F to 180°F (data not shown). No pre-heat time was required for the ASC. Temperature differential across the TCs placed in the BWC varied by < 2°F during the come-up time (n = 54) (data not shown). Temperature differential across the TCs placed in the ASC varied by less than 2°F by the end of the come-up time (n = 54) (data not shown). In each canner, maximum recorded temperature was 210 ± 1°F. The longest come-up time was observed when each canner was operated at full capacity (7 QT, 8PT, and 8HP jars), regardless of jar size, although the difference was not significant ($P > 0.05$) *(Table 1)*. As a result of these preliminary experiments, all subsequent trials with food products were conducted with canners operating at full capacity.

Statistical analysis indicated that initial product temperature significantly affected come-up time for all jar sizes when the canners were operated at full capacity ($P < 0.05$) *(Table 1)*. However, this difference was due almost exclusively to the difference in come-up time in the ASC with QT jars. While significant overall, initial product temperature did not affect come-up time in all jar sizes when each canner was operated half full or with only one jar. Research-tested recipes instruct consumers to pack jars with 'hot' product or to pour 'hot' liquid into jars *(20)*, i.e., no temperature is specified. While this portion of our study was limited to one food product and focused on canner operation and not lethality, results nevertheless suggest that target fill temperature may not dramatically impact the ability of the heating medium to reach the process temperature when jars are placed in an ASC or a properly preheated BWC. Because of the design of the ASC, all subsequent trials with food products were limited to jars not larger than PT size.

For each trial with each food product, one TC measured the temperature of the heating medium, and TCs placed in the geometric center of three different jars measured product temperature. The geometric center of the jar was the theoretical cold spot for each food product as determined by experimentation *(6)*. At the end of the processing time, jars were removed from the canner and placed on a lab bench to air cool until the average internal temperature of each jar reached 130°F (54°C). Temperature of each TC in °F was recorded at 1-min intervals throughout the experiment.

Applesauce, tomato juice, and cranberries in heavy syrup were processed in PT jars following research-tested recipes. Chocolate raspberry sauce was processed in HP jars following a tested recipe. Representative time/temperature thermal process curves for each product are shown in Fig. 2. The rate of heating and cooling for each food product, f_h and f_{cl}, respectively, were calculated *(Table 2)*. The integrated lethality for the heating (F_h) and cooling (F_{cl}) portions of the time/temperature curve, and the total lethality $F_{180°F}$, were also calculated assuming a reference temperature of 180°F (82°C) and a z-value of 10°F for *E. coli* O157:H7 as the target pathogen *(10)*. *E. coli* O157:H7 was chosen as the target pathogen because it has been linked to foodborne illnesses and has been shown to be the most heat- and acid-tolerant pathogen likely associated with acid foods *(3, 4)*. The come-up time was excluded from thermal processing calculations, and has been omitted from *Fig. 2,* because research has shown that the overall lethality contributed by the come-up process is slight *(19)*.

The rate of heating (f_h) was not dependent on heating medium/canner type. As shown by Etzel et al. *(6)*, this is because heat transfer within the jar dominates when the Biot number $N_{Bi} = hd_c/k$ is greater than 50, where h is the

TABLE 1. Average come-up time for the processing medium to reach the processing temperature, 210 ± 1°F, for tomato juice canned in various size jars

Jar Size	Initial Temp. °F (°C)[a]	BWC Come-Up Time (min)[b]			ASC Come-Up Time (min)[c]		
		Full[d]	½-Full	1 Jar	Full[d]	½-Full	1 Jar
Quart (QT)	75 (24)	11	9	8	6	9	8
	180 (82)	8	8	6	3	9	8
Pint (PT)	75 (24)	10	9	8	10	10	8
	180 (82)	9	7	8	9	9	8
Half-Pint (HP)	75 (24)	9	7	7	10	9	8
	180 (82)	8	8	7	9	9	8

[a] Target temperature of tomato juice when packed into jars

[b] Average time (min) boiling water canner (BWC) to reach processing temperature, 210° ± 1°F from 180°F, n = 3, excluding time required to heat water in canner from 75°F to 180°F, an average of 22 min per trial (n = 54 trials)

[c] Average time (min) atmospheric steam canner (ASC) to reach processing temperature, 210° ± 1°F, from 75°F, n = 3

[d] Full = 7 QT, 8 PT, or 8 HP jars; ½ -full = 3 QT, 4 PT, or 4 HP jars; or with only 1 jar per jar size

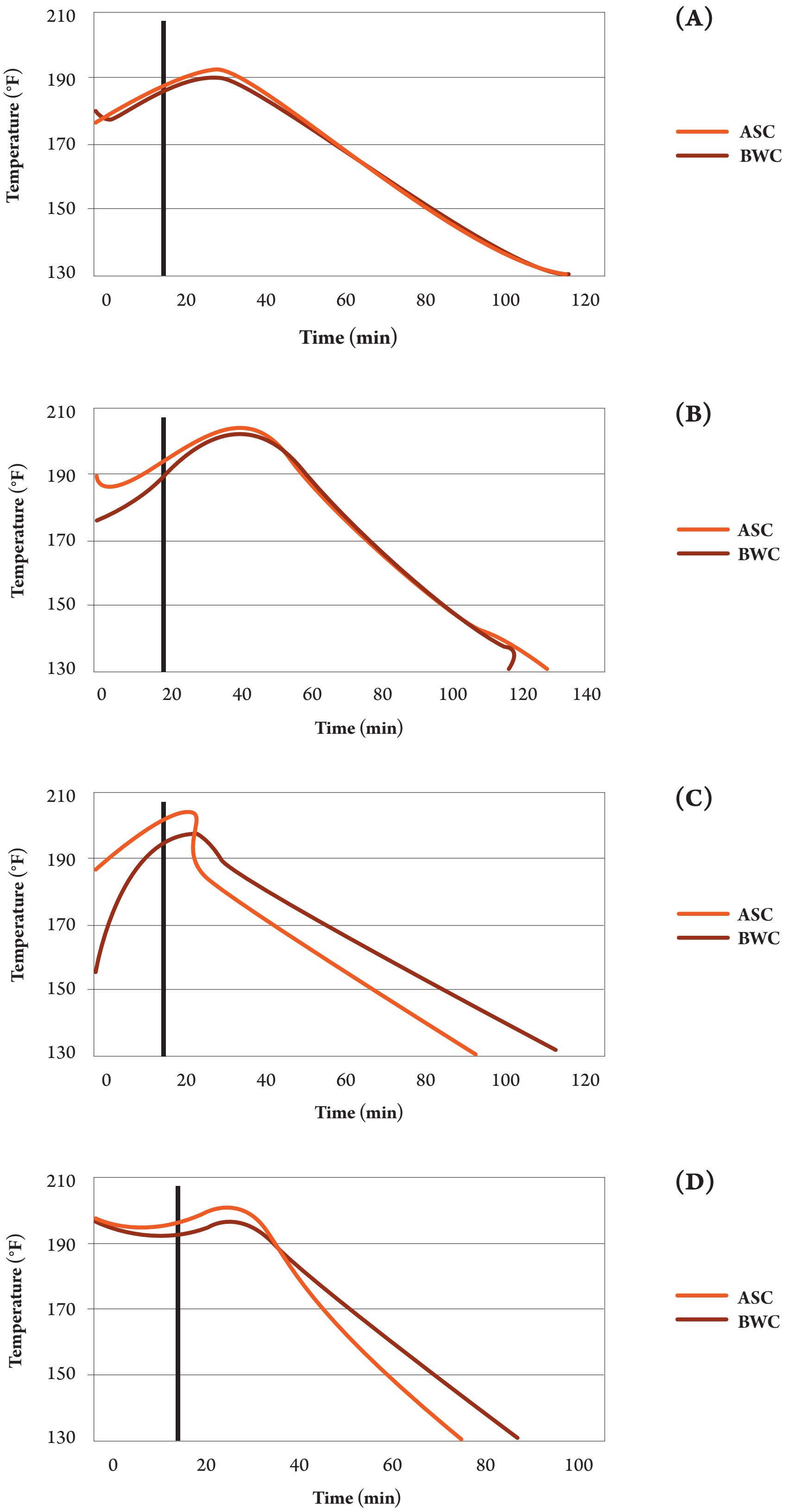

Figure 2. Representative internal temperature recording for food products processed in an ASC and BWC: applesauce (A), tomato juice (B), cranberries in heavy syrup (C), and chocolate raspberry sauce (D). Time 0 is the beginning of the thermal process; line marks the end of the thermal process when product was removed to the lab bench to cool to ~130°F. Process time was 15 min for applesauce, 35 min for tomato juice, 15 min for cranberries, and 10 min for chocolate raspberry sauce. Come-up time not shown

TABLE 2. Heat penetration rate (f) and calculated lethality (F) when typical food products are canned in a boiling water canner or an atmospheric steam canner

Food[a]	Canner type[b]	f_h (min)[c]	f_{cl} (min)[d]	F_h (min)[e]	F_{cl} (min)[f]	$F_{180°F}$ (min)[g]
Applesauce	BWC	n/a[h]	260 ± 20	9 ± 8	190 ± 90	200 ± 100
	ASC	n/a	250 ± 20	10 ± 6	140 ± 50	150 ± 60
Tomato Juice	BWC	58 ± 1	250 ± 10	700 ± 200	1800 ± 800	2500 ± 700
	ASC	52 ± 5	260 ± 10	1000 ± 300	2400 ± 1000	3200 ± 1000
Cranberries	BWC	31 ± 3	250 ± 10	770 ± 300	1700 ± 500	2500 ± 700
	ASC	27 ± 4	290 ± 30	560 ± 400	1680 ± 600	2200 ± 900
Choc. Rasp.	BWC	n/a	170 ± 10	2000 ± 2000	1630 ± 1000	3600 ± 3000
	ASC	n/a	185 ± 7	220 ± 100	230 ± 80	450 ± 200

[a] Applesauce, tomato juice, and cranberries in heavy syrup processed in pint (473 ml) jars; chocolate raspberry sauce processed in half pint (273 ml) jars

[b] Boiling water canner (BWC) and Atmospheric steam canner (ASC) operated full, 8 pint or half-pint jars

[c] Average ± SD rate of heat penetration rate during heating, n = 12

[d] Average ± SD heat penetration rate during cooling, n = 12

[e] Average ± SD calculated lethality during the thermal process at 211°F (99°C), n = 12, excluding come-up time

[f] Average ± SD calculated lethality during cooling to an end-point temperature of 130°F (54°C), n = 12

[g] Average ± SD integrated lethality for heating and cooling, excluding come-up time. For all lethality calculations, T_{ref} = 180°F (82°C), target organism was *Escherichia coli* O157:H7 with z = 10°F *(10)*

[h] n/a = not calculated

convection heat transfer coefficient in the heat transfer medium, k is the thermal conductivity in the jar, and d_c is the jar radius. In our experiments, h = 3,000 to 100,000 W/(m^2°K) or h = 5,000 to 100,000 W/(m^2°K) for boiling water and condensing steam, respectively, d_c = 4.1 cm for PT jars, and k ≈ 0.5 W/(m^2°K) for most foods *(17)*. Therefore, $N_{Bi} > 250$ for heating PT jars in a BWC or ASC ($N_{Bi} > 200$ for HP jars and > 290 for QT jars). Based on heat transfer theory and our experimental results, the rate of heating of the jar in a home canning situation does not depend on the heating medium itself, and boiling water and steam are equally rapid heat transfer media.

The theoretical value of f_h can be calculated and compared to the experimentally observed values. Using an infinite cylinder as a first approximation of a jar, $f_h \alpha/(d_c)^2 = 0.40$ for $N_{Bi} > 50$, where α is the thermal diffusivity, approximately 1.4 ± 0.4 $\times 10^{-7}$ m^2/s for most foods *(17)*. The theoretical value calculated for f_h is 40 to 70 min for HP jars (d_c = 3.3 cm), f_h 60 to 110 min for PT jars (d_c = 4.1 cm), and f_h 90 to 160 min for QT jars (d_c = 4.9 cm). The calculated value of f_h is similar to the experimentally observed value for PT jars of tomato juice, 52 ± 5 min and 58 ± 1 min for the BWC and ASC, respectively *(Table 2)*, but longer than the value observed for cranberries, f_h = 31 ± 2 min for the BWC and 27 ± 2 min for the ASC, respectively *(Table 2)*. It's likely that some convection heating occurred inside the jar when cranberries were heated, speeding heat transfer compared to purely conduction heating, whereas the viscosity of tomato juice impeded heat transfer and limited convection heating inside the jar. Tomato juice is commonly considered to be a liquid, but in the absence of force it is considered to be a weak gel that heats mostly by conduction *(2)*.

The rate of product cooling in air (f_{cl}) is dramatically different from the rate of heating in the canner. For air cooling, $N_{Bi} \approx 0.8$ for a PT jar, where h ≈ 10 W/(m^2°K). When $N_{Bi} < 0.2$, convection heat transfer into the air outside the jar dominates, and conduction heat transfer from inside the jar does not limit the cooling rate. This means that heating the jars in either the ASC or the BWC is fast and controlled by heat penetration inside the jar, whereas cooling is slow and mostly, but not entirely, controlled by convection heat transfer in the kitchen air. Furthermore, the cooling rate is largely independent of the type of food in the jar, because heat transfer inside the jar is faster than heat transfer in the air surrounding the jar.

The theoretical value of cooling rate parameter is $\alpha f_{cl}/(d_c)^2 = ½\ln(10)/N_{Bi}$, or f_{cl} = 220 min (HP jars), f_{cl} = 280 min (PT jars), and f_{cl} = 340 min (QT jars). This calculated value agrees well with the observed average value of f_{cl} = 260 min for PT jars and f_{cl} = 180 min for HP jars *(Table 2)* and confirms that convection heat transfer in the air controlled the rate of cooling. Furthermore, as predicted on the basis of heat transfer theory, the experimentally determined values of fcl are not dependent on the heating method, BWC or ASC, or the food product.

Lethality was calculated for the heating (F_h) and cooling (F_{cl}) portions of the processing curve and for the total process ($F_{180°F}$) *(Table 2)*. Unlike the values observed for rates of heating and cooling, wide ranges were seen in calculated lethality. Integrated lethality for the cooling portion of the process curve for PT jars (applesauce, tomato juice, and cranberries), F_{cl}, was significantly greater than lethality for the heating portion of the curve, F_h *(Table 2)*, and was the dominant factor in calculated overall lethality, $F_{180°F}$. F_{cl}, as a percentage of $F_{180°F}$, was 93, 70, and 75% in the ASC and 95, 72, and 70% in the BWC for applesauce, tomato juice, and cranberries, respectively *(Fig. 3)*. Canner type had little to no effect on lethality for PT jars (F_h, F_{cl}, and $F_{180°F}$) *(Table 2)*. This observed canner independence agrees with heat transfer theory where the values of the heat penetration parameters f_h and f_{cl} for PT jars were similar for the two canner types. It also agrees with the observation that canner type has no effect on the air-cooling rate and that most of the lethality occurs during air cooling.

For the smaller (HP) jars containing chocolate raspberry sauce, lethality during cooling nearly equaled lethality during heating *(Table 2)*. F_c and F_h were 45 and 55%, and 51 and 49% for chocolate raspberry sauce processed in a BWC and an ASC, respectively *(Fig. 3)*. This was attributed to the high initial temperature of the chocolate raspberry sauce (200 ± 5°F) causing a lethal rate versus time curve distinctly different from the bell-shaped curve of the other foods tested (data not shown). For the chocolate raspberry sauce, the lethal rate curve started high, fell slightly as jars were placed into a heating medium cooler than the initial food temperature, rose as the canner approached the boiling point, and then fell during air cooling.

Heat transfer theory can be used to generalize our results to other foods and jar sizes. All foods are bracketed by two extremes: purely conduction-heating foods such as applesauce and purely convection-heating foods that have water-like viscosity. Conduction heating foods have the lowest heat penetration rates f_h and f_{cl} and are characterized by no fluid motion during heating and cooling. The largest value of N_{Bi} occurs for these foods, and $N_{Bi} > 50$ for all jar sizes. Heating is controlled by heat transfer inside the jar and not by the heating medium. Lethality for the heating portion will be the same for the BWC an ASC. Because canner type has no effect on the air-cooling rate, and most of the lethality occurs during air cooling, the total lethality will not be significantly different for food processed in a BWC versus an ASC. Conduction-heating foods are the worst-case scenario for food safety, yielding the smallest values for calculated lethality. Nevertheless, research-tested recipes that provide parameters for safe processing of conduction-heating foods in a BWC can be safely applied to these same foods processed in an ASC when operated at the temperature of pure steam.

Convection-heating foods, on the other hand, exhibit rapid rates of heating, f_h. Cranberries are the closest to a pure convection-heating food in our study. Nevertheless, canner type will not affect the heating rate, because heat transfer in boiling water or condensing steam is far faster than in the heavy syrup inside the jar. Once jars are taken out of the canner, then canner type will not affect the air cooling rate. Therefore, recipes safe for convection heating foods in a BWC will be safe for an ASC that is operated at the temperature of pure steam.

The level of vacuum seal attained for each product further supports the efficacy of each type of canner in processing foods. A strong vacuum seal was achieved for jars processed in either type of canner, averaging 25 psi for applesauce, tomato juice and cranberries processed in PT jars (n = 25/food product), and 20 psi chocolate raspberry sauce in HP jars (n = 12).

Scant research has been published that compares the safety of an ASC and BWC for home food preservation. Ramakrishnan et al. *(15)* evaluated the efficacy of a BWC and an ASC for home processing of tomatoes, tomato juice, and applesauce. The canning methods adopted for the study were methods recommended by the USDA at the time, the 1976 edition of the USDA home canning guidelines. All products were hot packed, with initial product temperatures set at 180°F for tomato products and 190°F for applesauce. Each canner was operated full, using 7 QT jars or 8 PT jars. Process lethality was calculated assuming a reference temperature of 250°F, a $D_{250°F}$ of 0.01 min, a z-value of 18°F, and a target 6-log reduction of *Bacillus coagulans* for tomato products. For applesauce, the criteria were a z-value of 20°F and a target 4-log reduction. The authors did not determine lethality or the rate of heat transfer during air cooling. For each food product, there was no difference in observed lethal capacity, F_c, between the canner types.

More recently, Samida et al. *(16)* compared processing of tomato juice, sliced peaches, tomatoes, and applesauce in a BWC and a flowing steam ASC. The authors identified a target temperature of 180°F at the center of the product and concluded that foods reached the target temperature regardless of the type of canner used. Thermal process calculations were not performed. Unfortunately, flaws in

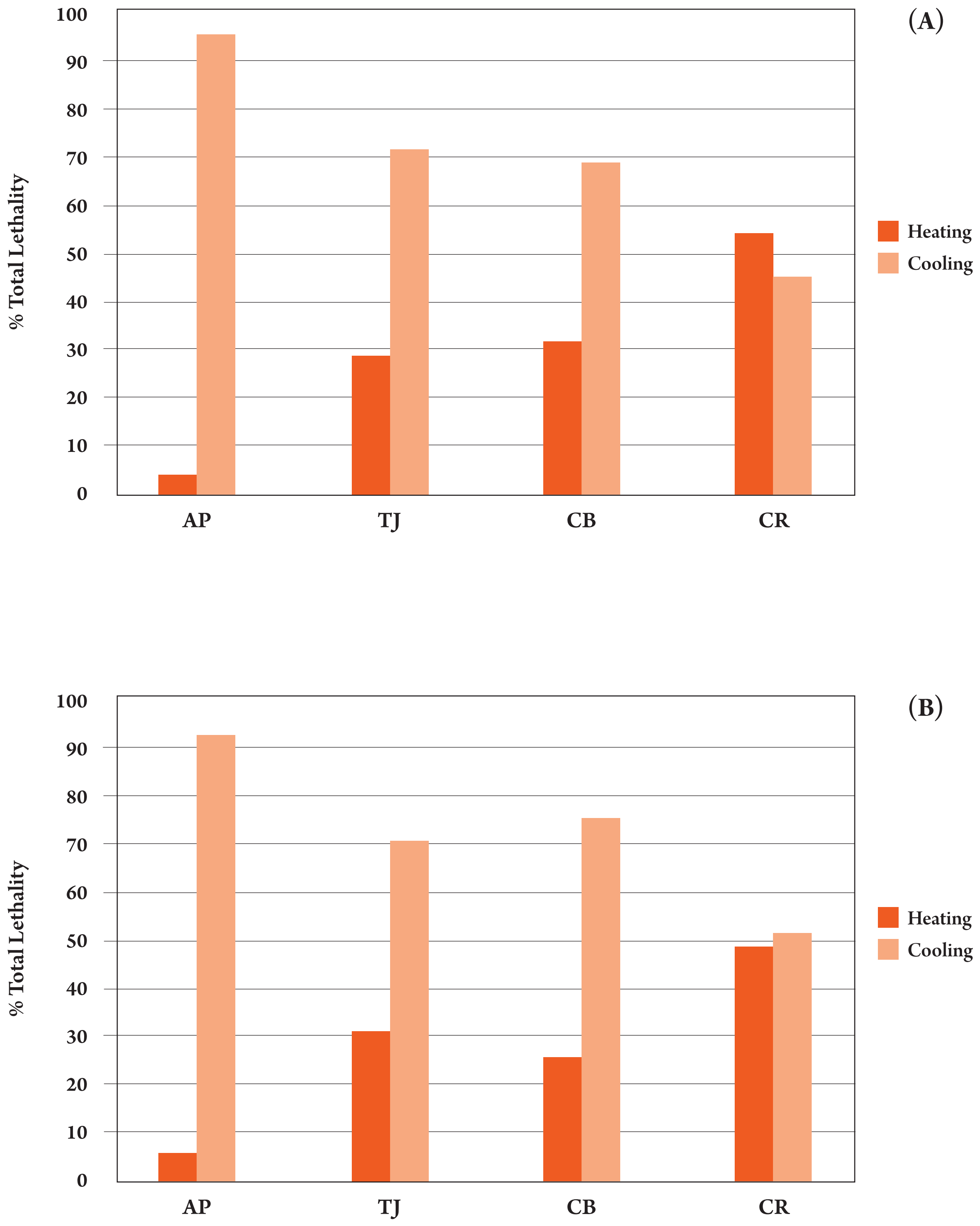

Figure 3. Percent total lethality ($F_{180°F}$) attributed to heating and cooling of applesauce (AP), tomato juice (TJ), cranberries in heavy syrup (CB), and chocolate raspberry sauce (CR) processed in a boiling water canner (A) and an atmospheric steam canner (B)

study design and execution, such as failure to determine the cold spot in each food product prior to thermocouple placement, use of the BWC without a lid, and failure to follow recommended guidelines (e.g., cold-packing of applesauce, placing jars of peaches and tomato juice into water pre-heated to 212°F) led to lack of acceptance of this work by home canning experts *(8)*.

A log reduction value (LRV) can be used to estimate the destruction of *E. coli* O157:H7 achieved by the calculated lethality $F_{180°F}$ for each food product processed in each canner (Equation 3).

Equation 3. $LRV = F_{180°F} / D_{180°F}$

Using Equation 3, we can estimate the approximate log reduction of the processes, assuming $D_{180°F} = 0.00008$ min and z = 10°F for *E. coli* O157:H7 in applesauce, cranberries and chocolate raspberry sauce *(10)*. For tomato products, Peng et al. *(14)* calculated a $D_{180°F} = 78$ min for spores of *B. coagulans* 185A in tomato juice at pH 4.3. Assuming a target 5-log reduction of *E. coli* O157:H7 for acid and acidified foods *(3)* and the 6-log reduction assumed by Ramankrishnan and colleagues *(15)* for *B. coagulans* in tomato products, we can calculate a $F_{180°F} = 0.0004$ min for *E. coli* O157:H7 in applesauce, cranberries and chocolate raspberry sauce, and $F_{180°F} = 468$ min for *B. coagulans* spores in tomato products. It is clear from Table 2 that all processes easily met, and far exceeded, these microbial lethality targets. Our lethality values do not take into account any additional lethality achieved during the food preparation process, when products were hot-filled at a target 180°F, or any lethality achieved during come-up time. Regardless, this assurance of microbial lethality highlights an important benefit of using in home canning, research-tested recipes such as those found in the USDA Complete Guide to Home Canning *(20)* or those from the National Center for Home Food Processing and Preservation *(12)*.

This study has corrected the flaws identified in the work of Samida and colleagues *(16)* and has expanded upon the work of Ramakrishnan et al. *(15)*. Most importantly, we have extended thermal process calculations to encompass the cooling stage. Gradual air cooling of home-canned products to room temperature after heat processing is a standard recommendation in all approved home canning guidelines. The crucial contribution to overall lethality of product cooling, a step common to canning with both the BWC and ASC, lends support to the argument for the recommended use of the ASC for home canning of high acid foods.

RECOMMENDATIONS

We have established the effectiveness of the ASC for home processing of acid or acidified foods with pH ≤ 4.6. Using the data that we have collected, it is possible to identify critical process parameters that will allow safe processing of food in an atmospheric steam canner at home.

- **Food product pH must be less than, or equal to, 4.6, i.e., high in acid.** Either a BWC or an ASC can be used to safely preserve foods high in acid if a tested recipe is used.
- **The atmospheric steam canner must be used in conjunction with a current, research-tested recipe developed for a boiling water canner.** Approved recipes may be found in the USDA Complete Guide to Home Canning *(20)* or may be sourced from Extension programs, e.g., the National Center for Home Food Processing and Preservation *(12)*. Our experience suggests that information supplied in the instruction booklet accompanying an atmospheric steam canner would not be considered research tested.
- **Temperature in the atmospheric steam canner must be monitored to ensure that the process begins only when the temperature of pure steam is reached (~212°F).** When the steam temperature in the canner dome reaches the boiling point (~212°F), venting is complete and all air is purged from the canner, and heat transfer is at the highest possible value. The consumer should monitor temperature with a dial-stem or digital thermometer placed in the vent port. We found that some atmospheric steam canners come with a built-in temperature sensor in the dome lid, and our limited use of this style of lid suggests that it may be able to accurately indicate temperature. Steam vent size or intensity is not an accurate indicator of temperature of the heating medium.
- **Jars must be heated prior to filling and all effort made to minimize cooling prior to the start of the processing time.** Hot jars filled with hot food will begin cooling when placed in either an unheated atmospheric steam canner or a boiling water canner that has not been preheated. The time during which jars cool prior to processing should be minimized. All research-tested home canning recipes call for jars to be heated prior to filling. Our research indicated that there is more flexibility in other operating parameters for an atmospheric steam canner: the canner may be operated full, half-full, or nearly empty (1 jar); half-pint, pint, and quart-size jars may be used for canning; and hot-packed or raw-packed foods may be safely canned, if a current, research-tested recipe is followed.
- **Recipe modifications for elevation are required.** Extending the processing time for elevations above 1,000 feet is required and recommendations in research-tested recipes for the boiling water canner should be followed.
- **Processing time should be limited to 45 min or less.** Only foods with a research-tested process time of ≤ 45 min should be canned in an atmospheric steam canner; otherwise, the canner may run dry. Foods with extended boiling-water process times, e.g., tomatoes packed in juice, or tomatoes raw-packed with no added liquid, which have a processing time of 85 min prior to any adjustments for

elevation, should not be processed in an atmospheric steam canner. Consumers should not open the canner to add water during the process, as this will impact temperature and may result in the food being under-processed.

- **Cooling should be done in still, ambient temperature air.** Because most of the lethality occurs during air cooling, the cooling procedure is of great importance. Placing the jars in water, in the refrigerator, or in front of a fan should not be used to speed the cooling process.

Consumers who follow these critical processing parameters can be assured that they are preparing safe food for their family through use of an atmospheric steam canner.

ACKNOWLEDGMENTS

This work was supported by the National Institute of Food and Agriculture, United States Department of Agriculture, under a subcontract to Agreement No. 2011-51110-30995, National Center for Home Food Processing and Preservation, University of Georgia. The authors gratefully acknowledge a year of Advanced Opportunity Fellowship (AOF) funding awarded to P. Willmore. The authors also thank Dr. Arnoldo Lopez for assistance in mathematical calculations.

REFERENCES

1. Andress, E. L. 2002. A global look at some home canning activity today. Available at http://nchfp.uga.edu/educators/natl_survey_summary.html. Accessed 11 February 2014.
2. Augusto, P. E. D., V. Falguera, M. Cristianini, and A. Ibarz. 2013. Viscoelastic properties of tomato juice: applicability of the Cox-Merz rule. *Food Bioproc. Technol.* DOI 10.1007/s11947-011-0655-y.
3. Breidt, F., K. Kay, J. Osborne, B. Ingham, and F. Arritt. 2014. Thermal processing of acidified foods with pH 4.1 to 4.6. *Food Prot. Trends* 34:132–138.
4. Breidt, F., K. P. Sandeep, and F. M. Arritt. 2010. Use of linear models for thermal processing of acidified foods. *Food Prot. Trends* 30:268–272.
5. Dickerson, S. 2010. Can it: at-home preserving is ridiculously trendy. Slate. Available from http://www.slate.com/id/2246148/. Accessed 11 February 2014.
6. Etzel, M. R., P. Willmore, and B. H. Ingham. 2014. Heat penetration and thermocouple location in home canning. *Food Sci. Nutr.* (accepted October 10, 2014). Published online December 9, 2014: http://onlinelibrary.wiley.com/doi/10.1002/fsn3.185/full.
7. Institute for Thermal Processing Specialists. 2014. Guidelines for conducting thermal processing studies. Available from http://www.iftps.org/protocols.html. Accessed 11 February 2014.
8. Ito, K. 2003. Review of steam canner situation. Provided by Dr. E. Andress, personal communication.
9. Kingry, J., and L. Devine. 2006. Ball complete book of home preserving. Robert Rose, Inc., Toronto, Canada.
10. Mazzotta, A. S. 2001. Thermal inactivation of stationary-phase and acid-adapted *Escherichia coli* O157:H7, *Salmonella*, and *Listeria monocytogenes* in fruit juices. *J. Food Prot.* 64:315–320.
11. Moskin, J. 2009. Preserving time in a bottle (or jar). The New York Times. Available from http://www.nytimes.com/2009/05/27/dining/27cann.html?_r_2. Accessed 11 February 2014.
12. National Center for Home Food Preservation. 2014. How do I….Can? Available from http://www.uga.edu/nchfp/. Accessed 11 February 2014.
13. Padilla-Zakour, O. 23 August 2013. Personal communication.
14. Peng, J., J-H Mah, R. Somavat, H. Mohamed, S. Sastry, and J. Tang. 2012. Thermal inactivation kinetics of *Bacillus coagulans* spores in tomato juice. *J. Food Prot.* 75:1236–1242.
15. Ramakrishnan, T. V., E. A. Laperle, and K. M. Hayes. 1987. Comparison of steam canner processing with other methods of home canning. *J. Food Proc. Preserv.* 11:43–61.
16. Samida, M., L. Geer, and G. K. York. 2005. Home processing of tomatoes and other acid foods in flowing steam and hot water bath canners. *Food Prot. Trends* 25:178–181.
17. Singh, R. P., and D. R. Heldman. 2009. Heat transfer in food processing, p. 265–417. In Introduction to Food Engineering, 5th ed. Academic Press, San Diego, CA.
18. Stoforos, N. 2010. Thermal process calculations through Ball's original formula method: a critical presentation of the method and simplification of its use through regression equations. Springer Science+Business Media, LLC doi: 10.1007/s12393-010-9014-4.
19. Succar, J., and K. Kayakawa. 1982. Prediction of time correction factor for come-up heating of packaged liquid food. *J. Food Sci.* 47:614–618.
20. United States Department of Agriculture. 2009. Complete guide to home canning. Agriculture Information Bulletin No. 539. Available at: http://nchfp.uga.edu/publications/publications_ usda.html. Accessed 26 March 2014.