AN ABSTRACT OF THE THESIS OF

Ricardo José Simpson-Rivera for the degree of Master of Science in Food Science and Technology presented on June 6, 1990.

Title: Optimization and Computer Control of Batch Retort Process Operations: Conduction-Heated Foods

Abstract approved: Dr. J. Antonio Torres

Several computer programs were developed to predict transient energy consumption, and to optimize and control on-line batch retort process operations for conduction-heated foods. Transient energy consumption restricted variable temperature profiles to those feasible without retort modifications. A transient heat energy balance was developed to account for the heat exchange between the can and the steam, and also for the mass and heat exchange between the retort and its environment. All three models were linked with an optimization technique, and used to implement a computer program to search for variable temperature profiles reducing process time. The search was restricted to processes with energy consumption, safety, and food quality similar to the one obtained with optimized constant retort-temperature processes. Depending upon product specifications, we found variable retort-temperature profiles reducing process time by 18 to 55 min. Hence, a change to variable retort-temperature processes could increase canning capacity by 20-50 %.

The computer control program is capable of automatically adjusting process time to compensate for any unexpected variation in retort temperature. The program calculates an integrated average F_o taking into account the accumulative lethality of the heating and the cooling period. The program was validated using several processes reported in the literature.

Optimization and Computer Control of Batch Retort Process Operations: Conduction-Heated Foods

by

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submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Completed June 6, 1990

Commencement June, 1991

APPROVED:

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Date thesis is presented: June 6, 1990

ACKNOWLEDGMENTS

I dedicate this work to my wife, Anita Carolina, who deserves all my love. I must acknowledge with deep appreciation her indispensable aid and encouragement.

My love and admiration for always...

... and to my children Jose Ignacio y María Jesus for their lovely innocence and purity.

I express my gratitude to my major professor, Dr. Jose Antonio Torres, for his guidance in my studies.

I also express my appreciation to the members of my thesis committee, Dr.Ezra Tice, Dr. Joseph McGuire and Dr. Joel Davis for their critical evaluation of my thesis work.

Sincere gratitude and appreciation is expressed to the faculty and staff of the Department of Food Science and Technology.

Appreciation is extended to the Catholic University of Valparaiso, Chile.

Special thanks to my friends Marlene, Yerko, Rodrigo, Mauricio, Sergio, Hugo, Miriam, Silvana, Ernesto, Eugenia Ines, Pedro, Monica and Jorge.

My deep appreciation to Karl Drobnic for his very special friendship.

My deep gratitude to my parents, Jorge and Carmen and also to my brothers Jorge, Christian and to my special sister Maria Isabel.

AUTHORS CONTRIBUTIONS

Mathematical Models and Logic for the Computer Control of Batch Retort Processes Operation: Conduction-Heated Foods

Ricardo Simpson, M.S. graduate student, implemented and validated the numerical method to solve the heat transfer equation and designed improvements to computer control logic reported in the literature. **Sergio Almonacid**, Visiting Scientist from Catholic U. of Valparaíso, designed and implemented the methodology to evaluate the integrated lethality methodology used in this project and contributed to the improvements of the computer control logic. **J. Antonio Torres**, Assistant Professor, served as supervisor and principal investigator for the project.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Optimization and Computer Control of Batch Retort Process Operations: Conduction-heated foods

INTRODUCTION

General considerations

The objective of the canned food industry is to produce safe, high-quality, wholesome food at a competitive price. However, heating requirements affect quality. In general, canned foods cannot be at the same time infinitely safe, high in quality, and low in cost. The more severe the sterilization process, the greater will be the degradation of food quality, both in consumer appeal (color, flavor, texture) and in loss of nutritional factors.

Commercial sterilization processes are those which inactivate those microorganisms, or their spores, causing spoilage or health hazard problems under food storage conditions. Food products are not sterile in the strictest sense of the word since viable spores survive but cannot germinate under the conditions of storage. Most commercially sterile foods are packaged under conditions which insure anaerobic conditions because: (1) spores of anaerobic organisms are generally less heat resistant than spores of aerobic organisms resulting in less severe thermal processes; (2) it is relatively easy to maintain anaerobic conditions; and, (3) oxidative reactions which could occur during heating are minimized. The traditional packaging system for maintaining anaerobic conditions is the can and the glass container. More recently plastic and aluminum foil pouches have been utilized.

The thermal death of microorganisms follows first order kinetics, i.e., the concentration of microorganisms approaches zero asymptotically but never reaches this value. The sterilization process for canned foods, therefore, is a compromise that produces adequately safe products with minimum quality changes. Obviously the compromise should also incorporate energy consumption and processing time. Finally the situation for each cannery will be different and will need to take into account, and simultaneously, all the processing lines in the plant.

Quality retention

The effect of the heat sterilization process on food quality and nutritive value retention has been a major concern of food processors since Nicholas Appert first discovered the art of canning in 1809. One result of these efforts has been the development of aseptic canning methods, which utilize the benefits of high temperature-short time processing. These methods, however, do not apply to solid-packed foods.

Improvements in thermal processing with respect to nutrient retention, product quality, product safety, and process throughput have not been a result of systematic investigation. Only recently have "optimization" procedures been applied to this problem. Interestingly, any change of process parameters toward maximizing throughput and quality, generally resulted in improved nutrient retention.

Energy consumption

Heightened awareness that nonrenewable energy sources are limited in long-term availability has underscored the need for critical evaluation of energy requirements of the various unit operations used in a food processing plant. Processing equipment designed when energy was plentiful is becoming expensive to operate at current energy cost; and higher costs are projected for the future. The various unit operations in a processing plant must therefore be critically analyzed in terms of energy requirements.

The energy analysis of food sterilization is useful in two respects. First, it provides quantitative information on the energy requirements needed to design the energy generating and delivery system, and second, it evaluates the modes of energy loss. Information obtained from the energy analysis can be used for quantifying energy conservation practices.

Computer control

Rapid developments in the computer industry have brought about the availability of a wide variety of low-cost microprocessors and programmable controllers along with related peripheral equipment which have advanced the state-of-the-art in computer-based process-control technology to a considerable extent. Electronic digital systems for the control of process equipment are already in place in the power, chemical, petrochemical, steel, rubber, plastics, and textile industries (Jutila, 1981). Although the food industry continues to lag behind these other industries in the use of advanced control technology, food processors are beginning to realize the potential benefits of advanced process-control systems as they seek ways to reduce processing costs. This is particularly true of the food canning industry, which produces commodity products that face stiff price competition in the marketplace. Faced with increasing cost for labor, energy, and raw materials, with little flexibility in selling prices, food canners are being forced to upgrade processing operations to remain profitable.

Research goals and objectives

The goal of our research efforts has been the identification of optimum processes using physically valid variable time-retort temperature. This goal was achieved by identifying the following objectives:

1. To develop a transient energy model for batch retort process operations that allows the identification of physically-valid time-retort temperature profiles.
2. To identify physically valid time-retort temperature profiles that minimize energy consumption and total process time while maintaining a specified quality and process lethality.
3. To develop mathematical models and a logic for the on-line control of thermal processes designed with the integrated average F_o concept.

LITERATURE REVIEW

Mathematical modeling

A model is defined by Webster's Collegiate Dictionary as "a miniature representation of a thing". A mathematical model is a representation using symbols which can be manipulated by the law of mathematics. If the "thing" represented is a sterilization process, then the symbols represent such properties as temperature, distance, and concentration of microorganisms and quality factors (nutrients, color, texture, etc.). The manipulation laws are those governing heat transfer and biochemical kinetics.

The general mathematical model for food sterilization might be contrasted with more traditional methods of process analysis, such as the classic formulas (Ball and Olson, 1957; Stumbo, 1973). First, it is important to note that these methods are not so much models as they are calculation approaches. That is, they generally rely on empirical data, such as heat penetration curves, rather than on the more fundamental heat transfer equation. The traditional methods are pragmatic, practical, and oriented toward the commercial user in contrast to the more theoretical and philosophical orientation of mathematical models. To achieve convenience, the traditional methods have made certain assumptions regarding the kinetic and transport processes. For example, they most often focus on the slowest heating element of a container rather than attempt to integrate lethality over the entire volume. In general a fundamentally based mathematical model is more powerful and therefore more useful than an empirically based approach. Additional reasons for constructing a model based on theoretical fundamentals include:

1. A good model can replace experiments which may be difficult to perform or deliver results of dubious value.
2. A model can guide research by illuminating assumptions which need checking and by expediting the study of the consequences of various assumptions.
3. A model can aid in process scale-up; this may be its most common application in process engineering.
4. Finally, we cannot neglect the intellectual satisfaction of understanding a process so well that one's model of it is accurate.

In general, the procedures for formulating a mathematical model are well known to most physical scientists and engineers. For some reason, those who deal with foods seem to forget how easy it really is when it comes to food processes. Perhaps it was not so easy before computers were so powerful and widely available, but there is little excuse today.

Mathematical procedures for heat sterilization processes

It is important to distinguish between mathematical modelling and mere computation. Although both require calculations, the purpose of mathematical modelling is to execute calculations that improve our understanding of an actual process. Sterilization, one of the most important unit operations used in the food industry, is a good example of the benefits of mathematical modelling. The mathematical equations for the physical laws involved are all well known and supported by a large volume of experimental data. Moreover, experimentation with mathematical models offers practical and economic advantages over the physical system which is often inconvenient to test (Clark, 1978).

The mathematical determination of a sterilization process requires temperature and kinetic information, i.e. microbial lethality and destruction rate of quality factors. Food temperature can be measured directly or predicted theoretically with excellent accuracy (Manson *et al.*, 1974). Microbial lethality is mathematically approximated by the following equation (Charm, 1971):

$$D_r/D = 10^{(T - Tr)/z} \qquad (1)$$

The quality factor degradation usually follows first-order reaction kinetics and the temperature effect on the rate constant usually follows the Arrhenius model (Clark, 1978).

The estimation of proper heat processes is based on the calculation of a sterilizing value, F_o, which can be computed as follows (Charm, 1971):

$$F_o = \int 10^{(T - Tr)/z}\, dt \qquad (2)$$

Several methods have been reported for sterilization calculations and can be classified as shown in Figs. 1 and 2 (Hayakawa, 1978). Group I procedures are based on the evaluation of the lethality at the slowest heating point (Fig. 1) while those in

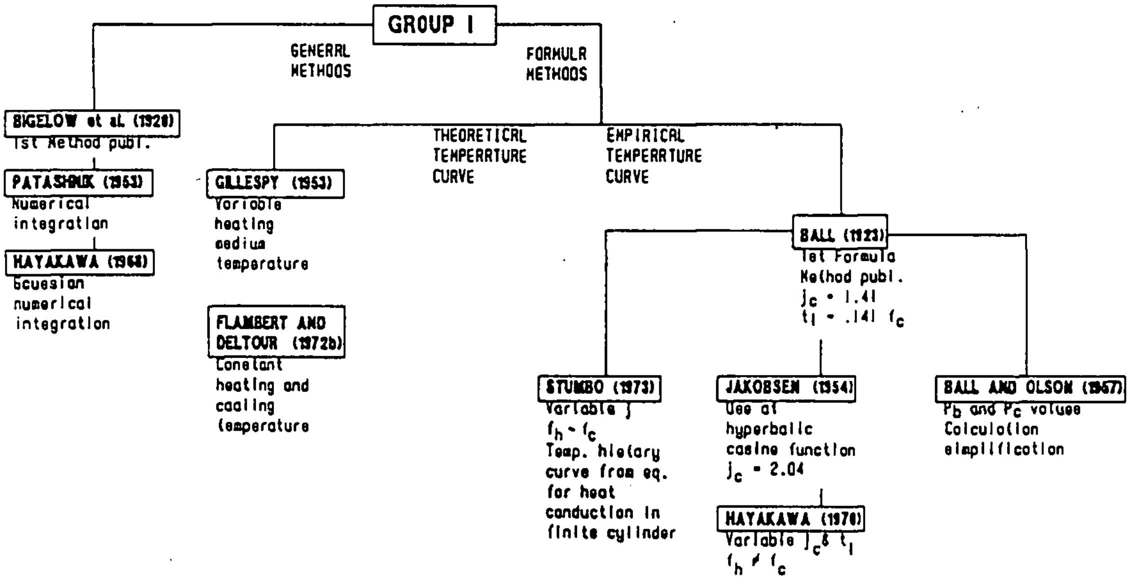

Figure 1.

Methods of evaluation for the estimation of lethality at the slowest heating point

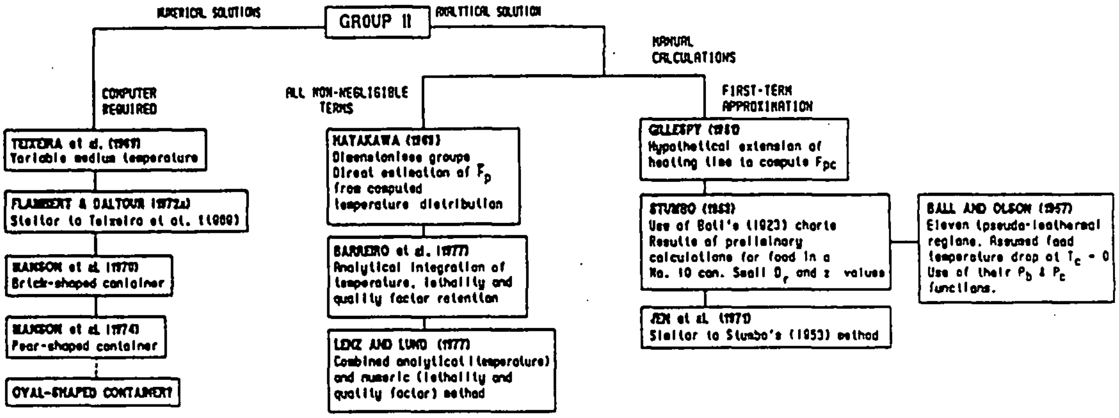

Figure 2.

Methods of evaluation for the estimation of the integrated mass average lethality group II are based on the evaluation of integrated lethality for the whole container (Fig. 2). The latter have the advantage of an easy incorporation of estimates for nutrient retention (or any other quality factor) and can also include energy consumption calculations. This type of information is extremely necessary in today's highly competitive markets. Other possible and rather simple modelling options include process deviation considerations.

Group I (Fig. 1) procedures can be divided into general methods and formula methods. General methods usually do not provide a means of predicting the food time-temperature relation. On the other hand, formula methods have built-in means for this prediction. General methods are the most frequently used procedures of estimating the lethality of a process. Experimental heat penetration data are used directly in lethality calculations without any assumptions on the time-temperature relation.

Formula methods may be subdivided into two subgroups depending upon the nature of the formulas used for predicting the temperature history curve of a food undergoing a heat process: those based on the use of empirical formulas and those based on the use of theoretical formulas. In empirical methods, food temperatures collected during heat processing are usually plotted on semi-log paper, on which a log scale represents temperature differences between food and the surrounding heating or cooling medium while a linear scale represents heating or cooling time. The first empirical method was developed by Ball (1923) and is still widely used by many processors. Several modifications have been published to increase its flexibility and accuracy (Fig. 1).

Several researchers have developed theoretical formulas to predict the heat transfer process in a can. Most of these methods are applicable only to cylindrical cans of solid food (i.e. foods heated only by conduction). The first method developed assumed that the food was initially at a uniform temperature, that the thermophysical properties of the food were independent of location and temperature, that the surface temperature of the food was identical to the surrounding medium temperature at any time during the process, and finally that there was no can headspace (Hayakawa, 1978). Later methods have removed some of these restrictions (e.g. Hayakawa and Ball, 1971).

Group II methods (Fig. 2) are based on integrated lethality (F_o) and have the advantage that they can be adapted to include prediction of nutrient(s) retention. All published procedures have included solutions of a heat-conduction equation to estimate transient-state temperature distributions. To estimate the mass average concentration of a vulnerable factor in cylindrical cans of solid food, Teixeira *et al.* (1969b) determined transient-state temperature distributions in the food by numerically solving a heat-conduction equation through the application of a finite-difference technique. Because of the massive calculations required they used a digital computer for this estimation.

Manson *et al.* (1970) developed a method for estimating the mass average sterilizing value of a thermal process applied to solid food in brick-shaped containers. Their general approach is similar to the one used by Teixeira *et al.* (1969b). Manson *et al.* (1974) also developed an interesting method for estimating thermal processes applied to solid foods in pear-shaped cans usually used for packing cured fresh ham. More recently, Simpson *et al.* (1989b) described a mathematical model for the sterilization of conduction-heated foods in oval-shaped containers to estimate the mass-average bacterial lethality and the retention of a quality factor with known kinetics of destruction.

Maximizing quality retention

The optimization of the quality retention in thermally processed foods is based on the differences in temperature dependence between the spore inactivation and the changes in the sensory and nutritional quality of a food. The markedly higher temperature dependence of the spore inactivation suggests that processing at high temperature for a shorter time (HTST-processing) is advantageous in minimizing the heat-induced quality changes (Lund, 1977).

The advantages of HTST-processing have been both theoretically and experimentally shown. The limited possibilities of utilizing the HTST-principle in solid foods packed in cans of normal sizes, due to the slow conduction-heating, have also been demonstrated. Teixeira *et al.* (1969b) found that the optimal processing temperature for maximal thiamin retention in cylindrical cans was close to 119°C. To describe the sensory quality changes during heat processing Mansfield (1962) proposed a cook-value (C-value) defined similar to the well known F_o-value (Ball and Olson, 1957):

$$C = \int_0^t 10^{(T-100)/z_c} \, dt \qquad (3)$$

Experimental determination of the temperature dependence of the C-value (z_c) has been presented by Ohlsson (1979b).

Thermal processing affects the sensory quality of foods in both a positive and negative direction. These changes are related to chemical reactions in the foods, which generally have a temperature dependence that can be described by a z-value of 33°C (Lund, 1977). The z-value corresponds to the temperature shift needed for a tenfold change in the rate of a chemical reaction or a biological inactivation. The inactivation of bacterial spores, with a z-value of around 10°C, is generally the basis for the duration of the sterilization process.

Teixeira *et al.* (1969b) developed a digital computer for the determination of bacterial lethality and nutrient retention in conduction-heated foods in cylindrical cans. They found that an increase in the temperature dependence of the nutrient thermal degradation rate, z, shifted the optimum process to higher temperatures, and an increase in the nutrient decimal reduction time, D, simply raised the overall level of retention without affecting the process temperature that would yield an optimum retention.

Teixeira *et al.* (1975) and Barreiro *et al.* (1979) carried out investigations of various container geometries. The investigations were restricted to circular cylinders of various height-to-diameter ratios (L/D) enclosing a constant volume equal to that of a No.2 can. The results showed a strong effect of the can geometry on the process time and nutrient (thiamin) retention. These advantages, however, might be offset by increased container costs relative to the greater surface area required in the various geometries.

Energy consumption

One of the first theoretical approaches to energy consumption calculation in canning was carried out by Singh (1977) who described how to determine a thermal energy balance for a continuous atmospheric retort. Bhowmik and Hayakawa (1988) examined three different types of retort temperature policies for nutrient retention and steam consumption by using 211x300 cans in a food simulator. Computer programs were developed to estimate maximum nutrient retention for selected variable temperature profiles. They noted that ramp and single square wave temperature profiles produced slightly higher nutrient retention while consuming slightly less steam in comparison to a process using a standard constant temperature profile.

Barreiro *et al.* (1984) developed a procedure to minimize the energy consumption of batch food sterilizing processes. Application of the procedure was illustrated for pea puree packed in 307x409 cans and heat processed in a pilot-scale retort at six different time-temperature combinations providing the same lethal value. An optimum value of 121.8°C for 64.8 minutes was found to correspond to minimum energy consumption.

Optimization Techniques

Several mathematical optimization methods are available in the food engineering literature. One approach is the Complex Optimization method which is a direct search technique (Beveridge and Schechter, 1970). This method can be used for the optimization of dynamic systems. A dynamic optimization problem involves the minimization (or maximization) of a mathematical function which is itself a function of time. This can be described mathematically as follows:

$$W = f(e(t)) \qquad \text{where } t = \text{time} \tag{4}$$

The problem is therefore reduced to find e(t) which optimizes the function W. The problem can be solved by assuming that the time function e(t) is a function with unknown values for its parameters. This reduces the problem to a search for the parameters for the function of time that optimizes the function W. Among the most frequently methods applied to the solution of dynamic optimization are:

1. Calculus of variations
2. Bellman's principle of optimality (dynamic programming)
3. Pontryagin's maximum principle, and
4. Complex method

Saguy and Karel (1979) used the maximum principle theory to optimize thiamin retention during sterilization of conduction-heated canned food using variable retort-temperature processes. The optimal retort temperature profile determined by this procedure improved thiamin retention by more than 2% as compared with other methods, and showed that a single solution for the optimum temperature profile exists. Teixeira *et al.* (1975) applied trial-and-error search techniques to determine the "best" conditions for improving thiamin retention in thermally processed food. Even though the work presented by Saguy and Karel (1979) has a more sophisticated and theoretical approach than the one utilized by Teixeira *et al.* (1975), both efforts are limited to optimization process with a single objective function. A more desirable optimization process should take into account product quality, energy consumption and processing time.

NOMENCLATURE

C = unit of cook

D = decimal reduction time at any temperature

D_r = decimal reduction time at reference temperature

F_0 = sterilizing value of heat process

F_{pc} = sterilizing value of heat process

$\overline{F_p}$ = mass average sterilizing value of heat process

f = slope index of heating in cooling curve

j = intercept coefficient of heating or cooling curve

P = parameter, introduced by Ball and Olson (1957), related to the sterilizing value of heat process

t = processing time

t_c = heating time

T = temperature

T_r = reference temperature

z = slope index of thermal death time curve

Dynamic Simulation of Energy Consumption and Optimization of Thermal Processes with Variable Temperature Profile

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ABSTRACT

A general model was developed to simulate batch retort operations for conduction-heated foods. The model uses a heat transfer equation for heat conduction in cylindrical cans, first order kinetics for microbial inactivation, first order kinetics for the destruction of a quality factor and a transient energy balance for the estimation of steam consumption. The inclusion of a transient energy balance equation allowed the identification of physically valid time-retort temperature profiles without direct experimentation. The Complex method and the sterilization model were combined to find physically valid time-temperature profiles that minimize energy consumption or total process time for a given lethality process and quality retention. Depending upon product specifications, we found variable retort temperature profiles reducing process time by 18 to 55 minutes. Hence, a change from constant to variable retort temperature could increase canning capacity by 20-50%.

INTRODUCTION

Food retort processing is an energy intensive operation. Furthermore, the varying quantity of available raw materials affects the efficient use of canning facilities. After a peak season, the availability of raw materials decreases significantly, reducing the incentive to increase plant capacity.

Mathematical models exist to find the effect on nutrient retention, energy consumption and food safety of constant and variable retort temperature processing conditions (Teixeira *et al.*, 1969b; Ohlsson, 1980a,b; Simpson *et al.*, 1989a,b). However, mathematical models to verify the physical validity of variable temperature profiles have not been developed. Temperature profiles could be proposed which are not feasible without retort cooling or steam removal devices (Saguy and Karel, 1979). Although several energy analyses of food sterilization processes have been reported, no published procedure for transient energy balance have been found (Barreiro *et al.*, 1984; Bhowmik *et al.*, 1985).

This paper presents a methodology to identify physically-valid, variable retort temperature profiles using a transient energy model for batch retort process operations. The model was used to examine the physical validity of published variable time-retort temperature profiles. In the past, the feasibility of the process could only be confirmed by direct experimentation. Finally, an optimization technique was used to identify physically valid time-retort temperature profiles that minimize energy consumption or total process time while maintaining a specified quality and process lethality.

METHODOLOGY

Development of model

A general model for commercial sterilization was developed by examining the following phenomena and their governing equations:

(a) Unsteady state conduction heat transfer equation with thermophysical properties independent of temperature:

$$\frac{1}{\alpha}\frac{\partial T}{\partial \theta} = \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2} + \frac{\partial^2 T}{\partial z^2} \tag{5}$$

(b) Kinetics of cell destruction

$$\frac{dN}{d\theta} = -kN; \tag{6}$$

$$k = k(T)$$

(c) Kinetics of destruction for a quality factor

$$\frac{dC_i}{d\theta} = k_{ci}C_i; \quad i = 1,2,\ldots w \tag{7}$$

with $k_{ci} = k_{ci}(T)$

(d) Transient energy balance for a system which is in the case defined as the autoclave, the cans without the food product, and the steam and its condensate. By definition of the system there is no work term and the heat transfer terms include radiation and convection to the plant environment, and heat transfer to the food in the can. Therefore, we can express the first law of thermodynamics as:

$$\left[\sum_{i=1}^{n} m_i \hat{H}i\right]_{in} - \left[\sum_{j=1}^{m} m_j \hat{H}_j\right]_{out} + \sum_{i=1}^{p} Q_i' = d(\hat{E}\ M)_{system}/d\theta \tag{8}$$

The previous equations were solved simultaneously using an explicit finite difference method for equation (1) with a time increment of 7.5 seconds (Teixeira *et al.*, 1969b). The calculation of microbial lethality, quality factor retention and energy consumption was performed as follows:

(a) Microbial lethality and quality retention

$$\frac{dN_{(r,z)}}{d\theta} = -k_{(r,z)} N_{(r,z)} \tag{9}$$

where $k_{(r,z)} = k_o \mathrm{EXP}(-E_a/RT_{(r,z)})$

This equation was integrated using a small time increment (7.5 seconds). The kinetic constant was evaluated using an average temperature during the time interval. The final expressions are

$$N_{(r,z)}^{\theta+\Delta\theta} = N_{(r,z)}^{\theta}\ \mathrm{EXP}\{k_0\ \ \Delta\theta\ \mathrm{EXP}(-E_a/RT_{(r,z)})\} \tag{10}$$

for microbial lethality. An analogous expression can be obtained for the quality factor:

$$C_{l(r,z)}^{\theta+\Delta\theta} = C_{l(r,z)}^{\theta}\mathrm{EXP}\{k_{c,l}^{\circ}\ \Delta\theta \mathrm{EXP}(-E_{a,cl}/RT_{(r,z)})\} \tag{11}$$

(b) The transient-energy balance equation was solved as follows:

$$(m_1'\hat{H}_1)_{in} - (m_1'\hat{H}_1)_{out} + Q_r' + Q_c' + Q_p' = d(\hat{E}\,M)_{system}/\,d\theta \tag{12}$$

where:

$$d(\hat{E}\,M)_{system}/d\theta = d(\hat{E}_1\,M_1 + \hat{E}_2\,M_2 + \hat{E}_3\,M_3)/d\theta \tag{13}$$

$$d(\hat{E}\,M)_{system}/d\theta = d(\hat{E}_1\,M_1)/d\theta + d(\hat{E}_2\,M_2)/d\theta + d(\hat{E}_3\,M_3)/d\theta \tag{14}$$

Therefore,

$$(m_1\hat{H}_1)_{in} - (m_1\hat{H}_1)_{out} + Q_r' + Q_c' + Q_p' = d(\hat{E}_1M_1)/d\theta + d(\hat{E}_2M_2)/d\theta + d(\hat{E}_3M_3)/d\theta \tag{15}$$

The steam consumption during each time interval (7.5 seconds) can be calculated using average properties as follows:

$$m_{vapor} = (m_1')_{in}\,\Delta\theta =$$

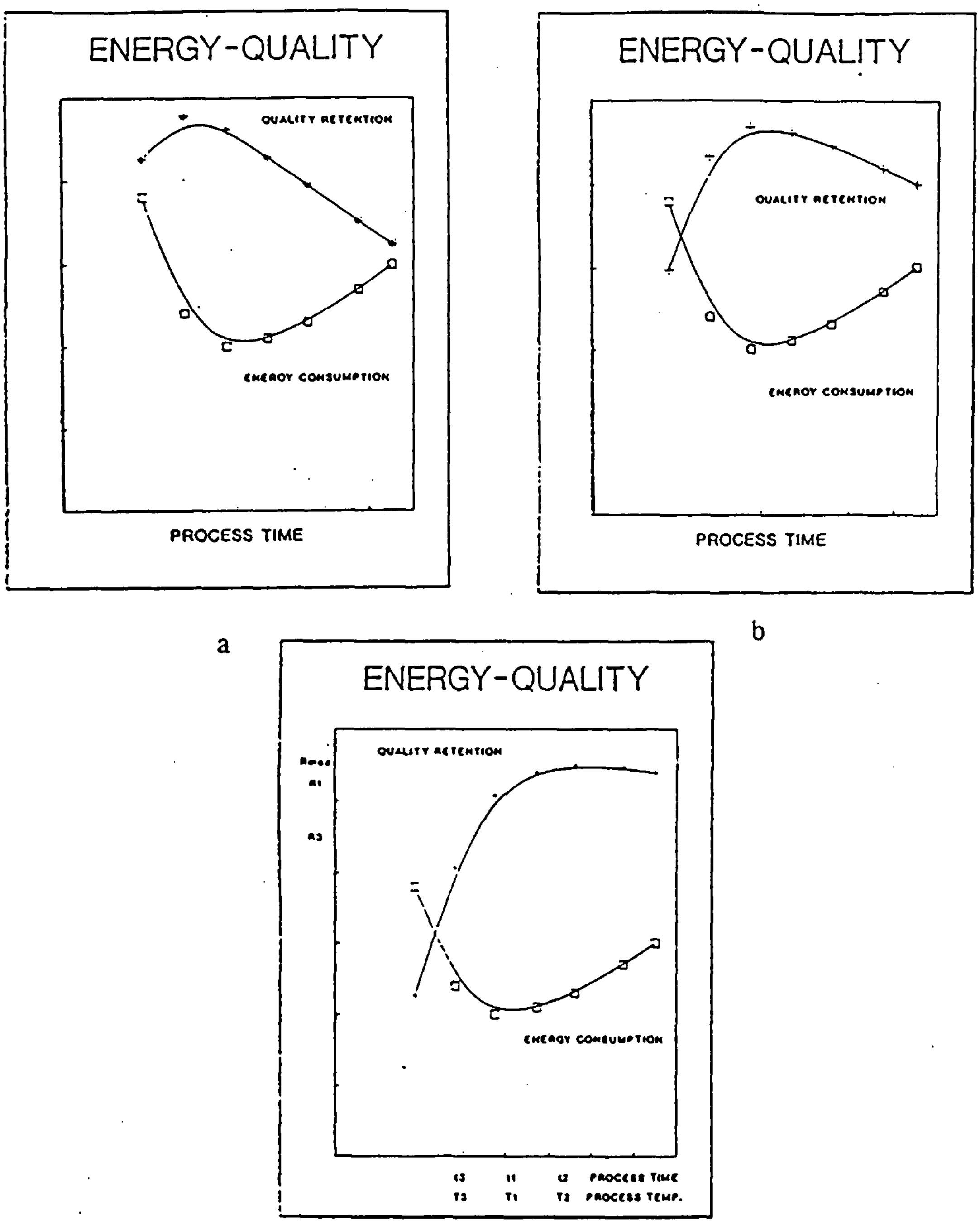
$$\frac{\Delta\hat{E}_1M_1 + \Delta\hat{E}_2M_2 + \Delta\hat{E}_3M_3 - \int_{\theta}^{\theta+\Delta\theta} Q'_R\,d\theta - \int_{\theta}^{\theta+\Delta\theta} Q'_C\,d\theta - \int_{\theta}^{\theta+\Delta\theta} Q'_P\,d\theta + (m'_1\,\hat{H}_{ave,1})_{out}\Delta\theta}{(\hat{H}_{average,\,1})_{in}} \tag{16}$$

Correlations, valid in the range of interest (105° - 135°C), were used to estimate the thermodynamic properties of steam and condensed water. Steam removed by bleeding ($(m_l')_{out}$) was calculated using the procedures described by Barreiro *et al.* (1984). The procedure described above was designed with the objective of identifying physically valid process and to compare the energy consumption of different retort temperature strategies. For this reason the calculation procedure does not need to include the energy consumption during the venting time. The characteristics of the retort assumed in these calculations are summarized in the Appendix and were obtained from Barreiro *et al.* (1984).

Optimization method

Three cases of quality factor retention and energy consumption as a function of retort temperature for sterilization processes with the same lethality effect are shown in Fig. 3. Figs. 3a and 3c show processes where maximum quality retention and minimum energy consumption do not coincide. Fig. 3b shows a process where the process temperature that maximizes quality retention and minimizes energy consumption is the same (temperature = T1; process time = t1).

The simultaneous optimization of quality retention, energy consumption and process time was accomplished as follows. First, optimum processes at constant temperature were identified independently for the quality factor and for the energy consumption. The best process should minimize process time using a physically-valid retort temperature profile retaining the same or higher concentration of the quality



a

b

c

Figure 3.

Schematic representation of quality retention and energy consumption for processes with the same lethality factor, and consuming the same or less energy than the best processes found at constant temperature.

The search for the optimum process was accomplished using the Complex method as follows (Fig. 3c). The best process from a quality factor point of view at constant temperature was identified as retort temperature T2, quality retention Rmax, and process time t2. The best process from and energy consumption point of view at constant temperature was identified as T1 with a retention R1 and process time t1. The search for the optimum process was begun by searching for a physically-valid retort temperature profile with a process time t1 maximizing quality retention and keeping Emin as a constraint for energy consumption. The search was stopped when the program found a process with the specified energy consumption and having at the same time a quality factor retention maximum at least equal to Rmax.

The search for an even better process was continued by searching for a process with retention Rmax and energy consumption Emin but now with t3 as process time. The t3 minutes process at constant temperature had a quality retention $R3 < Rmax$ and an energy consumption $E3 > Emin$ (Fig. 3c). The optimization program was run with energy consumption (E3) as a constraint and used to maximize quality retention. The program was stopped when it found a physically valid process with $R \geq Rmax$ and $E \leq E3$. Second, quality retention was used as a constraint ($R \geq Rmax$) to minimize energy consumption. The program was stopped when $R > Rmax$ and $E \leq Emin$ with t3 minutes as a process time. The search was continued by repeating the above procedure. Further details of the application of the Complex method are given in the Appendix I.

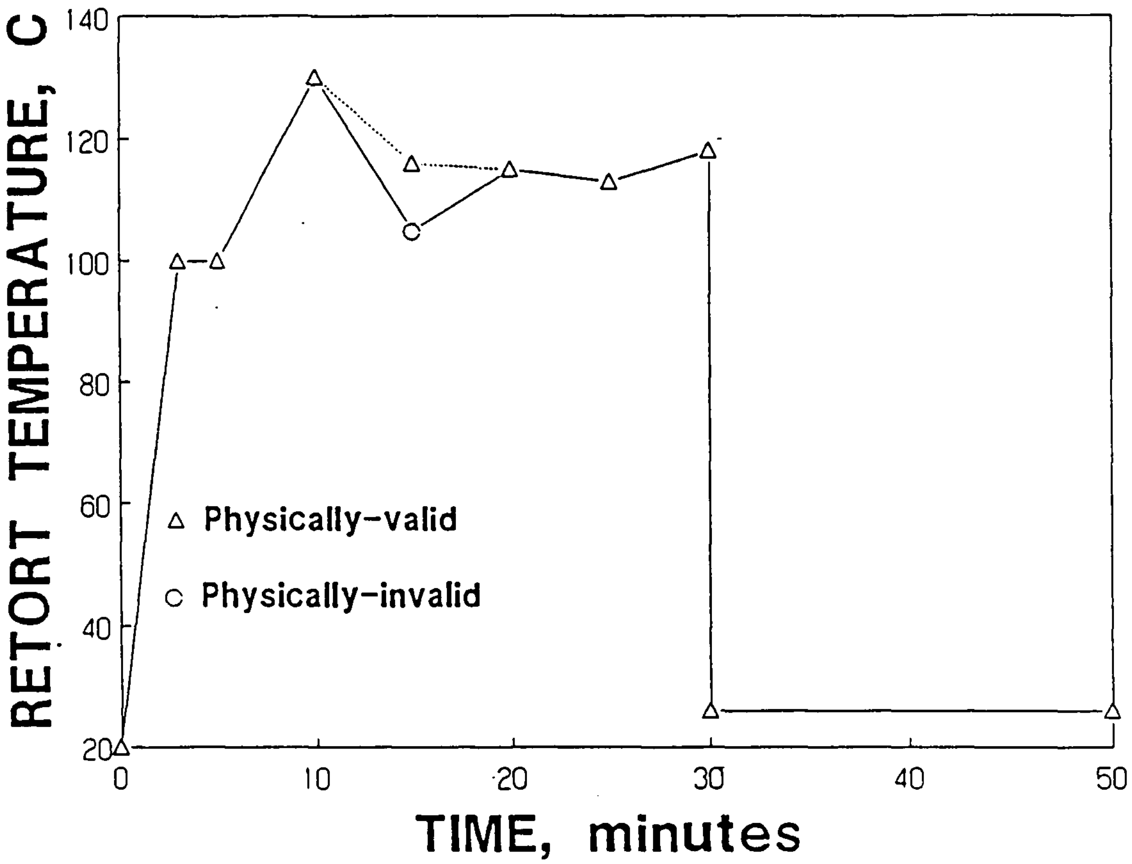


Figure 4.

Two time-temperature profiles for a retort process operation

RESULTS

Identification of physically valid time-temperature profiles

A changing temperature profile was selected to highlight the advantage of having a model that incorporates a transient energy balance equation. The process chosen was expected to be physically-invalid (Fig.4). Steam consumption as a function of time and calculated with the model showed that during the time period between 13 and 16 minutes, the steam consumption was negative (Fig. 5). In other words, the operation of this particular autoclave for the time-temperature profile specified would require not only closing the steam valve but also to eliminate heat by direct removal of steam mass or use of a cooling device.

The computer-implemented model was also used to find the temperature at time 15 minutes that would assure that no negative steam consumption occurred. In the original temperature profile, the temperature dropped from 130°C at time 10 minutes to 105°C at time 15 minutes. We found that the second temperature should be no lower than 116°C. The physically valid temperature profile and the corresponding steam consumption are shown in Figs. 4 and 5, respectively.

Evaluation of published variable temperature profiles

Published variable time temperature profiles were examined to determine if they could represent a case of negative steam consumption if used on a retort with the characteristics defined in the Appendix I. Fig. 6 shows a typical example of published variable time-temperature profiles. Fig. 7 shows the steam consumption after 10

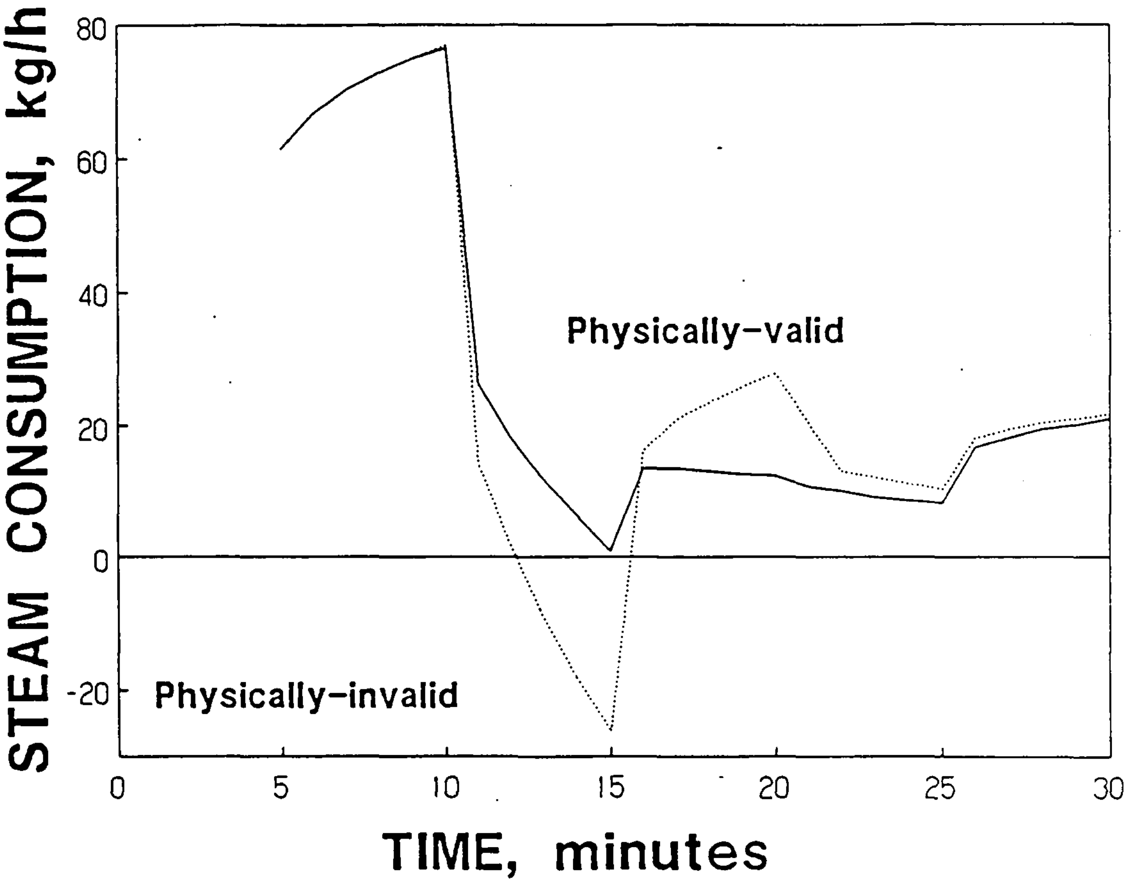


Figure 5.

Predicted flow steam consumption for two different time-temperature profiles

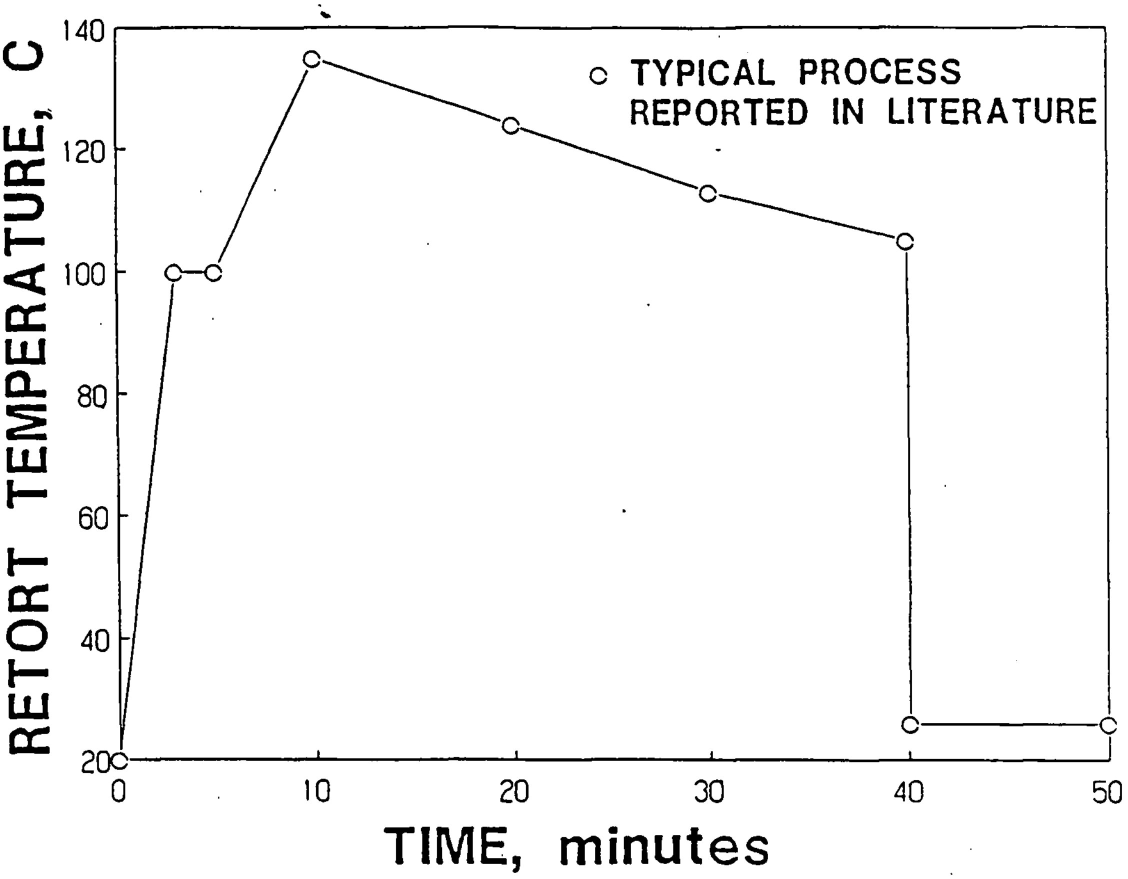


Figure 6.

A typical time-temperature profile reported in the literature

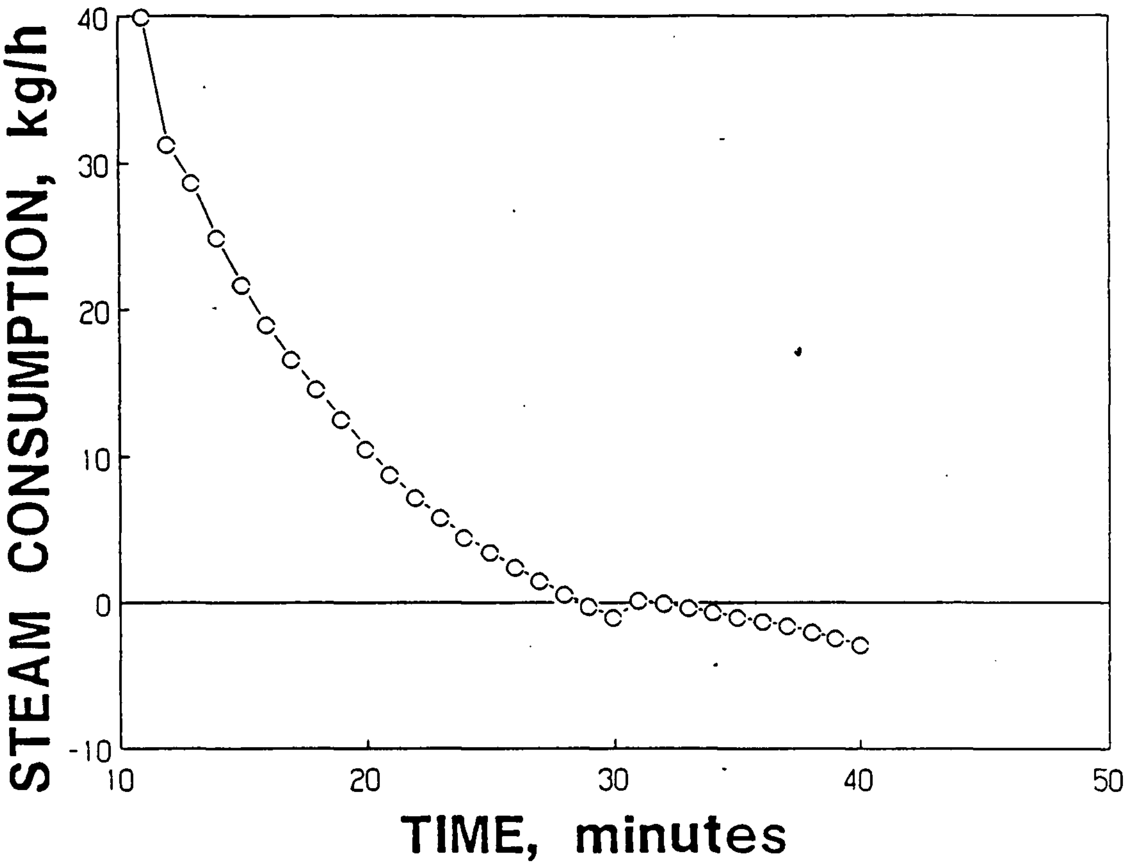


Figure 7.

Predicted flow steam consumption for a typical time-temperature profile reported in the literature minutes of retort operation and shows that after 30 to 40 minutes time period the steam consumption was negative.

It is important to highlight that steam consumption depends not only on the time-temperature profile but also on the characteristics of the food product and the autoclave (size, heat irradiation coefficient,etc.).

Process optimization

The effect on the retention of three quality factors, and the corresponding energy consumption, of equivalent lethality processes at different but constant retort temperature are shown in Fig. 8. A particular case occurs when $Z = 25°C$, because the retort temperature maximizing quality retention (46.8% at 122.15°C, 75 minutes heating time) also minimizes energy consumption ($1.2x10^8$ Joules). The optimization procedure identified a 70 minutes variable heating temperature process with the same energy consumption and quality retention (Table 1). An attempt to further reduce the process time identified a 56 minutes process with the same energy consumption but with a slightly lower nutrient retention, 44.2% instead of 46.8% (Table 1).

A more general process optimization situation results when $Z = 16.66°C$ (Fig. 8). The retort temperature that maximizes quality retention is different from the retort temperature that minimizes energy consumption. The optimization search procedure was started with a constant temperature process of 122.15°C (Table 1). It was not possible to find a physically-valid process at 122.15°C consuming $1.2x10^8$ Joules and retaining 55% of the quality factor. The search gave the following results, an energy

Table 1.

Process optimization for three different quality factors

a. Quality retention and energy consumption for three different quality factors for processes with equivalent lethality at constant temperature

		Nutrient Retention			
		Case			
		1	2	3	Energy
Process Time	Retort Temperature	Z=25°C D=188.7min	Z=16.66°C D=202min	Z=33.33°C D=202min	Consumption (Joule)
37	145.07	29.8	22.6	38.8	1.38x10^{8}
56	129.01	43.4	40.7	47.4	1.24x10^{8}
75	122.15	46.8	50.8	47.5	1.20x10^{8}
94	118.51	46.2	54.0	45.0	1.21x10^{8}
112	116.25	44.7	55.0	42.3	1.23x10^{8}
135	114.36	42.0	54.6	38.5	1.27x10^{8}
150	113.47	40.1	53.9	36.1	1.30x10^{8}

b. Nutrient retention and energy consumption for variable temperature processes with best temperature profiles. Calculations for the three quality factors described above.

Case	Process time, min	Retort Temperature	Nutrient Retention	Energy Consumption (Joule)
1	56	Best profile	44.2	1.20x10^{8}
2	56	Best profile	41.3	1.20x10^{8}
3	56	Best profile	48.1	1.20x10^{8}

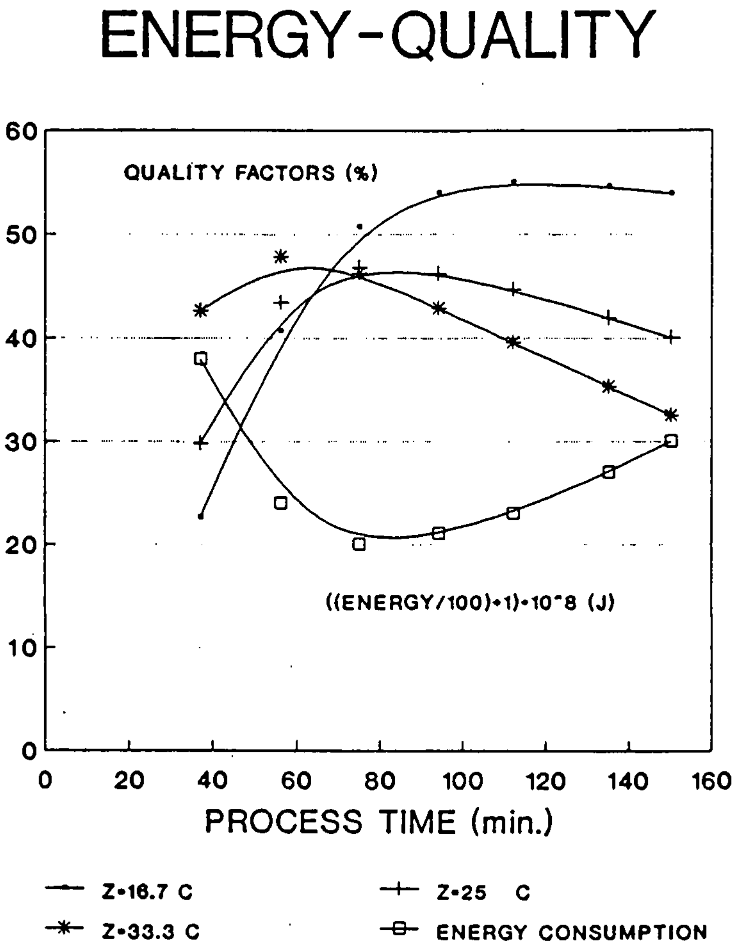


Figure 8.

Quality retention and energy consumption for three different factors for processes with the same lethality consumption of $1.2\text{x}10^8$ Joules and a 51.3% quality factor retention (Table 1). Nevertheless, the search to reduce process time was continued. The search for a 56 minutes variable retort temperature profile resulted again in the same energy consumption, but the quality factor retention was only 41.3%.

The case for Z = 33.33°C is analogous to the situation when Z = 16.66°C (Fig. 8). In this case the process time was not only reduced from 75 to 56 minutes but the program found also a retort temperature profile that maintained the minimum energy consumption and maximum quality factor retention of the constant temperature process (Table 1).

CONCLUSIONS

The use of a transient energy model has shown that variable temperature profiles can be used without retort modifications. Combining the above procedure and the Complex method, variable temperature profiles were identified that reduce process time by 18 to 55 minutes depending upon product and process specifications. This resulted in a 20 to 50% processing output increase. The implementation of these temperature profiles could be facilitated by the development of on-line computer control programs. Automatic control is needed to minimize differences between the actual and the specified variable retort temperature process.

The optimization methodology is particularly useful for processes where the constant retort temperatures for maximum quality retention and minimum energy consumption do not coincide. With the methodology developed in this paper the processor has the opportunity to find a variable retort-temperature process with the maximum quality retention and minimum energy consumption possible for the constant temperature process, and at the same time use less process time.

The energy consumption profiles obtained by the dynamic energy calculations could also be used to optimize the scheduling of retort operations and thus maximize the use of installed boiler capacity. Improved scheduling could also reduce the frequency of process deviations.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the contribution of Ms. Silvana Roncagliolo whose computer programming skills were essential for the completion of this project. This publication is the result of research sponsored in part by Oregon Sea Grant with funds from the National Oceanic and Atmospheric Administration, Office of Sea Grant, Department of Commerce, under grant no. NA85AA-D-SG094 (project no. #.ISG-6) and from appropriations made by the Oregon State Legislature.

NOMENCLATURE

N = number of viable cells per unit volume

$N(r,z)$ = microbial concentration in volume element (r,z)

E_a = activation energy (microbial inactivation)

$E_{a,c}$ = activation energy (destruction of quality factor)

C = concentration of quality factor (nutrient, color, etc.)

k = rate constant = f(temperature)

k^o, k_c^o = constants

k = first-order rate constant for cell destruction

k_c = first-order rate constant for factor destruction

R = universal gas constant

T = temperature at any point and any time θ

T_c = can center temperature

T_i = initial temperature

TR = retort temperature

(r,z) = cylindrical coordinates, radial axis and vertical direction

z = slope index of microbial death time curve

Z = slope index of quality factor destruction rate curve

α = thermal diffusivity

θ = time

$(m_i')_{in}$ = mass flow rate in, stream i, $i=1,2,\ldots,n$

$(m_j')_{out}$ = mass flow rate out, stream j, $j=1,2,\ldots,m$

M_{system} = total mass of the system

M_1 = steam mass (inside autoclave)

M_2 = condensate mass (inside autoclave)

M_3 = mass of autoclave, basket, tin cans

$\ddot{E}_1$ = steam specific energy (inside autoclave)

$\ddot{E}_2$ = condensate specific energy (inside autoclave)

$\ddot{E}_3$ = specific energy of autoclave, basket and tin cans

$(\hat{H}_i)_{in}$ = enthalpy in, stream i, $i=1,2,\ldots,n$

$(\hat{H}_j)_{out}$ = enthalpy out, stream j, $j=1,2,\ldots,m$

Q_i' = heat (term i), stream i, $i=1,2,\ldots,p$

Q_r' = heat lost by radiation

Q_c' = heat lost by convection

Q_p = heat exchange, product-steam

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Mathematical Models and Logic for the Computer Control of Batch Retort Process Operations: Conduction-Heated Foods

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ABSTRACT

A computer program was developed to implement a mathematical model to control on-line batch retort operations for conduction-heated foods. The model is based on a numeric solution for heat transfer in cylindrical cans. The heat transfer equation was solved using a numeric method with a variable grid. Integrated lethality values are calculated assuming first order kinetics for microbial inactivation. The program calculates an integrated F_o taking into account the cumulative lethality of the heating and subsequent cooling period. The program is capable of automatically adjusting process time to compensate for any unexpected variation in retort temperature and was validated using several processes reported in the literature. Published control strategies based on center temperature conditions are inaccurate when dealing with processes at high temperature or products with low thermal diffusivities.

INTRODUCTION

The advent of low-cost microcomputers has facilitated the implementation of strategies for the on-line control of processes. Computer control systems deliver uniform product quality while minimizing worker supervision, human error and energy consumption. In the specific case of canned foods, computer control addresses production problems without compromising product quality and safety. Computer control allows on-line corrections for temperature deviations from the pre-established process and also allows the implementation of optimum processes (Saguy and Karel, 1979; Ohlsson, 1980a,b; Van Boxtel and De Fielliettaz Goethart, 1982) identified by mathematical modelling. Examples of these attempts include work by Teixeira *et al.* (1975) and Ohlsson (1980b). Other potential benefits include automatic documentation of the process (Holdsworth, 1983) and on-line measurement of heat penetration data.

An automatic thermal sterilizer system is required to implement the control strategy to be employed. Design factors to be considered include the factory-installed capital cost of the system, interaction between operators and instruments, maintenance of hardware and software, reliability, instrumentation accuracy, and the interaction between management and the system. Lappo and Povey (1986) describes the development and performance of a facility, comprising a steam sterilizing retort, a microprocessor development system and all associated instrumentation and control equipment. The influence of instrument accuracy on the control of sterilization was also explored. A sterilization monitor capable of scanning 10 thermocouples and computing individual sterilization or "cook" values for each channel is also described.

Giannoni-Succar and Hayakawa (1982) developed a procedure to estimate the values of a correction factor, C_f, for deviant thermal processes for conduction-heated foods. Sterilizing values at the thermal center of the food were used as a criterion for the estimation. The procedure was based on a regression equation obtained through the dimensional and statistical analyses of theoretically determined C_f values.

Datta *et al.* (1986) developed a control logic algorithm for use with computer-based control systems for batch retort operations. The system is capable of automatically adjusting process time during the cook cycle to compensate for any unexpected deviation in retort temperature. To evaluate F_o, the temperature is taken to be the temperature of the slowest heating point in the product.

A review of the current literature found no control systems evaluating F_o values as a mass average lethality. Published control strategies based on center temperature conditions are inaccurate when dealing with processes at high temperature or products with low thermal diffusivities. Stumbo (1949) demonstrated that the slowest heating point is not where the probability of bacterial survival is greater. Computer supported experiments have been used to show that this location will vary, depending on the container geometry, food product, and the processing conditions (Teixeira *et al.*, 1969a).

Teixeira *et al.* (1969b) and more recently Simpson *et al.* (1989a,b) have shown that the accuracy of the predicted integrated lethality using numerical methods with uniform grid depends on a large number of space and time intervals. However, a software program for the on-line control strategy requires a program capable of completing all calculations before the next temperature reading. The method developed by Teixeira *et al.* (1969b) does not fulfill this requirement because of its large partitioning grid (10x10). The variable grid method developed by Hayakawa (1967) uses only 12 points of the can interior to calculate the integrated lethality and thus reduces computational time significantly.

In this paper we present simulation results of a computer program for the on-line control of thermal processing of canned foods in cylindrical containers using integrated F_o as the safety criteria. These calculations were executed while simulated arbitrary deviations in retort temperature were occurring.

METHODOLOGY

Sterilization Criteria

In controlling thermal processes, the objective is to meet the designed level of sterilization (F^d_o) for the process, irrespective of any retort temperature variation RT(t) occurring during processing time (t), and with a minimum of overprocessing. The lethal effect of thermal processing is achieved during the heating as well as the cooling period of the can, t_h and t_c, respectively. Thus, the objective function in thermal processing is to minimize F_o expressed as:

$$F_o = \frac{2}{La^2}\int_0^L \int_0^a \int_0^{t_h} 10^{[T(r,z,t)-250]/z}\, dt\, rdr\, dz + \frac{2}{La^2}\int_0^L \int_0^a \int_{t_h}^{t_h+t_c} 10^{[T(r,z,t)-250]/z}\, dt\, rdr\, dz \qquad (17)$$

subject to the constraint $F_o \geq F_o^d$. F_o is the accumulated integrated sterilization value for any temperature history during heating and cooling. The first integral represents the lethality contribution during the heating and the second integral represents the contribution to lethality during the cooling period.

An essential component of computer supported process control strategies is computational speed. To increase the computational speed, Eq. (1) was evaluated using the following numeric technique which required the following rearrangement of Eq. (1):

$$F_o =$$

$$\int_0^{t_h} \left[\frac{2}{La^2} \int_0^{a} \int_0^{L} 10^{[T(r,z,t)-250]/z} r\,dr\,dz \right] dt + \int_{t_h}^{t_h+t_c} \left[\frac{2}{La^2} \int_0^{L} \int_0^{a} 10^{[T(r,z,t)-250]/z} r\,dr\,dz \right] dt \qquad (18)$$

and using auxiliary variables we obtain:

$$F_o =$$

$$\int_0^{t_h} \underbrace{\left[k \int_0^{x_1} \int_0^{y_1} f(x,y)\, x\, dy\, dx \right]}_{A} dt + \int_{t_h}^{t_h+t_c} \underbrace{\left[k \int_0^{x_1} \int_0^{y_1} f(x,y)\, x\, dy\, dx \right]}_{B} dt \qquad (19)$$

where expressions A and B were solved every minute using a Gauss integration method (Abramowitz and Stegun, 1964). The time integrations (heating and cooling) were carried using a Simpson integration methodology. The grid defined to evaluate Gauss integration included six nodes in the radial direction and eight in the vertical direction. Since the cylindrical container is symmetric in both axis, Gauss integration

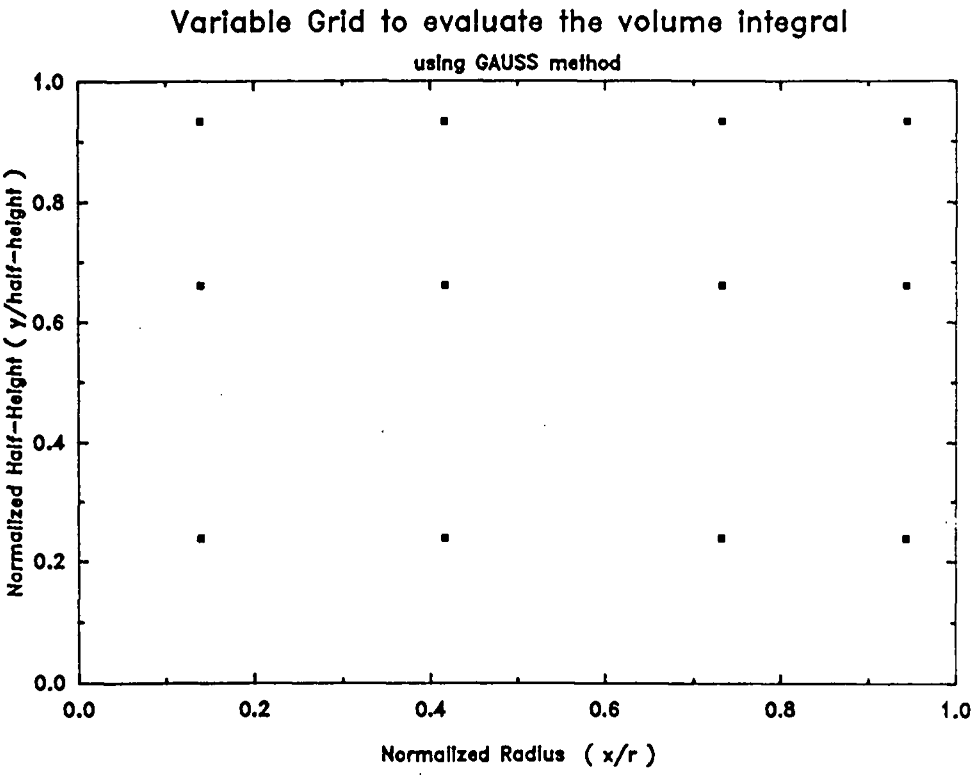


Figure 9.

Variable grid to evaluate the volume integral

by the Gauss method

was evaluated with 12 points as shown in Figure 9, and analogous to the variable 3x4 grid reported by Hayakawa (1967) to calculate integrated lethalities. To obtain the integrated lethality, the Gauss integration was evaluated every minute and the Simpson integration was evaluated every two minutes.

Modified variable grid (MVG) method

The numeric method used to solve the partial differential equation for heat transfer was the Alternating Direction Explicit Procedure (ADEP) reported by Allada and Quon (1966) combined with a variable grid. The expression for heat transfer in cylindrical coordinates is:

$$\frac{1}{\alpha}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial z^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2} \tag{20}$$

with the following boundary conditions:

$T_{surface\ (heating)}$ = RT(t) = retort temperature at any time t

$T_{surface\ (cooling)}$ = TW(t) = cold water temperature at any time t

The following expressions were used to evaluate the temperature inside the can at any point and at any time.

$$\frac{1}{r}\frac{\partial T}{\partial r} = \frac{1}{R_{(i)}}\left[\frac{\Delta R(i-1)\ [T(i,j) - T(i+1,j)]^{t}}{\Delta R(i)\ [\Delta R(i) + \Delta R(i-1)]} + \frac{\Delta R(i)\ [T(i-1,j) - T(i,j)^{t+1}}{\Delta R(i-1)[\Delta R(i) + \Delta R(i-1)]}\right] \tag{21}$$

$$\frac{\partial^2 T}{\partial r^2} = 2\left[\frac{[T(i,j) - T(i+1,j)]^t}{\Delta R(i)\,[\Delta R(i) + \Delta R(i-1)]} + \frac{[T(i-1,j) - T(i,j)^{t+1}}{\Delta R(i-1)[\Delta R(i) + \Delta R(i-1)]}\right] \tag{22}$$

$$\frac{\partial^2 T}{\partial z^2} = 2\left[\frac{[T(i,j+1) - T(i,j)]^t}{\Delta z(j)\,[\Delta z(j) + \Delta z(j-1)]} + \frac{[T(i,j-1) - T(i,j)^{t+1}}{\Delta z(j-1)[\Delta z(j) + \Delta z(i-1)]}\right] \tag{23}$$

$$\frac{1}{\alpha}\frac{\partial T}{\partial \theta} = \frac{[T(i,j)^{t+1} - T(i,j)]^t}{\alpha\Delta\theta} \tag{24}$$

Substituting Eqs. 3-6 in Eq. 2 and rearranging it is possible to obtain and expression for $T(i,j)^{t+1}$. Although this expression is an implicit equation, a proper choice of the initial point conditions generates explicit calculations (Allada and Quon, 1966).

Control program strategy

The effect of the lethality accumulated during the cooling phase on the evaluation of total mass average lethality was included to avoid overprocessing. The algorithm simulates the cooling cycle assuming constant water temperature and evaluates the integrated average F_o before the next temperature reading.

The first calculation step is to design a process to achieve the desired sterilization process and used it to define the following variables:

$F_o(t)$ = accumulated lethality at time t

F_{od} = integrated lethality desired

F_{oh} = integrated lethality achieved during heating with no temperature deviations

t_h = heating time

t^* = heating time to accomplish 80% of F_{oh}

While $t < t^*$, the program reads the temperature of the autoclave every 10 s. This information is used to calculate all temperatures inside the can and also to predict an integrated average $F_o(t)$ value. When the accumulated $F_o(t)$ is $\geq 0.8F_{oh}$, i.e., when $t \geq t^*$, the program simulates the cooling phase and predicts a final F_o value. Given that now too many calculations are needed to accomplish the cooling simulation, the time for each reading of the autoclave temperature is increased to 20 s. Preliminary experiments showed that the simulation time required to predict $F_o(t)$ after each temperature reading takes only 0.16 s and that the simulation of the cooling phase takes ~10 s. Other strategies used to reduce the number of calculations while predicting the cooling phase include temperature predictions using a 20 s time increment and the calculation of integrated average F_o values only every 120 s.

Implementation of the Control Program

The computer control program was implemented on an IBM PS2 Model 55SX using IBM Advanced Basic. The logic for the on-line control program is based on the work reported by Datta *et al.* (1986). First, input data are checked against specifications for the product. If they agree, steam is turned on and the computer completes the venting cycle. The retort temperature comes up and through a controller interface the computer attempts to maintain the design retort temperature (RT^d). As the heating cycle continues, the retort temperature RT(t) is read at intervals of time t. The temperature distribution within the can, T(r,z,t), is then calculated from RT(t) using the MVG method. The integrated average lethality, $F_o(t)$, is then calculated.

The input data includes a specified F_{oh}, which is the integrated average F_o value normally achieved during heating when there are no temperature deviations. When $F_o(t)$ exceeds the value $0.8F_{oh}$, the computer also simulates the cooling cycle in addition to calculating T(r,z,t) and $F_o(t)$ during the elapsed heating period. If the $F_o(t)$ accumulated so far, together with the simulated contribution from cooling, exceeds the design total F_o value for the process (F_o^d), i.e. when the condition

$$F_o(t)^{heating,\ calculated} + (F_o)^{cooling,\ simulated} \geq F_o^d \tag{25}$$

is satisfied, the computer turns off the steam and lets in cooling water. The computer still keeps reading the retort temperature RT(t) and continues with the calculations of T(r,z,t) and $F_o(t)$. When T_{center}, the calculated temperature at the can center is below a certain specified value, cooling is ended by stopping the flow of cooling water and the water is drained prior to unloading the retort. At the end of the process, a complete documentation of measured retort temperature history RT(t), calculated can center temperature history T(t) and the accomplished F_o is kept on file and can be documented in both tabular and graphical form through printer and plotter.

There are three differences between the method reported by Datta (1986) and the procedures here reported. First, $F_o(t)$ is calculated using the integration method given by Hayakawa (1969). The second difference is the cooling phase simulation ending criteria which was chosen as,

$$F_o(t) - F_o(t-120) \leq 0.001 \; F_o(t) \qquad (26)$$

When this condition is satisfied the computer stops the cooling simulation. The next equation must be satisfied before turning off the steam and letting in the cooling water.

$$F_o(t) \geq F_{od} \qquad (27)$$

The criteria to stop the cooling simulation was derived from many computer-supported experiments. When two consecutive F_o values (using 120 s intervals) vary less than 0.1%, subsequent F_o values will not change significantly. Figure 10 shows two examples of F_o accumulated during the entire cooling period, RT = 122.15°C. The dotted lines represent the end of the F_o predictions and indicate that after the computer interrupted the predictions no further significant changes occurred in process lethality.

The third difference is the time intervals used to solve the differential heat transfer equation. There are three different time intervals, two intervals for the heating phase (10 s and 20 s), and one interval for the cooling phase (20 s).

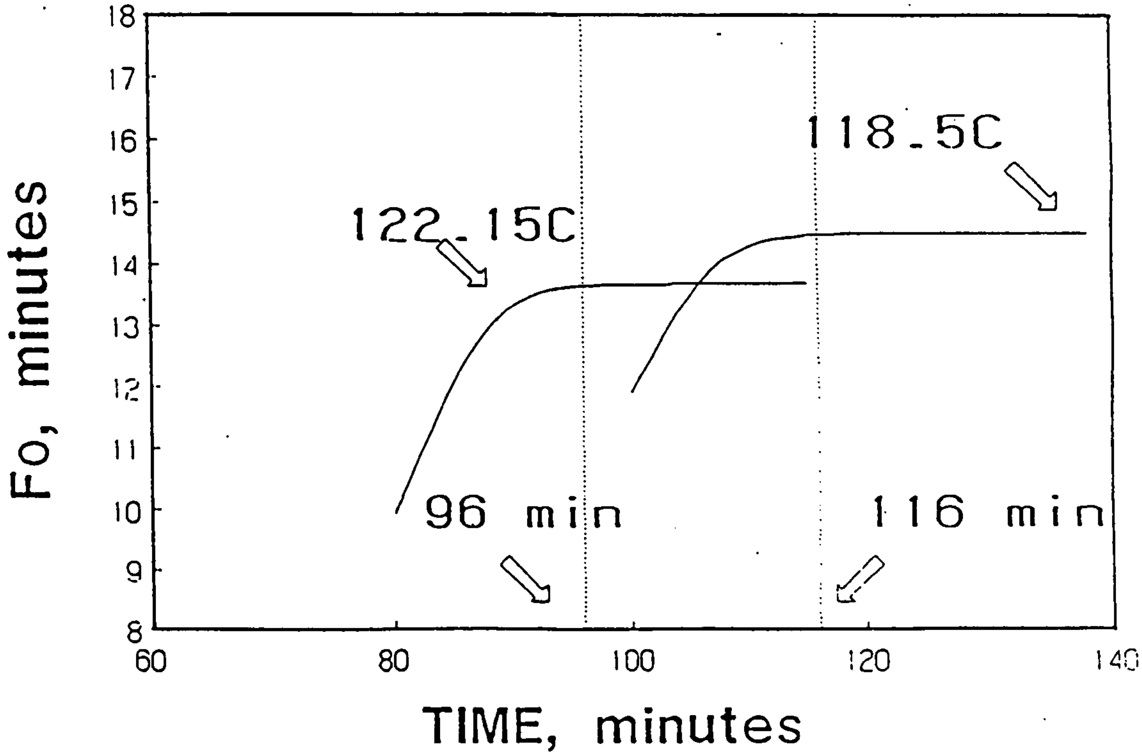


Figure 10.

Simulation of F_o values during the cooling period

Experimental details are given in the Appendix (Part A)

Table 2

Validation tests of the MVG Method

	Heating time, minutes	
Process Type[a]	Published Method[b]	MVG Method
a. w/ constant temperature		
Experiment 1	80	80
Experiment 2	100	100
Experiment 3	140	142
b. w/temperature deviations		
Experiment 1 0-50 min, 121.1°C 50-72 min, 129.4°C 72-79 min, 121.1°C	79	80
Experiment 2 0-20 min, 121.1°C 20-40 min, 129.4°C 40-83 min, 121.1°C	83	82
Experiment 3 0- 60 min, 120.0°C 60-112 min, 115.0°C	112	112

---

[a] Data used to conduct computer supported experiments is summarized in the Appendix II

[b] Teixeira *et al.* (1969b)

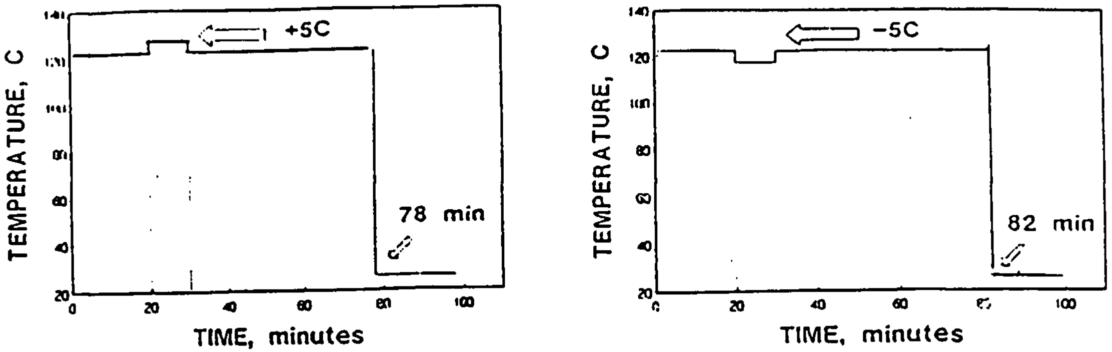
RESULTS

The MVG method was verified against results obtained with the methodology reported by Teixeira *et al.* (1969b). Three cases of constant temperature conditions were analyzed, and the results show no major accuracy difference between the MVG and Teixeira *et al.* (1969b) methods. Table 2 shows that the validation of the control program for a non-constant retort temperature was also successful. The control program results compare well with the values obtained using the method reported by Teixeira *et al.* (1969b).

Additional tests were conducted to examine the effect of various time varying boundary conditions (Fig. 11). In all cases, the computer control program behaved as expected stopping the heating period earlier or later depending upon the type and severity of the temperature deviation.

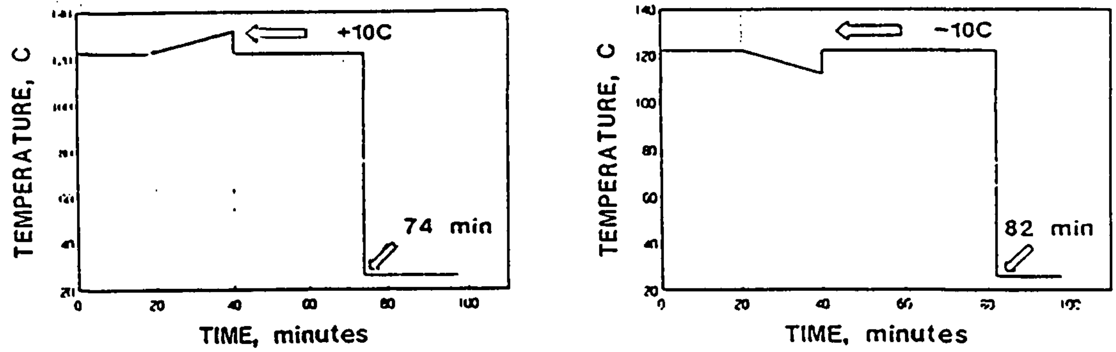
CONCLUSIONS

Several strategies were incorporated to develop a computer program capable of controlling the retort processing of conduction-heated foods using an integrated average F_o concept. This program is a unique software contribution because it can make practical use of calculations reported in the literature using the integrated F_o concept.



b. Single square wave, negative

a. Single square wave, positive



d. Single ramp, negative

c. Single ramp, positive

Figure 11.

Examples of process corrections after various type of temperature deviations

Heating time for the constant temperature process = 80 minutes

Further experimental details are given in the Appendix (Part A)

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the contribution of Ms. Silvana Roncagliolo whose computer programming skills were essential for the completion of this project. This publication is the result of research sponsored in part by Oregon Sea Grant with funds from the National Oceanic and Atmospheric Administration, Office of Sea Grant, Department of Commerce, under grant no. NA85AA-D-SG094 (project no. #.ISG-6) and from appropriations made by the Oregon State Legislature.

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APPENDICES

APPENDIX I: Processing Conditions

Can: 73x31 mm (European type)

mass, 0.0112 kg/can

936 cans/batch

Retort: mass, 163.6 kg

area, 2.97 m^2

volume, 0.356 m^3

c_p, 0.5 kJ/kg °C

bleeder area, 7.94x10^{-6}m^2

Microorganism: T_r, 121 C

D_r, 3 min

z, 10°C

Product: thermal diffusivity, 1.6x10-7m^2/s

c_p, 3.8 kj/kg k

density, 1,100 kg/m^3

Operation conditions: initial retort temperature (T_i), 20°C

initial product temperature, 71.1°C

environmental temperature, 30°C

process temperature, variable

Optimization method: Can, 307x409; F_o, 15 minutes

Thermal diffusivity, 1.695x10^{-7} m/s

Temperature profile limits, 110-135°

APPENDIX II: Experimental Conditions for Validation Tests

a. Constant temperature tests

Can type	307x409
Thermal diffusivity	1.6E-7 m^2/s
Initial food temperature	71.1°C
T_r	121°C
z	10°C
D_r	3 min
TW (cooling water)	26.6°C

Simulation results:

	Experiment 1	Experiment 2	Experiment 3
F_{oh}, min	9.938	11.899	13.359
F_{od}, min	13.679	14.452	14.536
Retort temperature, °C	122.15	118.5	114.36

b. Variable temperature tests

Can type	307x409
Thermal diffusivity	1.538E-7 m^2/s
Initial food temperature	71.1°C
T_r	121°C
z	10°C
D_r	4 min
TW (cooling water)	26.11°C

Simulation results:

	Experiment 1	Experiment 2	Experiment 3
F_{oh}, min	11.121	10.939	13.8
F_{od}, min	16.961	15.0	15.0
Retort temperature, °C	see Table 2	see Table 2	