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ANALYSIS OF THERMAL PROCESS OF LOW- AND HIGH-ACID FOODS IN SEMIRIGID CONTAINERS

BY
KAN-ICHI HAYAKAWA
JIAJUN WANG
SEYMOUR GILBERT
FOOD SCIENCE DEPARTMENT
COOK COLLEGE
RUTGERS UNIVERSITY
NEW BRUNSWICK, NJ 08903

*LAURIE OLEKSYK

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NATICK, MA 01760-5018

*FOOD ENGINEERING DIRECTORATE

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One military prototype meal consists of thermostabilized low- and high-acid foods in semirigid containers. These foods have in the past been thermoprocessed separately because of greatly different lethality requirements. In order to minimize production costs, the present study sought to examine the feasibility of simultaneously processing one meal consisting of chili con carne, white rice, and sliced peaches in syrup. The simultaneous processing was not possible by adjusting initial food temperatures according to computer-simulation using food temperature data collected experimentally. However, simultaneous thermostabilizing was possible when a container for the peach item was insulated properly with expanded polystyrene. The proper insulation thickness was slightly dependent on the z value of the target inactivation factor.

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PREFACE

The following is a report on the computer analysis of simultaneous processing of high and low acid foods in semirigid containers. The Intergovernmental Personnel Act (IPA) Assignment Agreement was awarded to Food Science Department, Rutgers University, New Brunswick, New Jersey, under Project 1L162786AH99BC059. The work was completed during the period November 1987 to December 1988.

Natick Project Officers for IPA Assignment Agreement were Angela Fong and Laurie Oleksyk with Peter Burke as alternate Project Officer.

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ANALYSIS OF THERMAL PROCESS OF LOW- AND HIGH-ACID FOODS IN SEMIRIGID CONTAINERS

INTRODUCTION

The concept of thermostabilized food in semirigid plastic containers has been accepted by the general consumer because of the packages' easily recognizable profiles, the foods' shelf stability, and their convenience. Procedures for the thermal processes of food in those containers are described in several articles (Dahlgren, 1985; Wachtel, 1987).

A prototype tray meal consisting of an entree, a starch and dessert in semirigid containers is under consideration for some types of military feeding, for example, remote site feeding. High- and low-acid foods usually are included within one meal. These packaged food components are processed separately according to the current practice since their target process lethalities vary greatly. The simultaneous processing of one complete meal would greatly reduce the production costs of the military rations since the need for separate thermal processes would be eliminated. The objective of the present work is to analyze the feasibility of simultaneously processing high- and low-acid foods packaged in one semirigid compartmented container.

PROCEDURES

A meal consisting of chili con carne, white rice, and peach slices in syrup was selected for the present study. The first two items and the remaining one are low- and high-acid foods, respectively.

Two approaches for accomplishing the simultaneous processing of the three stated foods were examined for the present work.

The first is to adjust initial food temperatures and retort temperatures. The second is to apply a layer of insulation to the compartment containing the peach slices, which require the least process lethality among the three. A computer program -- a modified version of one previously developed for the accurate evaluation of thermal processes (Hayakawa, 1977) -- was used to examine feasibility for the simultaneous processing of these foods. The thermal death-time parameters of the target microorganisms and the heat transfer parameters of packaged foods were required for this examination. The parameters were obtained as described below.

Thermal Death Time Characteristics

A target sterilizing value, F_p, should be defined for the thermal processing of each food. This value was estimated using the temperature data of each food which underwent a proper thermal process as described in Table 1 (Data were provided by the U.S. Army Natick RD&E Center). All processes were done in a still retort that was manufactured by the Berlin Food Processing Equipment Co. The heating medium was hot water pressurized with air.

The following equation was used to estimate the proper sterilizing values (Ball and Olson, 1957),

$$F_p = \int_0^{t\ end} 10^{(T-T_r)/z}\,dt \qquad (1)$$

where: t end = Time at the end of the process

T_r = Reference temperature

z = Slope index of thermal death time curve

The temperature data were placed in 'T' of eq. 1 and an F_p value was estimated through numerical integration using Simpson's rule (a general method).

Table 1. Processing Conditions of Selected Food in Semirigid Containers

Food	Net Weight g	T_o ^oC	T_1 ^oC	P_a x $10^5 P_a$	t_{up} h	t_b h
Peaches	227 (136*)	24.8	104.4	1.082	0.117	0.267
White rice	227	30.3	118.1	2.324	0.517	0.633
Chili con carne	326	34.2	115.6	2.234	0.183	0.817

*Drained weight

T_o = Food temperature at beginning of thermal process

T_1 = Holding temperature of heating medium

P_a = Pressure in pascal

t_{up} = Come-up heating time

t_b = Processing heating time

It is clear from eq. (1) that the proper values of z, the slope index of the thermal death-time curve of target microorganisms, and T_r, a reference temperature, should be chosen to estimate an F_p value. Since chili con carne and white rice are low-acid foods, target microorganisms for the thermal processing of both foods are Clostridium botulinum spores. Therefore, a standard z value of 10 C^o was used to estimate the sterilizing value. There was no published information available on the target microorganisms of peach slices in syrup. However, one reference book (Lopez, 1981) states bacteria (e.g., Clostridium pasteurianum, Lactobercillus sp., Leuconostac sp.), yeasts (only in case of gross underprocessing) or molds (Byssochlamys fugtra) being the target factors for the thermal processing of high-acid foods. Another reference book (Tanikawa et al., 1969) states Saccharomyces cervisiae as the target factor for canned mandarin orange segments. The z values of these microorganisms are likely within the range between 4.2 C^o and 12 C^o according to reference books (Hugo, 1971; Samson et al., 1984). Therefore, these three z values were used to estimate the lethalities of peach slices in syrup: 4.2 C^o, 10 C^o and 12 C^o. Note that 10 C^o was included for comparison purposes.

As for T_r, 121.11 ^oC (Celsius conversion of 250 ^oF) is commonly used to estimate F_p for the thermal processes of low-acid foods. It is a common practice to use a T_r below 100 ^oC for high-acid food. However, 121.11 ^oC was used as the T_r for peach slices for two reasons. First, an F_p based on T_r may be converted easily to another F_p based on another T_r by:

$$F_{p2} = 10^{(T_{r1}-T_{r2})/z} F_{p1} \qquad (2)$$

where: F_{p2} = Subsequent sterilizing value

$T_{r}2$ = Subsequent reference temperature

Where secondly, one obtains final conclusions identical to those based on different T_r values if enough significant digits are retained in estimated F_p values. This may be easily accomplished through double precision computations.

Heat-Penetration Parameters:

Empirical heat-transfer parameters, f and j values, in packaged food were estimated from six temperature-history curves for each food, which were provided by the U.S. Army Natick RD&E Center. Parameters f and j may be determined from a curve obtained by plotting the common logarithmic of unaccomplished temperature differences against heating or cooling times. The unaccomplished temperature difference is a difference between surrounding heat exchange medium and food temperatures. A curve for conduction heated or cooled food normally consists of an initial curvilinear part and subsequent linear part. Parameters f and j are related to the slope and intercept of the linear part as shown below:

$$\log_{10} (|T_a-T|) = - t/f + \log_{10}[j(|T_a-T_i|)], \qquad (3)$$

where: T_a = Temperature of surrounding heat exchange medium.

T_i = Food temperature at the beginning of heating phase (identical to T_o) or at the beginning of cooling phase.

The f and j values (f_h and j_h) of a heating curve (a semilogarithmic temperature history in the heating phase of a thermal process) were estimated by using a computer program previously developed (Hayakawa, et al., 1981) after making a correction for come-up heating (Ball and Olson, 1957).

The f and j values (f_c and j_c) of a cooling curve (a semilogarithmic temperature history in the cooling phase of a process) were determined through similar computations.

where:

f_p = f value of rectangular parallelepiped (a brick shape)

j_p = j value of rectangular parallelepiped

f_L = f value of plate of thickness 2L

f_W = f value of plate of thickness 2W

f_H = f value of plate of thickness 2H

j_L = j value of plate of thickness 2L

j_W = j value of plate of thickness 2W

j_H = j value of plate of thickness 2H

Conduction heat transfer in the food was assumed to examine the experimental temperature history curves as discussed later.

Temperature Response Properties of Peach Slices in Syrup

Principles of heat transfer were used to estimate the f and j values of peach slices in a syrup package with a layer of insulation material over its outside surface. To apply these principles, the inside space configuration of the container was approximated by a rectangular parallelepiped with a volume identical to the container.

The parameters f and j of a rectangular parallelepiped, 2L X 2W X 2H, are related to respective heat-penetration parameters of infinitely wide plates of thicknesses 2L, 2W, and 2H according to the analysis of analytical conduction formula as shown below (Pflug et al., 1965):

$$1/f_p = 1/f_L + 1/f_W + 1/f_H \tag{4}$$

$$j_p = j_L \cdot j_W \cdot j_H \tag{5}$$

The parameters f and j of an infinite plate may be estimated from the analytical formula when thermal diffusivity, α, and Biot number, Bi_H, are available. For example, the f and j values of an infinite plate of thickness 2H may be estimated by:

$$f_H = H^2 (\ln 10)/(p_{1H}{}^2 \alpha) \tag{6}$$

where H = one half of effective inside height of container whose shape is approximated by a brick shape.

$$j_H = j_{Hc} \cos\ (p_{1H} x/H), \tag{7}$$

where p_{1H} is the first positive root of the following equation:

$$p \tan p = Bi_H \tag{8}$$

where $Bi_H = h\ H/k$. (9)

where h = overall coefficient for heat transfer from heat exchange medium to food surface.

In eq. 7, j_{Hc} is the j value on the center plane of the plate, which may be estimated by:

$$j_{Hc} = 2Bi_H \sec p_{1H} / \{Bi_H(Bi_H + 1) + p_{1H}{}^2\}. \tag{10}$$

From eqs. (8) and (10), one obtains,

$$1/f_p = (\alpha/\ln 10)\ \{(L/p_{1L})^2 + (W/p_{1W})^2 + (H/p_{1H})^2\}, \tag{11}$$

where p_{1L} and p_{1W} are the first positive roots of the following equations:

$$p_{1L}: \qquad p \tan p = S_L Bi_H \tag{12}$$

$$p_{1W}: \qquad p \tan p = S_W Bi_H \tag{13}$$

The temperature data were calculated at the center of each ration container. Therefore, the central j may be estimated from eqs. 4 and 9:

$$j_p = 8Bi_H^2 S_L \cdot S_W \sec p_{1W} \cdot \sec p_{1H} / [(S_L Bi_H (S_L Bi_H + 1) + p_{1L}^2) \ (S_W Bi_H (S_W Bi_H + 1) + p_{1W}^2) \ (Bi_H (Bi_H + 1) + p_{1W}^2)] \quad (14)$$

The values of Bi_H and corresponding first positive roots p_{1L}, p_{1W}, and p_{1H} were determined by substituting an experimentally determined j value into eq. 14 (noting that there is only one unknown since all roots are related to Bi_H as shown by eqs. 8, 12, and 18). The effective thermal diffusivity α of peach slices in syrup was estimated by substituting an experimental f_p value and the roots into eq. 11.

The effective thermal conductivity of the food, k, was determined from the definition of α and the estimated density, ρ, and specific heat, C_p, of the food.

$$k = \alpha C_p \rho \quad (15)$$

The value of Bi is changed when a layer of insulation material is applied to all outside surfaces of a container since an effective, convective surface heat conductance is reduced from h to U, as seen by reducing eq.(9) by (16), leading to (17).

$$1/U = 1/h + I_n/k_n \quad (16)$$

$$Bi_{Hn} = UH/k \quad (17)$$

where:

U = Overall coefficient for heat transfer through insulated container wall

I_n = Insulation thickness

k_n = Thermal conductivity of insulation

Bi_{Hn} = Bi_H of insulation

For the present analysis, expanded polystyrene was chosen as an insulation material.

Equation 11 gives a relationship between the value of f for peach slices in an insulated container, f_{pn}, and f of those in a noninsulated container, f_p. The relationship follows:

$$f_{pn}/f_p = \frac{[(L/p_{1L})^2 + (W/p_{1W})^2 + (H/p_{1H})^2]}{[(L/p_{1Ln})^2 + (W/p_{1Wn})^2 + (H/p_{1Hn})^2]} \qquad (18)$$

Similarly, a relationship between j values of peach slices in insulated and noninsulated containers is obtained from eq. 14,as below:

$$j_{pn}/j_p = \mathcal{f}(Bi_{Hn})/\mathcal{f}(Bi_H),$$

where:

$$\mathcal{f}(Bi_H) = Bi_H^3 \sec p_{1L} \sec p_{1W} \sec p_{1H}/[\{S_L Bi_H(S_L Bi_H + 1) + p_{1L}^2\} \{S_W Bi_H(S_W Bi_H + 1) + p_{1W}^2\} \{Bi_H(Bi_H + 1) + p_{1H}^2\}]. \qquad (20)$$

$\mathcal{f}(Bi_{Hn})$ may be defined by replacing Bi_H, p_{1L}, p_{1W} and P_{1H} by Bi_n, p_{1Ln}, p_{1Wn} and p_{1Hn}, respectively.

For an assumed thickness I_n, of insulation material, a modified Bi, Bi_{Hn}, was estimated by eqs. 14 and 15. Then constants p_{1Hn}, p_{1Ln}, and p_{1Wn} were estimated by using eqs. 8, 12, and 13 (Bi_H in these equations was replaced by Bi_{Hn}). The values of f_h, f_c, j_h, and j_c applicable to an insulated container package were estimated by using eqs. 18 and 19.

Estimation of F_p, A Function of f and j and of Other Process Conditions

A modified version of a computer program developed previously (Hayakawa, 1977) was used to estimate F_p values as a function of heat-penetration parameters, z-value, retort temperature, initial food temperature and other processing conditions. This program has an option of specifying either conductive or convective food being processed. Because of an assumption previously stated, the option of heat-conductive food was used for the present analysis.

RESULTS AND DISCUSSION

Table 2 shows the target sterilizing values, F_p's, estimated from the temperature histories of foods. The F_p's of chili con carne and white rice are typical values for low-acid foods. The F_p of peach slices in syrup was highly dependent on the z value used. Since the temperatures of peach slices were below T_r, a smaller z value resulted in smaller values of integrand of eq. 1. Therefore, a smaller F_p value was obtained.

The examination of the temperature data used for the F_p estimation revealed that the temperatures of all three foods continued to increase during initial cooling periods. This implies that heat is transmitted mostly through heat conduction within these foods since there is no temperature increase during a cooling phase for convective heating of food. With chili con carne and white rice, this was expected since there were virtually no free liquids in these foods. With peach slices in syrup, there was a relatively small height profile of a container for peach slices, with an average inside height of 30 mm. This contributes to minimum convective flow of syrup within each container during a thermal processing. Based on the above observations, conduction heat flow within all foods was assumed as previously stated.

Table 2. Target Sterilizing Values (F_p) of Three Products in Semirigid Containers

Food	z Value (C^{o})	F_p (sec.)
Chili Con Carne	10.0	450
White Rice	10.0	450
Peach Slices in Syrup	4.2	0.00258
	10.0	3.00
	11.9	9.12

Table 3 shows the values of heat-penetration parameters and their standard deviations. Effective inside dimensions of the containers for the three selected foods are shown in Table 4. The dimensions of the containers for chili con carne and white rice are given as a comparison although they were not used for the present analysis.

Processes with Adjusted Initial Food Temperatures

The heating time, t_b, should be reduced for the low-acid food and increased for the high-acid food to accomplish the simultaneous processing of all foods at a common retort temperature. Therefore, the initial temperature, T_o, of white rice and chili con carne were adjusted between 29.4 and 82.2 ^oC and T_o of peach slices between 1.6 and 15.6 ^oC. Analyses were performed for two retort temperatures, 110.0 and 121.1 ^oC. The results are summarized in Table 5.

With the retort temperature of 110 ^oC, the t_b's of both low-acid foods were reduced only slightly when their T_o's were increased from 29.4 to 82.2 ^oC, about 9% reduction. It is of interest to note that the t_b's of the two foods are nearly identical to each other although their f_h values differ. This is due to the fact that the f_c of white rice is considerably greater than the f_c of chili con carne. The larger f_c value resulted in higher food temperature during the cooling phase because of a slower rate of cooling. Therefore, there was a greater lethality in the cooling phase for white rice as compared to that of chili con carne; This cooling phase rate compensated for a smaller lethality for the heating phase of white rice.

Table 3. Heat-Penetration Parameters of Three Products in Army Ration Containers

	Food		
Parameters[a)]	Chili Con Carne	White Rice	Peach Slices[b)]
f_h (h)	0.441 (0.0053)[c)]	0.471 (0.0058)	0.305 (0.0104)
f_c (h)	0.596 (0.0185)	0.987 (0.0610)	0.522 (0.0517)
j_h	1.235 (0.035)	1.375 (0.049)	1.170 (0.085)
j_c	1.209 (0.022)	1.431 (0.280)	1.170 (0.011)

a) f_h = Slope index of semilogarithmic temperature history curve of the heating phase of process.

f_c = Slope index of semilogarithmic temperature history curve of the cooling phase of process.

j_h = Empirical heat-penetration parameter related to the intercept of semilogarithmic temperature history curve of the heating phase of process.

j_c = Empirical heat-penetration parameter related to the intercept of semilogarithmic temperature history curve of the cooling phase of process.

b) Values of packs in uninsulated containers.

c) Values in parentheses are standard deviations.

Table 4. Effective Inside Dimensions (mm) of Containers

Container for	Height (2H)	Width (2W)	Length (L)
Peach Slices	30	70	118
Chili Con carne	26	92	136
White Rice	30	70	118

The t_b's of peach slices are 15 to 20% of the t_b's of the low-acid foods depending on the z value. The use of the smallest z value resulted in the longest t_b's. The use of the largest z value gave the shortest t_b's. There was no significant increase in t_b when the initial food temperature was lowered to 1.6 ^{o}C.

With the retort temperature of 121.1 ^{o}C, relative differences in the t_b's of the low- and high-acid foods became less than those at the lower retort temperature, a 35 to 40% difference. There were relatively large reductions, 20%, in the heating times for low-acid food when the initial temperatures were increased. However, there were no significant increases in the high acid food heating times when the initial temperatures were lowered. The z values did not significantly influence the high-acid food heating times. It is clear from Table 5 that the simultaneous processing of all foods is not possible by adjusting the initial food to temperatures at both retort temperatures.

Application of Insulation on High-Acid Food Containers

An effective thermal diffusivity of peach slices in syrup was estimated as previously described, 2.07 mm^2/sec (an average of six values, $\pm$ 10%). The specific heat, c_p, and density, ρ, of the food were required to estimate its thermal conductivity using eq. 15.

To obtain the named physical property values, the food was assumed to be equilibrated with a 15% sugar solution (mass basis). Therefore, c_p was estimated by using the Mollier chart of sugar solution (Burke, 1954), 3.81 J/(g^{o}C). The same chart showed the refractive index, n, of the solution being 1.356. The density, ρ, of solution was estimated by using an empirical

Table 5. Predicted Heating Times of Three Rations of Different T_o's and Different T_1's[1)]

	T_1 = 110 °C				T = 121.11 °C		
Food[2)]	T_o (°C)	z (C°)	t_b h(min)	Food	T_o (°C)	z (C°)	t_b h(min)
C	29.44	10	2.283(137.0)	C	29.44	10	0.746(44.74)
	37.78		2.262(135.7)		37.78		0.727(43.64)
	65.56		2.167(130.1)		65.56		0.690(38.97)
	82.22		2.078(124.7)		82.22		0.581(34.87)
R	29.44	10	2.283(137.0)	R	29.44	10	0.761(45.65)
	37.78		2.277(136.6)		37.78		0.741(44.48
	65.56		2.177(130.6)		65.56		0.658(39.50)
	82.22		2.082(124.9)		82.22		0.585(35.11)
P	1.67	4.2	0.452(27.14)	P	1.67	4.2	0.295(17.69)
	4.44		0.450(26.99)		4.44		0.294(17.61)
	10.00		0.445(26.68)		10.00		0.278(16.67)
	15.56		0.427(25.62)		15.56		0.275(16.49)
P	1.67	10	0.3485(20.91)	P	1.67	10	0.260(15.62)
	4.44		0.345(20.70)		4.44		0.251(15.44)
	10.00		0.338(20.27)		10.00		0.251(15.06)
	15.56		0.329(19.76)		15.56		0.244(14.64)
P	1.67	10	0.364(21.86)	P	1.67	11.96	0.271(16.26)
	4.44		0.361(21.66)		4.44		0.268(16.08)
	10.00		0.354(21.22)		10.00		0.261(15.67)
	15.56		0.346(20.77)		15.56		0.254(15.26)

1) Cooling water temperature was assumed to be 12 °C.

2) C = chili con carne, R = white rice, P = peach slices.

formula correlating n and ρ, thus

$$\rho = 0.00452\ (n^2-1)/(n^2-2) = 0.001060\ g/mm^3.$$

Therefore, from eq. 15, one obtains:

$$k = 2.07 \times 3.81 \times 0.001060 = 0.00836\ W/(mm\ ^oC).$$

The thermal conductivity of expanded polystyrene was 4.19×10^{-5} W/(mm ^{o}C), according to the literature (anonymous, 1988). The effective thermophysical property values of peaches in syrup and the thermal conductivity of the insulation material were used to convert the experimentally determined f and j values of peach slices in syrup packaged in an uninsulated container to those in an insulated container, as previously described.

Proper thicknesses of expanded polystyrene layers on the peach container were estimated for the three different z values through many trial computations. The following two different sets of results were obtained: 1. Different initial temperatures, yielding virtually identical heating times, which satisfied the required, target lethalities; 2. Same initial temperature, yielding slightly different heating times, which satisfied the lethality requirement.

The estimated initial food temperatures, insulation thickness and processing times (heating time) are shown in Tables 6, 7, and 8. Table 6 shows that the simultaneous processing of all three foods is possible at 120 ^{o}C with the insulation thickness of 1.23 mm when the peach-z value is 4.2 C^o. Virtually identical processing times (heating times) were obtained when the initial food temperatures were 18.3 ^{o}C for chili con carne, 26.7 for rice, and 27.2 for peach slices.

When the initial temperatures of all foods were equal to 23.9 °C, slightly different processing times at 120 °C resulted: 0.825 h for peach slices, 0.803 h for chili con carne, and 0.823 h for rice. Therefore, the three foods may be processed simultaneously for 0.833 h (50 min) since the differences in the heating times are less than 0.0167 h (1 min).

It should be noted that the estimated heating times are defined in terms of thermal processes with no come-up time. Therefore, a process with a come-up time has a longer heating time (time measured from an exhaust completion time). For example, if there is a 0.167 h (10 min) come-up time, a heating time counted from the beginning of the process is 10 + 50 - 0.42 x 10 = 55.8 or 56 min (0.933 h) (Ball's correction used).

When the z value for peach is 10 C°, the estimated insulation thickness was 1.65 mm (Table 7). Required initial food temperatures for virtually same processing times were 18.3 °C for chili con carne, 23.1 for peach, and 26.7 for rice. When the initial temperatures of the three foods were set to 23.9 °C, the estimated processing times were 0.80 h (48.5 min) for chili con carne, 0.811 (48.7) for peach, and 0.823 (49.4) for rice. Therefore, all three foods, whose initial temperatures are set to 23.9 °C may be processed for 0.833 (50 min.) at 120 °C.

The results of simulations for the peach-z value of 11.9 C° are shown in Table 8. The required insulation thickness was 1.62 mm. The required initial temperatures for virtually the same processing times for chili con carne and rice are identical to those of the two previous peach-z values. The initial temperature of peach, 23.9 °C, is slightly above that for the peach-z of 10 C°.

Table 6. Simulation with an Insulated Peach Container and with Peach-z Being 4.2 C^{o}

Different Initial Temperatures

		Chili Con Carne	White Rice	Peach Slices
z	(C^{o})	10	10	4.2
f_h	(h)	0.442	0.472	1.00
f_c	(h)	0.596	0.9885	1.214
j_h		1.23	1.375	1.054
j_c		1.209	1.431	1.077
T_o	(^{o}C)	18.33	26.67	27.22
T_1	(^{o}C)	120	120	120
T_w	(^{o}C)	11.7	11.7	11.7
t_b	[h(min)]	0.818(49.098)	0.818(49.072)	0.818(49.081)
F_p	[h(min)]	0.125(7.5)	0.125(7.5)	7.17×10^{-7} (4.3×10^{-5})
I_n	(mm)	-	-	1.23

Same Initial Temperature

		Chili Con Carne	White Rice	Peach Slices
z	(C^{o})	10	10	4.2
f_h	(h)	0.442	0.4272	1.002
f_c	(h)	0.596	0.988	1.214
j_h		1.235	1.375	1.054
j_c		1.209	1.431	1.077
T_o	(248C)	23.89	23.89	23.89
T_1	(^{o}C)	120	120	120
T_w	(^{o}C)	11.7	11.7	11.7
t_b	[h(min)]	0.808(48.452)	0.824(49.431)	0.825(49.468)
F_p	[h(min)]	0.125(7.5)	0.125(7.5)	7.17×10^{7} (4.3×10^{-5})
I_n	(mm)	-	-	1.23

When the initial temperature of all foods was 23.9 ^{o}C, the required processing time for peaches was 0.817 h (49.03 min), slightly longer than that for the peach-z of 10 C^{o}. Again, all foods may be processed simultaneously for 0.833 h (50 min) at 120 ^{o}C when their initial temperature is 23.9 ^{o}C.

The above analysis is based on the assumption that there is no contact resistance between the insulation layer and outside surface of a peach container. Therefore, a thinner layer of insulation is required when there is significant contact resistance. Another assumption is that the thermal conductivity of expanded polystyrene does not change during processing. A thicker insulation layer will be required if there is an increase in the thermal conductivity owing to moisture permeation. Thus, a closed cell structure is necessary for insulation.

Some further suggestions for tray design are as follows: The tray should be thermoformed from a high temperature melting polymer or coextruded set of polymers. Among the suitable candidates are:

polypropylene

polyvinylidene chloride

nylon

ethylene-vinyl alcohol.

Insulation for the heat sensitive food components can be provided by a foamed plastic insert, such as foamed polypropylene. This may be best provided as a preformed and filled separate compartment insert designed to minimize heat transfer. Thermoforming should include both vacuum and plug assist since thick walls may be used. Consideration should also be given to the use of aluminum foil as an overwrap to extend shelf life when low-barrier plastics are used for the tray.

Table 7. Simulation with an Insulated Peach Container and with Peach-z Being 10 C^{O}

Different Initial Temperatures

		Chile Con Carne	White Rice	Peach Slices
z	(C^{O})	10	10	10
f_h	(h)	0.442	0.472	1.234
f_c	[h (min)]	0.596	0.988	1.436
j_h		1.235	1.375	1.044
j_c		1.209	1.431	1.064
T_o	(^{O}C)	18.33	26.67	23.06
T_1	(^{O}C)	120	120	120
T_w	(^{O}C)	11.7	11.7	11.7
t_b	[h(min)]	0.818(49.098)	0.818(49.072)	0.817(49.023)
F_p	[h(min)]	0.125(7.5)	0.125(7.5)	$8.33x10^{4}$(0.50)
I_n	(mm)	-	-	1.65

Same Initial Temperatures

		Chili Corn Carne	White Rice	Peach Slices
z	(C^{O})	10	10	10
f_h	(h)	0.442	0.472	1.234
f_c	(h)	0.596	0.388	1.436
j_h		1.235	1.375	1.044
j_c		1.209	1.431	1.064
T_o	(^{O}C)	23.89	23.89	23.89
T_1	(^{O}C)	120	120	120
T_w	(^{O}C)	11.7	11.7	11.7
t_b	[h(min)]	0.808(48.452)	0.824(49.431)	0.812(48.716)
F_p	[h(min)]	0.125(7.5)	0.125(7.5)	$8.33x10^{-4}$(0.050)
I_n	(mm)	-	-	1.65

Table 8. Simulation with an Insulated Peach Container and with Peach-z Being 11.9 C^{o}

Different Initial Temperature

	Chili Con Carne	White Rice	Peach Slices
z (C^{o})	10	10	10
f_h (h)	0.442	0.472	1.219
f_c (h)	0.596	0.988	1.421
j_h	1.235	1.375	1.045
j_c	1.209	1.431	1.965
T_o (^{o}C)	18.33	26.67	23.89
T_1 (^{o}C)	120	120	120
T_w (^{o}C)	11.7	11.7	11.7
t_b [h(min)]	0.818(49.098)	0.818(49.092)	0.817(49.029)
F_p [h(min)]	0.125(7.5)	0.125(7.5)	2.08×10^{-3}(0.152)
I_n (mm)	-	-	1.62

Same Initial Temperature

	Chili Con Carne	White Rice	Peach Slices
z (C^{o})	10	10	11.96
f_h (h)	0.442	0.472	1.219
f_c (h)	0.596	0.388	1.421
j_h	1.235	1.375	1.045
j_c	1.209	1.431	1.065
T_o (^{o}C)	23.89	23.89	23.89
T_1 (^{o}C)	120	120	120
T_w (^{o}C)	11.7	11.7	11.7
t_b [h(min)]	0.808(48.452)	0.824(49.431)	0.817(49.029)
F_p [h(min)]	0.125(7.5)	0.125(7.5)	2.08×10^{-3}(0.152)
I_n (mm)	-	-	1.62

The application of insulation material on the peach container introduces additional statistical variability in the process lethality. Therefore, a larger safety factor will be required for the simultaneous processing of the three foods.

CONCLUSIONS

Through the computer simulations, it was found that the simultaneous processing of the three foods in one sterilizer was not possible by adjusting their initial temperatures and holding the temperature of a heating medium. However, the simultaneous processing is possible when the peach container is insulated. The insulation thickness was slightly dependent on the peach-z value.

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GLOSSARY

Bi Biot number = hl/k.

Bi_H = hH/k.

C_p Specific heat of food.

f Slope index of semilogarithmic temperature history curve.

F_p Sterilizing value.

H One half of effective inside height of container whose shape is approximated by a brick shape.

h Overall coefficient for heat transfer from heat exchange medium to food surface.

I_n Insulation thickness.

j Empirical heat penetration parameter related to the intercept of semilogarithmic temperature history curve.

k Thermal conductivity.

L One half of effective inside side dimension of container whose shape is approximated by a brick shape.

l Half thickness of a plate.

n Refractive index.

P_1 First positive root of $p \tan p = Bi$.

S_L = L/H.

S_W = W/H.

T Temperature.

T_a Temperature of surrounding heat exchange medium.

T_i Food temperature at the beginning of heating phase (identical to T_o) or at the beginning of cooling phase.

T_o Food temperature at beginning of thermal process.

T_1	Holding temperature of heating medium.
T_W	Temperature of cooling water.
t	Time.
t_1	Heating or cooling time at the beginning of a linear part in semilogarithmic temperature history curve.
U	Overall coefficient for heat transfer through insulated container wall.
W	One half of effective, inside side dimension of container whose shape is approximated by a brick.
x	Location variable. Distance measured from central plane of infinite plate.
z	Slope index of thermal death time curve.
α	Thermal diffusivity.
ρ	Density.
$f(\ )$	Function defined by eq. 18.

Subscript

b	Processing phase of process (constant heating phase).
c	Cooling phase of process.
end	End of process (end of Cooling phase).
H	Related to plate of thickness 2H.
h	Heating phase of process.
L	Related to plate of thickness 2L.
n	Insulation.
p	Rectangular parallelepiped.
r	Reference value.
up	Come-up heating.
1,2	First and second values, respectively.

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