EVALUATION OF RETORT PERFORMANCE AND INFLUENCE OF ENTRAPPED AIR ON HEAT TRANSFER INTO FLEXIBLY PACKAGED SIMULATED FOODS

by Stuart N.M. Campbell

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Department of Food Science
and Agricultural Chemistry

Macdonald College of
McGill University
Montreal
Canada

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ABSTRACT

The performance of a new horizontal retort (Steriflow Standard 1-Basket Model, Barriquand, Paris, France) was evaluated on the basis of temperature, heat and lethality distribution. These tests were also conducted on a positive-flow pilot scale steam retort (Dixie Canner Co., Georgia, U.S.A.), which was modified to operate on steam/air heating media under pneumatic and electro-pneumatic control systems. Time-temperature data for these studies were obtained from bare thermocouples (type T), and rectangular bricks fabricated from Teflon™ and Lexan™ with thermocouples positioned at their geometrical centres.

Although large temperature oscillations were characteristic of the new Barriquand retort, temperature and lethality distribution were satisfactory. The Dixie retort performed slightly better than the Barriquand model, without such large temperature oscillations.

The effect of entrapped air on processing parameters for bricks packaged in retort pouches was determined using silicone rubber bricks (10 x 14.5 x 2 cm), containing 5 thermocouples with their junctions positioned from the geometrical centre to near the top surface. The processing media employed were steam/air at two temperatures (121.1°C and 115.6°C) and two levels of superimposed air over-pressure, corresponding to 65% and 75% steam content.

With the exception of the highest level of over-pressure (116 kPa), 60 ml of entrapped air caused the heating rate index (f_h) to double. At low levels of air over-pressures, the slowest heating region (often assumed to be the geometrical centre) in the brick was shifted to a height equivalent to 3/4 of the brick thickness from the centre when the entrapped air volume was 60 ml. For similar conditions, the location receiving the least combined lethality during heating and cooling was near the top surface of the brick.

RESUME

Les performances d'un nouvel autoclave horizontal (Steriflow Standard 1-Basket Model, Barriquand, Paris, France) ont été évaluées suivant la répartition de la température, chaleur et mortalité. Des tests ont aussi été effectués sur un autoclave, modèle pilote, à flux positif (Dixie Canner Co., Georgia, U.S.A.), transformé pour fonctionner avec un système de control électro-pneumatique et pneumatique, utilisant un mélange vapeur/air comme source de chaleur. Les variations de températures en fonction du temps ont été obtenues à partir de thermocouples (type T) nus puis de thermocouples placés au centre géométrique d'une brique rectangulaire, fabriquée à partir de Teflon^R et de Lexan^R.

Bien que de fortes oscillations de températures, caractéristique de l'autoclave Barriquand, aient été observées, les résultats obtenus pour la répartition de la température et de la mortalité furent satisfaisants. On a observé une légère amélioration des performances de l'autoclave Dixie par rapport à l'utilisation du modèle Barriquand, sans qu'il n'y ait d'aussi larges variations de températures.

L'effet de l'air emprisonné sur les paramètres de traitement thermique de briques a été analysé. Ces briques de silicone (10 x 14.5 x 2 cm), emballées dans des sachets flexibles stérilizables, contenaient cinq thermocouples dont les jonctions étaient alignées du centre géométrique à la surface de la brique. Le milieu de traitement employé était un mélange vapeur/air à deux températures (121.1°C et 115.6°C) et deux niveaux de surpression d'air superposé correspondant à 65% et 75% de vapeur.

A l'exception du plus haut niveau de surpression (116 kPa), 60 ml d'air emprisonné a doublé la valeur f_h (index de taux de réchauffement). A faible niveau de surpression d'air, la zone de réchauffement la plus lente de la brique (souvent considérée comme son centre géométrique) a été déplacée d'une hauteur équivalant aux 3/4 de l'épaisseur de cette brique, lorsque le volume d'air emprisonné était de 60 ml. Dans des conditions semblables, la région de plus faible mortalité due au réchauffement combiné au refroidissement, était localisée près de la surface de la brique.

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I - INTRODUCTION

Steam heated water with air over-pressure and steam/air are two heating media commonly used to sterilize food in glass containers, and recently in flexible and semi-rigid packages such as retort pouches and thermo-stable plastic trays. Some early studies (Pflug and Borrero, 1967; Pflug, 1964; Parcell, 1930a, b) indicated serious concerns that steam/air media may produce a nonhomogeneous media with poor temperature distribution if the two gases (steam and air) were not adequately mixed. Because of these concerns, there was some hesitation in North America to acknowledge the suitability of steam/air media for thermal sterilization processes even after their commercialization in Europe and Japan. Subsequent detailed studies of steam/air media (Yamano, 1976; Ramaswamy, 1983; Ramaswamy et al., 1983; Tung et al., 1984; Tung and Ramaswamy, 1986) on temperature and heat transfer distribution demonstrated that with proper mixing, distribution and flow conditions, steam/air media could be successfully used as heat transfer media in over-pressure processes.

The importance of temperature uniformity becomes readily apparent when its influence on process lethality is evaluated. For a temperature deviation of ± 0.5 °C, Berry (1979) reported differences in the process lethalities of up to 14% at 121°C and Martens (1980) showed that a similar change in retort temperature at 135°C could introduce a change in the resulting process lethality of up to 3 min. The IFTPS (Institute for Thermal Processing Specialists, Washington, DC) and NFPA (National Food Processor's Association, Washington, DC) recommend stringent temperature distribution verification of all retorts for assurance of adequate performance (NFPA, 1985). Any new retort equipment or modification must therefore take into consideration the necessity of providing adequate temperature and heat distribution under fully loaded operating conditions.

Although temperature uniformity is an important factor in thermal processing, the surface heat transfer coefficient (h), a property of the processing media and the package surface, can also limit the heat transfer into a packaged food. When large surface heat transfer coefficients exist, as with processing of containers in pure steam, the heat transfer into the food may be considered to be dependent on the temperature alone. In this case, surface resistance to heat transfer from the medium becomes negligible in relation to the resistance within the container. The temperature difference between the retort and the product provides the main driving force for the heat transfer in this situation, and therefore a given temperature distribution may be expected to yield a particular heat transfer pattern.

With over-pressure retort systems based on either water/air or steam/air heating media, the associated surface heat transfer coefficients (h) are usually not very large. Usually h is dependent on several factors such as medium flow rate, flow direction, loading pattern etc. (Pflug, 1975, Pflug and Borrero, 1967). In these situations, the product lethality could depend on other factors in addition to temperature. Additional analysis of distribution in the form of various parameters such as heating and cooling rate indices (f_h and f_c) and lag factors may be required to assure satisfactory performance of the retort.

The reason for the use of over-pressure during retort processes is to oppose the expansion of entrapped gases. As well as posing a danger of package rupture (Wallenberg and Jarnhall, 1957), entrapped gases have been reported to cause increased f_h values (Berry and Kohnhorst, 1983), and nearly double required processing times (Kopetz et al. ,1979). Although residual air after vacuum-sealing of the pouch may be the principal source of entrapped gases, release of gases from product due to decreasing gas solubility at increased temperatures may add to the volume of entrapped gases (Davis et al., 1960).

The use of superimposed air pressure during steam or water processes is commonly used as a means of preventing expansion of entrapped air. Weintraub (1984) reported considerably less influence on the heat transfer parameter, f_h as the steam fraction was reduced from 85% to 65%. Although the surface heat transfer coefficient is reduced at the lower steam fractions, this is often outweighed by the improved heat transfer within the package contents at the higher air over-pressure levels, and results in improved heat transfer and lethality.

The use of air over-pressure in the retorting of flexible packages reduces the expansion of entrapped gases, but regardless of their volume, the gases remain in the packages, where they may have a substantial effect on the heat transfer. Process parameters (h, f_h, f_c F, etc.) are usually calculated from temperature data collected from thermocouples placed at the slowest heating region in the package. This region, often referred to as the "cold spot", is assumed to be the least processed region. For conduction heating of both cans and pouches, thermocouples are generally placed in the geometrical centre of the package, where the cold spot is believed to be located. However, during the processing of flexible packages such as the retort pouch, entrapped gases will tend to collect above the packaged product, between the top of the food and the package. At this location, entrapped gases may hinder the heat transfer from above, and move the cold spot toward the top of the package. At increasing entrapped gas volumes, shifts of the cold spot from the geometrical centre to 2/3 height have been reported (Berry and Kohnhorst, 1983; Huerta-Espinosa, 1981). Despite such findings, most temperature data are still collected from thermocouples located at the geometrical centre of the packages. Depending on the volume of entrapped gases inside the package, process calculations based on data from thermocouples positioned as such may be deceptive.

The purpose of monitoring the cold spot of a product is to ensure that the least processed location in the food is adequately processed. The ultimate goal of this form of heat processing is to impart a pre-determined microbial lethality to the least processed region. Under-processing may pose health risks, while excessive processing reduces product quality. The location of the least processed region is typically determined as the slowest heating region during heating, yet there is no evidence that the slowest heating point is necessarily the point of lowest lethality.

The objectives of this research were:

1- To evaluate the performance of a new horizontal retort (Steriflow Standard 1-Basket Model, Barriquand, Paris, France) operated on a unique water-spray heating principle, and compare the performance of this retort to the previously mentioned positive-flow retort.

2- To examine the effects of different levels of entrapped air during heating under various steam-air mixtures.

3- To determine the location of the least processed region in a test brick at different entrapped air contents and processing media during the different stages of processing.

4- To modify a positive-flow pilot-scale vertical retort (Dixie Canner Equipment Co., Athens, Georgia, U.S.A.) operating on pure steam or Water/air media, for processing retort pouches in steam-air media with a microprocessor control system (This last objective was required to conduct the study).

II - LITERATURE REVIEW

Historical Background

The retort pouch is a flexible package designed to withstand the high temperatures applied in commercial sterilization of low acid food products. The retort pouch was developed in the late 1950's by the U.S. Army Natick R&D division to replace the conventional can as the C-ration (combat container). The objective of the military research was to develop a light, stable, single portion package that could be carried by a soldier without interfering with his movement or posing any hazard should a soldier fall on it. In terms of commercial production, the retort pouch promised to became a container for more than just soldier's food.

The thin profile of the pouch allows for much shorter process times and hence higher quality retention than the relatively large tin can. Many studies have concluded that the quality, both by sensory and objective evaluation, of various food products packaged in the retort pouch is equal to or superior than that of the same food packaged in cans of similar capacity (Chia et al., 1983; Lyon and Klosse, 1981). Reductions of 32 to 37% in processing time and significant quality improvements for equivalent lethalities in retort pouched seafood compared to canned product have been reported by Mahadeviah (1989).

Several cost analyses have shown definite advantages to the manufacturer of producing food products packaged in the retort pouch rather than in the tin can. These advantages are largely due to lower transportation costs of the pouches, both full and empty (Williams et al., 1981), and lower energy requirements and container costs for a retort packaging system (Steffe et al., 1980). However , according to Williams et al. (1983), although the operating costs of a retort pouch system are less than a canning line, large initial capital expenditures can offset these advantages.

The first limited commercial use of the retort pouch was in Italy in 1960, Denmark in 1966, and Japan in 1969 (Lampi, 1980). By 1974, 70 million retort pouches had been sold in Europe (Davis, 1981). In 1975, Japan produced 170 million pouches each day, whereas in the U.S., where the retort pouch was first developed, production was estimated at a relatively insignificant 10 million units annually (Peters, 1975). The most obvious reason for the low use of the retort pouch in the U.S.A. was that no laminates met F.D.A. approval until 1974. In 1978, just four years after it's acceptance by the F.D.A., the retort pouch earned the I.F.T. Industrial Achievement Award, and there were predictions that the pouch would capture a large part of the annual can production market of 34 billion units per year (Pinto, 1978). Despite this optimism, now, over a decade later, the retort pouch has made little impact on the U.S. Packaging market. Although the retort pouch was an American invention, Swan Valley Foods, in Canadian British Columbia, in 1975 was the first North American company to introduce foods processed in the retort pouch on a commercial level, and since then, several other Canadian companies have marketed foods in the pouches (Magic Pantry Foods Inc., Ont.; Empaquetage, J.B. Inc, Que.; Domfoods Star Inc., Que.).

Although the use of the retort pouch has been significant in both Europe and Canada, by far the greatest success of the retort pouch has been in Japan. There are several possible reasons for the success of the retort pouch in Japan and it's failure in the U.S. The reduction of material cost and space of the retort pouch (both full and empty) compared to the tin can is much more important in

Japan than in the U.S. Line speeds of the retort pouch are much slower than for the tin can. Manufacturers in the U.S. are not willing to write off their investments in canning lines and U.S. consumers are more attached to the tin can than predicted (Sacharow, 1984). The common retort pouch, with it's aluminum layer, cannot be heated directly in the microwave, which puts it at a competitive disadvantage with frozen microwavable foods. The American food processing giant, Kraft, were enthusiastic about the retort pouch, reporting a reduction in processing time of 50%, but it's shelf stable "a la Carte" line of entrees failed in the early 1980's (Cage and Clark, 1980).

The future of the retort pouch, especially in the U.S., is presently looking much brighter, thanks to the successful development and F.D.A. approval of a microwavable pouch, developed and tested in 1986 in Canada by Lundlow Flexible Packaging (Freshour, 1987). This new pouch utilizes saran instead of aluminum as a barrier layer. The increasing use of domestic microwave ovens gives this new pouch an undisputable edge over the tin can, and puts these pouched foods in direct competition with the fast food market. Meals marketed for preparation and consumption by children are now being marketed successfully in the U.S. by My Own Meals, Inc. (MOM) using this microwavable, boilable package with it's one year shelf life (Morris, 1989). This new construction is perhaps the breakthrough that will move the retort pouch into the forefront of the shelf-stable food market.

Retort Pouch Construction

The modern retort pouch is manufactured from a three ply laminate, the three plies, from inside to outside, contributing the functions of heat-sealibility and food compatibility, barrier, and toughness. Although various inner heatsealable layers have been employed, eg. Polyethylene, P.V.C., Nylon & Polypropylene, the middle and outer layers have almost exclusively remained as aluminum foil and polyester.

The outer polyester layer of a retort pouch, which must provide physical toughness to protect the aluminum foil barrier layer, is also responsible for the transfer of heat into the package by condensation of steam on it's outer surface. Condensation occurs in either filmwise or dropwise form, the latter imparting heat transfer rates as much as ten times higher than for filmwise condensation (Holman, 1986). Goodrich et al. (1983) reported that filmwise condensation prevails in thermal processing, and that heat transfer rates can be as much as two orders of magnitude higher for dropwise than filmwise condensation. The condensation mechanism can be modified, as illustrated by Holman (1986) who demonstrated that a coating of cupric oleate on the surface of a copper plate causes a shift from filmwise to dropwise condensation, but there is no published data on food processing modifications of this nature.

Retort pouch Processing Media

There are three media recognized for use in sterilizing low-acid foods in hermetically sealed containers. These are pure steam, steam heated water with air over-pressures and steam/air mixtures. The choice of processing media for processing of cans is not a great concern, since the relatively large radius causes the surface resistance to be relatively small, indicating potentially high heat transfer coefficients with respect to the processing medium. For the retort pouch, however, Beverly, (1979) performed calculations based on the work of Pflug (1964) and reported overall heat transfer coefficients for a 5" X 7" water-filled pouch in pure steam, water, and 75% steam/air mixture to be 965, 596, and 497 $W/m^2/^{\circ}C$, respectively.

Pure Steam

Because of the large amount of heat released during condensation, pure steam has been traditionally believed to be the ideal medium for sterilizing packaged food, and is frequently used for processing canned products. Theoretically, in a pure steam heating medium, the internal vapour pressure inside a pouch can never reach retort pressure, since salts reduce the vapour pressure in the pouch liquid to below that of pure steam (Goldfarb, 1970). However, once the pouch contents reach processing temperature, small fluctuations in retort pressure may result in rupture of the pouches due to their internal pressure exceeding the retort pressure. For pure steam processes, positive flow of the heating media is required to ensure uniform heating, and air is required in the retort during cooling to counteract the high internal pouch pressure.

The Japanese have developed a system known as the "hi-retort" (Tsutsumi, 1979a) and the "U-retort (Tsutsumi, 1979b) which incorporate pure steam at relatively high temperatures of 135°C and 150°C respectively compared to conventional processes, which typically employ temperatures at around 121°C. The result of this high retort temperature is that the process is completed before the packages reach the retort temperature, thereby reducing the danger of pouch bursting due to retort temperature fluctuations. This system also requires air during cooling, and since retort temperatures are so high, careful monitoring of process time is crucial. There are no reports of such systems being used, except on a limited scale in Japan.

Pflug et al. (1963) reported that pure steam would be the ideal processing media if all non-condensible gases could be removed from the flexible package prior to processing; but since air is always present in some volume in the retort pouch packaged food, the use of 100% steam is not practical. The expansion of non-condensible gases during heating exerts an additional stress on the package since it's effect is independent of vapour pressure.

Steam Heated Water with Air Over-Pressure

Steam heated water with air over-pressure is the most common heating medium used in the U.S. and in some parts of Europe. The greatest advantage of this media is the flexibility permitted by the independent control of temperature and pressure. In the past, water processes have been long, because of the time required to heat water at the beginning of the cook period, and to cool the water at the end of the process (Pflug et al., 1963). In recent models, to overcome this difficulty, the required volume of heating water is often pre-heated to processing temperature, and added at the beginning of the process. Likewise, at the end of the process, fresh cold water is often added as an alternative to cooling the hot processing water. Various modern retorts employ water as the processing medium. One such retort system, employed successfully for processing retort pouches (McGinnis, 1986a), is the FMC Convenience Food Sterilizer (FMC, Santa Clara, CA), a weir type retort, in which water flows horizontally across trays by gravitational flow and is then re-heated and returned to the top of the weir via a pump. Another retort employing water as it's heating medium is the newly introduced Barriquand Steriflow retort (Barriquand, Paris, France) which operates on a unique water-spray heating principle in which a small volume of water is recirculated at a high rate through a heat exchanger, and is sprayed down on the top tray of the product load, and trickles down onto consecutive trays. No published data is available on the performance of this retort, or the suitability of it's use for processing retort pouches.

Steam/Air Mixtures

Steam/air mixtures are used for processing of flexible packages in North America, Europe and Japan. Steam/air mixtures offer many of the advantages of pure steam media, while allowing the independent control of temperature and pressure. Turtle and Alderson (1971) reported steam/air processing to be quicker and cheaper, and unlike with water processes, there is no tendency for packages to float. The greatest drawback of this processing medium is the relatively lower heat transfer rates and hence longer process times and higher heating rate indices (f_h values) compared to either pure steam or water and air. Kopetz et al. (1979) reported a 5 to 16% increase in processing times for 75% steam (25% air), compared to water medium. In the same study, Kopetz et al. (1979) also reported a 6 to 12% reduction in process time for the steam-air process when the overriding air pressure was increased from 10 to 25 psig. Yamano (1976) found that the f_h values for food-simulating materials in flexible packages processed with overriding air pressure to be almost independent of composition of the steam/air mixture at steam contents higher than 70%.

A variation of the traditional steam-air and water immersion retorts is the previously mentioned Barriquand Steriflow retort, which employs a water spray heating principle to provide an environment that combines some of the properties of water and steam/air retort systems.

Temperature Distribution and Stability

Steam heated water with air over-pressure and steam/air are the two heating media most commonly used to sterilize food in flexible and semi-rigid packages such as retort pouches and thermo-stable plastic trays. Some early studies (Pflug and Borrero, 1967; Pflug, 1964; Parcell, 1930a, b) indicated serious concerns that inadequate mixing of the two gases (steam and air) may produce a nonhomogeneous media with poor temperature distribution. Because of these concerns, there was some hesitation in North America to acknowledge the suitability of steam/air media for thermal sterilization processes even after their commercialization in Europe and Japan. Subsequent detailed studies of steam/air media (Yamano, 1976; Ramaswamy, 1983; Ramaswamy et al., 1983; Tung et al., 1984; Tung and Ramaswamy, 1986) on temperature and heat transfer distribution demonstrated that with proper mixing, distribution and flow conditions steam/air media could be successfully used as heat transfer media in over-pressure processes. The concern for temperature and heat transfer non-uniformity is equally applicable to water immersion retorts with poor circulation of the heating medium. In a horizontal retort (FMC Convenience Food Sterilizer, Model 500, F.M.C., Santa Clara, CA) with weir-type water flow principle, McGinnis (1986a,b) found the surface heat transfer to be dependent on the location of the product within a tray as well as the tray level. Maximum surface heat transfer coefficients were reported to be at the middle tray level.

The importance of temperature uniformity becomes readily apparent when its influence on process lethality is evaluated. For a temperature deviation of ± 0.5°C, Berry (1979) reported differences in the process lethalities of up to 14% at 121°C and Martens (1980) showed that a similar change in retort temperature at 135°C could introduce a change in the resulting process lethality of up to 3 min. The IFTPS (Institute for Thermal Processing Specialists, Washington, DC) and NFPA (National Food Processor's Association, Washington, DC) recommend stringent temperature distribution verification of all retorts for assurance of adequate performance (NFPA, 1985).

Heat Transfer Considerations

The Heat Transfer Coefficient (h)

Heat transfer coefficients for pure steam processes are quite high, but as the steam/air ratio is reduced, the heat transfer coefficient (h) drops rapidly (Pflug, 1964; Yamano, 1976). Pflug (1964) used cylindrical aluminum and copper transducers to compare steam/air processing media at 100, 90 and 75% steam fractions, and reported h values of 5,053, 1,306 and 852 $W/m^2/^{\circ}C$. For a study involving the processing of a 40% bentonite solution packaged in retort pouches at 55% compared to 65-90% steam, Yamano (1976) reported drops in h values of 25%. Ramaswamy et al. (1983) and Tung et al. (1984) employed rectangular transducers of aluminum and stainless steel and used a regression approach to quantify the relationship between the steam content of a steam/air medium and h in a positive flow vertical retort and forced air circulation horizontal retort. The heat transfer coefficient was expressed as an exponential function of the form $h = a \exp(bS)$, where h and S were the heat transfer coefficient and steam fraction respectively. Constants a and b were generated for various temperatures and flow directions in the retort (Ramaswamy et al., 1983; Tung et al., 1984). Adams et al. (1983) and Tung et al. (1984) indicated that increasing the retort venting flow rates had a positive effect on the surface heat transfer coefficient.

The Heating and Cooling Rate Indexes (f_h, f_c)

Heating and cooling data are usually expressed in terms of heat penetration and cooling curves, respectively. These curves are constructed by plotting the temperature difference between the retort and the product or the product and the cooling medium (for f_h and f_c respectively) on a logarithmic ordinate against time in the linear abscissa. The heating and cooling rate indexes (f_h, f_c) are taken as the indexes of the slope of the respective plots, and are defined as the time in minutes for the plots to traverse one log cycle (Stumbo, 1973).

The Heating and Cooling Lag Factors (j_{ch}, j_{cc})

The heating and cooling lag factors (j_{ch}, j_{ch}) are calculated as follows:

$$j_{ch} = \frac{T_r - T_{pih}}{T_r - T_{ih}} \quad (1)$$

$$j_{cc} = \frac{T_w - T_{pic}}{T_w - T_{ic}} \quad (2)$$

where: j_{ch} = heating lag factor.
j_{cc} = cooling lag factor.
T_r = retort temperature.
T_w = temperature of the cooling water.
T_{pih} = intercept of the straight line portion of the heating curve extended to the beginning of heating as defined by Ball (1923).
T_{pic} = intercept of the straight line portion of the cooling curve extended to the beginning of cooling as defined by Ball (1923).
T_{ih} = initial temperature of the food at the beginning of the heating cycle.
T_{ic} = initial temperature of the food at the beginning of the cooling cycle.

Lethality (F_o)

The ultimate goal of retort processing a packaged food product is to impart a pre-determined degree of heat treatment, referred to as process lethality (F_o), to achieve a certain microbial destruction, and is expressed in terms of equivalent minutes at 121°C. Ball (1923) developed an equation for relating the lethality imparted at any temperature (T) to it's equivalent lethality at 121°C:

$$L = 10^{\{(T - 121)/z\}} \tag{3}$$

where L is the lethality, also termed (F), expressed as minutes at 121°C. T is the processing temperature (°C), and z is the temperature required to cause the D value of the micro-organism to change by a factor of 10. The D value (decimal reduction time) is the time at a given temperature which will result in one decimal reduction in the surviving microbial population. For low acid foods (pH>4.5), the reference micro-organism is *Clostridium botulinum* with a decimal reduction time of 0.21 minutes at 121°C and a z value of 10°C. The accumulated lethality of the process is given the term F_o which refers to the integrated lethality at the "thermal centre" over the entire heating and cooling period.

Patashnik (1953) developed a numerical integration procedure to calculate F_o:

$$F_o = \int_0^t L\,dt \tag{4}$$

Where L is the lethality determined from the lethality equation of Ball (1923), and the limits of the integral are from time zero to t.

Process Calculations

Ball's method

Ball's formula method has been the industry standard since it was first introduced (Ball, 1923). One of the primary limitation of this method is the use of a constant cooling lag factor of 1.41 (j_{cc}). The procedure makes use of experimentally evaluated heat penetration parameters (f_h and j_{ch}), the retort operating conditions, and a set of tables or figures to compute the process time required to achieve a given process lethality (F_o) or vice versa.

Stumbo's method

Stumbo (1973) published several tables for process evaluation taking into account the variability of j_{cc} values. The Stumbo formula method is essentially similar to the Ball formula method except that it is somewhat more versatile in accounting for the thermal effects of cooling when the cooling lag factor (j_{cc}) differs from 1.41 as assumed by Ball. Stumbo's tables have been reported to produce results which are often in better agreement with those obtained from general method calculation than do similar calculations using Ball's method (Smith and Tung, 1982).

Temperature Conversions

Slight variations in retort temperature and in the initial product load temperature from one run to the next are unavoidable. In commercial retorting operations, such variations are compensated for by adjusting the processing times to ensure adequate lethality. For research applications, where heat transfer rates are being considered, variations in the retort and initial product load temperature may cause considerable non-uniformity with reference to the delivered lethality.

Schultz and Olson (1940) developed equations for converting both retort and initial product load temperatures to other temperatures.

Different Retort Temperature

If time-temperature data is to be converted for a different processing temperature, while the initial food temperature is not changed, the following equation can be used:

$$T'_c = T'_r - \frac{T'_r - T_i}{T_r - T_i}(T_r - T_c) \tag{5}$$

where: T_r = original retort temperature.
T'_r = new retort temperature.
T_i = product initial temperature.
T_c = product temperature (at any given time) before conversion.
T'_c = product temperature (at the same time) corresponding to T'_r.

Different Initial Temperature

If temperature data is to be converted for a different initial product temperature (T'_i), while the retort temperature is not changed, the following equation can be used:

$$T'_c = T_r - \frac{T_r - T'_i}{T_r - T_i}(T_r - T_c) \tag{6}$$

Entrapped Gases

Although much of the work that led to the development of the modern can is applicable to the retort pouch, the effect of entrapped gases is a problem unique to flexible packages. Rigid containers such as cans do not permit significant expansion of gases, and if a jar fails to restrain the expansion of gases, it is not likely to pose a health risk, since it will never reach the marketplace. Since the development of the retort pouch in the early 1950's, it has been recognized that due to the flexible nature of the package, expansion of the contents of the pouch interferes with transfer of heat into it's contents. Studies have demonstrated that increasing head space gases can cause an increase in heating rate index (f_h). In fact, Berry and Kohnhorst (1983) found that a residual air volume of 250 ml in institutional-sized retort pouches containing approximately 2.4 kg of product, caused the f_h value to nearly double. Other studies have reported increases in required process times of as much as 35% in institutional-sized retort pouches containing 150 ml of residual gas (Kopetz et al. 1979). Expansion of the contents of the pouch may also lead to the build-up of internal pressure, and ultimately, the rupture of the pouch. Davis et al. (1960) attributed the build-up of pressure inside flexible pouches at increasing temperatures to the increasing vapour pressure of water in the container, increasing pressure of occluded air, release of gases from product due to decrease in gas solubility, and thermal expansion of the food itself.

Air removal from retort pouches is usually accomplished by either sealing the pouch within a vacuum chamber, or flushing with steam immediately before sealing, in which case steam replaces the head-space gases, and condenses upon cooling. Wallenberg and Jarnhall (1957) published a table relating maximum permissible enclosed air volume to package surface area if rupture of the pouch is to be avoided. Although rupture of the pouch is undesirable, it is not the only consequence of entrapped gases. Lampi (1977) expressed other complications such as difficulty in detection of spoilage (swelling), hindrance of cartoning and casing, and non-uniform and unpredictable heat transfer during retorting.

Although nearly all commercial retorting systems process pouches in a horizontal orientation, some research has been performed using racks that hold the retort pouches in a vertical orientation (Pflug et al., 1963; Davis et al., 1972). The intention of such a method is that the gases inside the pouch remain at the top end and do not interfere significantly with heat transfer into the package contents. For packages processed vertically, product thickness must be defined by the rack spaces, requiring that both surfaces of the pouch be in contact with the rack, which may interfere with contact between the package and the processing media. Yamano and Komatsu (1969), Yamano (1976), and Roop and Nelson (1981) concluded that there was no significant difference in the heat transfer rate between horizontal and vertical orientation of the package. Some decrease in the heat transfer rates have been observed by Berry (1979) for pouches in vertical orientation, but this was attributed to excessive space between plates of the rack, which resulted in slumping of the pouch contents, causing an increased pouch thickness.

Another method used to reduce the volume of gases at the surface of flexible packages is the application of physical pressure, or constrainment of the two principle heat transfer surfaces. This method has been proven effective in maintaining the maximum thickness of the package at the shelf spacing. Using this method, Ramaswamy (1983) found that entrapment of 15-30% air in a 16 x 23 cm pouch did not influence heat transfer rates into constrained pouches, but caused increases of up to 260% in the f_h values of unconstrained pouches. In the same study, Ramaswamy (1983) noted that overriding air pressures of 70-100 kPa also prevented deterioration of heat transfer rates.

Davis et al. (1960) and Ramaswamy (1983) applied the ideal gas law to approximate the behaviour of noncondensible gases within a package:

$$(P_1 \cdot V_1) / T_1 = (P_a \cdot V_a) / T_a \tag{7}$$

Where (V_1) is the volume of entrapped air at the packaging temperature (T_1) and pressure (P_1), which will expand to a volume (V_a) at retort temperature (T_a) and pressure (P_a). To prevent expansion, the retort pressure must be selected such that:

$$P_a \geq P_1(T_a / T_1) \tag{8}$$

At sterilization temperatures, the pressures associated with steam are adequate to prevent the expansion of gases. However, as expressed by Ramaswamy (1983), when the package contents reach retort temperature, the water vapour pressure inside the package can be assumed to be the same as that of saturated steam outside (neglecting the lowering of vapour pressure due to solutes in package liquid). Weintraub et al. (1989) also used the perfect gas law to calculate theoretical expansion factors relating the initial volume of entrapped gases to the volume of entrapped gases at processing conditions.

In actual food processing applications, since the package usually contains both entrapped gases and has a high water activity, the actual expansion of the pouch contents is the sum of the expansion of entrapped gases and water vapour. Thus, in order to keep the magnitude of the total expansion low, it is necessary to use superimposed air pressure over the steam pressure.

Air Over-pressure and Entrapped Gases

Most modern pouch retorting operations make use of air over-pressure as a means of preventing the expansion of entrapped gases. Certain restrictions on the levels of air in the processing medium must be respected so that the surface heat transfer between the medium and the product surface does not limit heat transfer (Yamano, 1976). Yamano (1976) stated that 21 to 28 kPa (3 to 4 lb/in^2)

of superimposed air pressure is required in order to prevent bursting of the pouch. This level of over-pressure was also respected by Weintraub (1984).

For studies of the effect of various entrapped air volumes at different levels of over-pressure for processing of Teflon slabs in 16 x 23 cm pouches at 115°C in a Lagarde retort, Weintraub et al. (1989) reported little influence of air volumes up to 30 ml while processing in a steam/air medium containing 65% steam. However, with the steam/air medium at 75% steam content, Weintraub et al. (1989) reported a significant linear increase in f_h values at entrapped air contents beyond about 15 ml, and a greater linear increase in f_h from the minimum entrapped air content of 5 ml during processing in steam/air containing 85% steam. Kopetz et al. (1979) reported a 6 to 12% reduction in process time for the steam-air process by increasing the overriding air pressure from 70 to 170 kPa.

Since there are many variables contributing to the effect of gas expansion in pouches (pouch size, nature of food, effectiveness of vacuum, packaging and processing temperatures), general guidelines for calculating required over-pressure are not easily established, and much work is still required in this area.

Measurement of Entrapped Gases and Leak Detection

Measuring the volume of entrapped gases in the retort pouch can be accomplished either destructively, or non-destructively. The destructive test, which is outlined by Shappee and Werkowski (1972) has the advantage of being simple to execute. The procedure involves opening the package under water, and allowing the gases to escape from the package into an inverted measuring graduate. Depending on the contents of the pouch, considerable time may be required in manipulation of the package and it's contents to assure that the entire volume of gases is forced out of the package. The nondestructive test, also outlined by Shappee and Werkowski (1972), involves weighing the package as it is suspended just below the water surface, and then placed in a hermetically sealed, transparent vessel containing water. A high vacuum is drawn into the vessel to check for leaks in the package, which would be indicated by a steady stream of escaping bubbles. Neutral buoyancy is then achieved by slowly increasing the vacuum until the gases in the package expand, causing it to float to the surface. The pressure is then increased very slowly until the package drops slowly to a neutral buoyancy position just below the water surface. An equation then relates atmospheric pressure, neutral buoyancy pressure and package weight in water to the volume of entrapped gases in the package. Leak detection during repeated processing, as encountered during repetitive experimentation with the same packages, can be monitored non-destructively by weighing the package in water, differences in weight being equivalent to the buoyant force caused by the displacement of water by gases in the package (Weintraub, 1984). Gylys and Rizvi (1983) used a similar technique, but used the volume changes of the submerged pouch at various levels of vacuum along with Boyle's law to determine the volume of entrapped gas. Gilchrist et al. (1989) modified the fluorescent dye test and the helium leak test, which were previously used to detect leaks in cans, and obtained successful results in detecting micron-sized holes in retort pouches.

Shift of Cold Spot

Although the use of air over-pressure in steam retorting of flexible packages may be sufficient to prevent the rupture of packages, the entrapped gases can pose a considerable problem leading to reduced heat transfer into the packages. Retort pouches have a thin profile, and in processing, heat transfer into the pouch is usually considered to be from both sides of the flat package, with the slowest heating region, or "cold spot" located at the geometric center of the retort pouch, as it is for other retortible packages. If, however, a gas layer is present between the top of the food and the package, the heat transfer into the food will be hindered, and the slowest heating region may occur toward the top of the package. Berry and Kohnhorst (1983) performed studies on institutional-sized packages of dimensions 30 x 36 cm, containing 2.4 kg of whole kernel corn in brine and condensed cream of celery soup, with a single thermocouple, positioned at either mid-height or 2/3 height. For both food types, they found that the slowest heating zone was located 2/3 of the height from the bottom of the package for entrapped air volumes above 50 ml. Huerta-Espinosa (1981) reported a similar shift in cold spot in packaged diced Bartlett pears in institutional-sized pouches. Based on time-temperature data obtained from three thermocouples located at the centre and two other locations, he concluded that air contents of 200 or 300 ml caused a shift in the coldest spot to 1/3 from the top of the package.

The shift in the slowest heating region of a packaged food poses a serious problem concerning the typical laboratory methods used to determine processing requirements, in which a thermocouple is placed at the geometric centre of the package, assumed to be the cold spot. Even presently, most temperature data are collected from thermocouples located at the geometric centre of the packages (Peterson and Adams, 1985; McGinnis, 1986). The National Food Processors Association (N.F.P.A.) included illustrations of various devices for locating thermocouples at pouch centre-points in their guidelines (NFPA, 1985). Depending on the magnitude of the shift of the cold spot inside the package, processing times determined from thermocouples positioned at the geometric centre may be deceptive.

III - EVALUATION OF RETORT PERFORMANCE

Introduction

The importance of temperature and heat transfer distribution was pointed out previously (section I). Detailed evaluation of retort performance was undertaken with reference to the Barriquand Steriflow retort because no such published reports were available on this new equipment. Similar studies were also made on the positive flow retort system with electronic control system since this represented a new modification to the previously established system. These were compared with the conventional positive flow steam/air retort with pneumatic controls.

Materials and Methods

Description of Retort Systems

Barriquand Retort

The system used was a standard 1-door, 1-basket horizontal retort (Steriflow Model Standard 1-Basket, Barriquand, Paris) located at the Agriculture Canada Food Research and Development Center at St. Hyacinthe, PQ. The "universal" loading car of the unit contained 8 trays, each 2 cm thick, with dimensions 0.81 x 0.81 m providing a load area of 0.65 m^2 with ample clearance between trays (0.1 m).

The retort operation is based on the recycling of a small volume of water (about 100 L), which is passed through a steam-supplied heat exchanger and is sprayed down on packages at the top tray of the car supplying heat as it flows down to the packages on the lower trays. A powerful pump recycles the heating water at about 40 m^3/hr, or once every 9 seconds (Manufacturer's Data, Steriflow, Barriquand, Paris, France). Cooling is achieved by providing the heat exchanger with cold water, thus using the same water to cool the product as was used for heating.

Process Control System for Barriquand Retort

The Barriquand Steriflow retort is equipped with a programmable Barriquand microprocessor control system, enabling the user to program a series of ramps and dwells as required by the process.

Dixie Positive Flow Pilot Scale Retort

The system used was a pilot-scale 1-door, 1-basket vertical retort (Dixie Canner Equipment Co., Athens, Georgia) located at Macdonald College of McGill University, Montreal, PQ. The inside of the retort is 0.61 m in diameter, with a usable height of 0.66 m.

The retort operation is based on the upward flow of the steam-air processing media which is introduced through a cross spreader at the bottom of the retort and exits through a port at the top of the retort. Temperature and pressure are independently controlled by proportional regulating valves. Continuous mixing of the media is accomplished by diverting a constant flow of air past the control valves, for which the steam control valve must compensate by increasing it's flow rate to maintain set-point temperature. Cooling was achieved by spraying cold water from above, until the water level was above the level of the packages. Throughout the cooling phase a continuous flow of air from below maintained the pressure and provided agitation of the cooling water.

Air By-pass Modification for Dixie Retort

An air bypass line, equipped with a hand valve and a flow meter (Hedland, division of Racine Federated, Inc. Wisconsin), was installed so that a constant overflow of air could be sent to the retort causing constant venting of the media. The venting rate was equivalent to the air bypass flow rate plus the steam fraction corresponding to the processing media employed.

Rack System for Dixie Retort

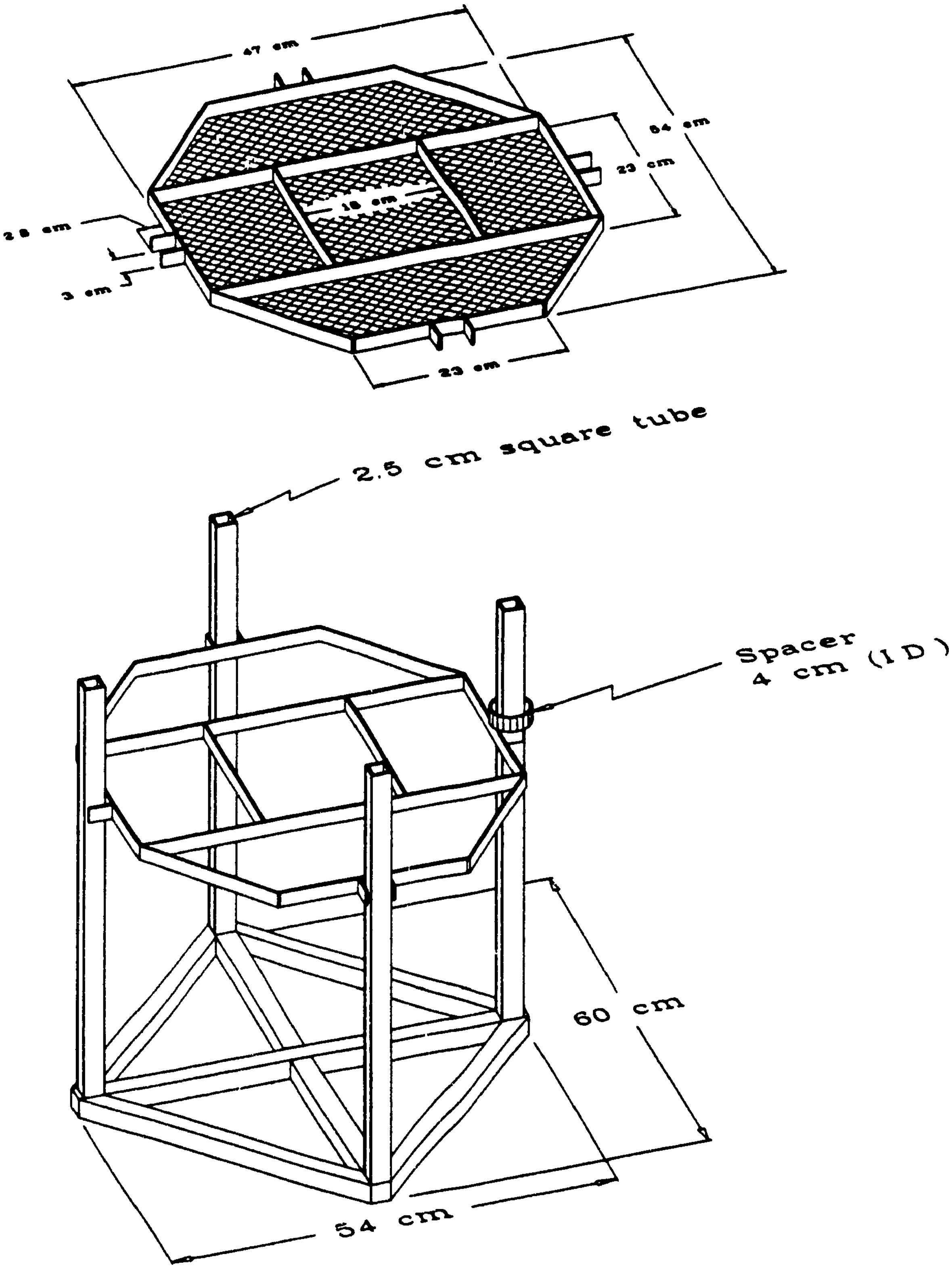
An appropriate rack system was developed since none was available for pouch processing in this retort. The racking system designed permitted loading of up to 14 trays, each tray preventing lateral movement of up to five individual packages while minimizing interference to the flow of the processing media. The design permitted the adjustment of tray spacing from zero to a gap determined by the height of the spacer, or combination of spacers, employed. Figure 1 shows the construction of the racking system, which was made of welded aluminum.

Process Control Systems for Dixie Retort

Standard Pneumatic Control System

The control system supplied with the retort was manufactured by Taylor Inc (Rochester, N.Y.). The control panel consisted of a recording temperature and pressure controller with a 12" diameter chart. The temperature was controlled via a single pneumatic "air to open" control valve, while the pressure was controlled by means of two valves, one "air to open" on the air line to the retort, and one "air to close" on the retort vent pipe. This system provided for independent control of temperature and pressure, permitting pressure-cooling to

Figure 1. Construction of aluminum racking system for retort pouch processing in Dixie positive flow retort.



counteract high internal pressures in packages during cooling due to expansion of entrapped gases, which can otherwise cause rupture of glass and flexible containers.

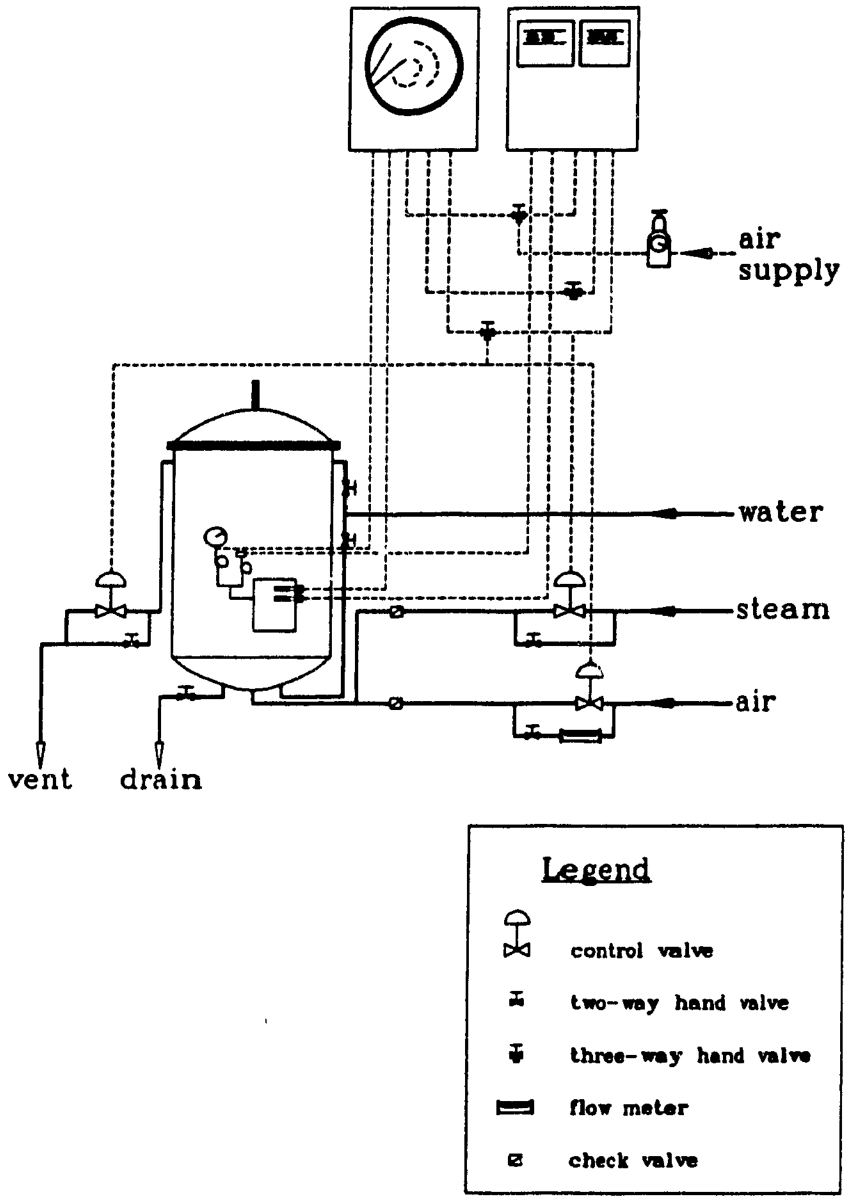
Electro-pneumatic Control System

A second control panel, incorporating a programmable electronic process controller was installed on the retort in parallel to the pneumatic panel, in a manner allowing the operator to switch from one system to the other simply by turning the three 3-way valves illustrated in Figure 2. The controllers employed were model 455 controller/programmer made by Control & Readout Limited (West Sussex, England). The two controllers, one supplied with a signal from a pressure transducer (model 218, Viatran Corporation, N.Y.), and the other receiving input from an R.T.D. (model RM-50, Intempco Controls Ltd., Quebec, Canada), controlled the standard pneumatic valves via two electro-pneumatic converters (Type 1000I/P, Bellofram Ltd., MA, U.S.A.). The retort and control systems are illustrated in Figure 2.

Data Acquisition System

The data acquisition system used for this study consisted of a Metrabyte™ "Dash-8" interface and 3 "EXP-16" expansion boards (Metrabyte Corp. Taunton, Massachusetts). The Dash-8 board was mounted in an internal slot of a personal computer and acted as an interface between the data acquisition software "EZlog" (Mayan Automation Inc. Dorval, Quebec) and the 3 EXP-16 boards. The 3 EXP-16 boards, each with a capacity of 16 thermocouples, were mounted within an instrument box and connected using type T thermocouple wire, to 48 female receptacles on jack panels (Omega Engineering Inc, Stamford, CT, U.S.A.)) mounted on the sides of the instrument box. Data were recorded in

Figure 2. Schematic diagram of Dixie positive flow retort modified for use with retort pouches, operating with pneumatic and electro-pneumatic control systems.



spreadsheet-compatible format at 15 second intervals on the hard disk of the personal computer.

Design of Food-Simulating Units for the Barriquand Study

For the experiments conducted in the Barriquand retort, Lexan™ bricks (Canadian General Electric, Montreal, Canada) were used for gathering heat penetration data. Food-simulating test units were fabricated by sandwiching a thermocouple tightly between two half-thickness Lexan slabs (10 x 15 x 1.0 cm) with its tip located at the geometric center of the brick as detailed in Ramaswamy et al. (1983). The thermocouple tip, which was secured by a blob of solder, was in good contact with the brick. NFPA (1985) suggested that Lexan polycarbonate could be used for fabricating test bricks for heat distribution studies and this was chosen as a substitute for the relatively expensive Teflon™. Further, the transparent Lexan slab permitted visual observation of the thermocouple wire for failure without actually dismantling the brick.

Experimental Layout for the Barriquand Retort

To simulate the fully loaded retort operation, each tray was loaded with 24 bricks of Lexan™ plastic (polycarbonate), each with dimensions of about 10 cm x 15 cm x 2 cm. With the eight trays numbered 1 to 8 from top to bottom, 6 thermocouples were located on each of tray numbers 1, 3, 6, and 8 by carefully tying thermocouples to the perforated racks so that their tips did not touch any brick or rack material.

With Lexan test transducers placed on the top, middle or bottom tray (tray #1, 5, or 8), experiments were carried out in duplicates at two temperatures, 115.6 and 121.1°C, and two air over-pressure levels corresponding to 65/35 and

75/25 steam/air mixtures (270 and 230 kPa at 115.6°C, 320 and 280 kPa at 121.1°C, respectively). For the temperature distribution tests with thermocouples distributed throughout the product loading zone, this was equivalent to employing six replicates per condition. During retort operation, both medium temperature from the 24 bare thermocouples and test brick temperature from the thermocouples in the 24 Lexan bricks were obtained at 15 second intervals throughout the entire process, which was continued for a minimum of 30 minutes (cook period) following retort come-up time. All thermocouples were calibrated against an ASTM mercury-in-glass thermometer.

Experimental Layout for the Positive Flow Retort

The temperature distribution studies for the positive flow retort were similar to those for the Barriquand retort, except that due to a limited datalogger capacity, only 8 bare thermocouples were employed. Three of these thermocouples were attached on each of trays #2 and #6, (top and middle) and two were attached to tray #10 (toward the bottom of the loading area). The remaining datalogger channels were occupied for the studies discussed later.

Data Analysis

Temperature Distribution & Stability in Retort Systems

Corrected temperature data were analyzed for means and standard deviations from all thermocouple locations at each recorded time (temperature stability) and for means and standard deviations at each thermocouple location over the cook period (temperature distribution) as originally suggested by Tung (1974) and detailed in Tung and Ramaswamy (1986). The overall standard deviation in temperature from all test locations over the cook period (an indicator of the amplitude of temperature oscillations) was taken as a measure of performance of the control system, while the maximum temperature difference within the retort was taken as a measure of the temperature distribution during the cook period. Mean cook temperatures on different trays were also computed to evaluate tray-to-tray variation in temperature.

Heat and Lethality Distribution in Barriquand Retort

Time-temperature data from Lexan bricks were employed to evaluate the heating and cooling rate indices (f_h and f_c), obtained as negative reciprocal slopes of the straight line portion of their heat penetration curves (Ball, 1923) by plotting the temperature difference between the retort and the test brick on logarithmic ordinate vs. time on the linear abscissa. The accumulated lethality of the process (F_0) was obtained from center temperatures of test bricks by numerical integration using the lethal rate equation of Ball (1923) as performed by Patashnik (1953) for the two processing temperatures (115.6°C and 121.1°C), and two steam contents (65% and 75%).

Results and Discussion

Temperature Performance of the Retort Systems

Temperature performance analysis was conducted to evaluate the recently introduced Barriquand Steriflow retort. The positive flow steam-air retort operating with and without the electronic control modification was tested, and used as a reference for the Barriquand system.

Three parameters were used to evaluate the temperature performance of the retort systems. The temperature history at each thermocouple location for all runs in the three retort systems was tabulated as shown condensed in Table 1 for a single run in the Barriquand retort. The last two columns in Table 1 are the computed means and standard deviations in temperature for the various thermocouples. From these two columns, the retort come-up period (time after steam-on when the mean retort temperature reaches the set-point temperature; 8 minutes for this example) can be identified. For the cook period (8 to 35 minutes for Table 1) the last two columns can be used to evaluate the *temperature stability* of the process. The bottom two rows of Table 1 are the computed means and standard deviations in temperature at each thermocouple location during the cook period, and are used to evaluate the *temperature distribution*. The maximum temperature deviation within the retort, and the overall mean temperatures with respect to different tray levels, along with the overall mean and standard deviation, are presented below Table 1. These data are used to analyse the *temperature deviation* for the retorts.

It is important to note that temperature distribution alone does not determine the efficacy of a process. Despite good temperature distribution, inadequate lethality may be imparted if the heat transfer distribution (as measured by surface heat transfer coefficient and/or heating rate index) is not uniform. This subject is addressed later in the section entitled Temperature Deviation.

Temperature Stability

Temperature oscillations are characteristic of all control systems and stable oscillations generally result only after steady state conditions are achieved in the retort.

Table 1. Temperature history of each location for sample run in Barriquand Steriflow retort at 121.1°C and 280 kPa (absolute) total pressure.

	Temperature at various thermocouple locations (°C)								
Time (min)	1	2	3	4	5	......	24	mean	s.d.
0.0	25.2	25.8	28.3	26.3	28.0	......	24.9	25.5	0.99
0.5	28.8	29.7	28.9	28.7	30.1	......	27.6	28.2	0.95
1.0	36.5	36.8	37.1	36.3	37.5	......	33.5	35.6	1.23
1.5	46.4	45.8	46.2	45.7	46.5	......	44.4	45.3	0.74
2.0	57.1	57.4	56.9	57.0	57.8	......	54.9	56.1	1.02
2.5	67.0	66.1	65.7	66.8	66.3	......	63.9	65.4	1.01
3.0	75.7	74.9	75.5	74.7	75.8	......	74.4	74.7	0.70
3.5	85.4	84.6	84.9	84.4	85.3	......	82.5	84.0	0.88
4.0	93.4	92.3	92.9	92.4	93.0	......	90.5	92.1	0.79
4.5	99.4	100.2	99.0	99.8	100.1	......	97.6	99.0	0.78
5.0	105.1	106.7	105.2	106.0	105.3	......	104.5	105.1	0.77
5.5	110.1	111.1	109.9	111.0	110.2	......	109.9	110.0	0.61
6.0	115.2	114.5	115.1	114.1	114.9	......	114.0	114.2	0.55
6.5	118.2	118.0	117.8	117.9	117.7	......	116.4	117.5	0.58
7.0	121.5	120.3	121.1	120.6	121.7	......	120.1	120.4	0.60
7.5	120.2	119.3	120.3	118.9	120.4	......	120.9	120.0	0.54
8.0	121.3	122.3	121.6	121.9	121.7	......	121.1	121.4	0.40
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
34.0	120.5	120.5	120.1	120.9	119.9	......	120.1	120.4	0.37
34.5	120.8	120.5	120.3	120.6	120.4	......	120.9	120.7	0.29
35.0	121.0	121.6	121.1	121.7	121.2	......	121.9	121.6	0.45
mean	120.90	120.90	121.00	120.70	121.10	......	121.10	120.90	
s.d.	0.62	0.73	0.61	0.74	0.61	......	0.57	0.61	

Maximum & Mean Temperature Deviations for Retort = 2.6, 1.4°C
Mean Temperature for:
Top tray = 121.0°C
Middle Tray = 120.9°C
Bottom Tray = 121.0°C
Overall mean Temperature = 120.9 °C.
Overall standard deviation (s.d.) = 0.61 °C.

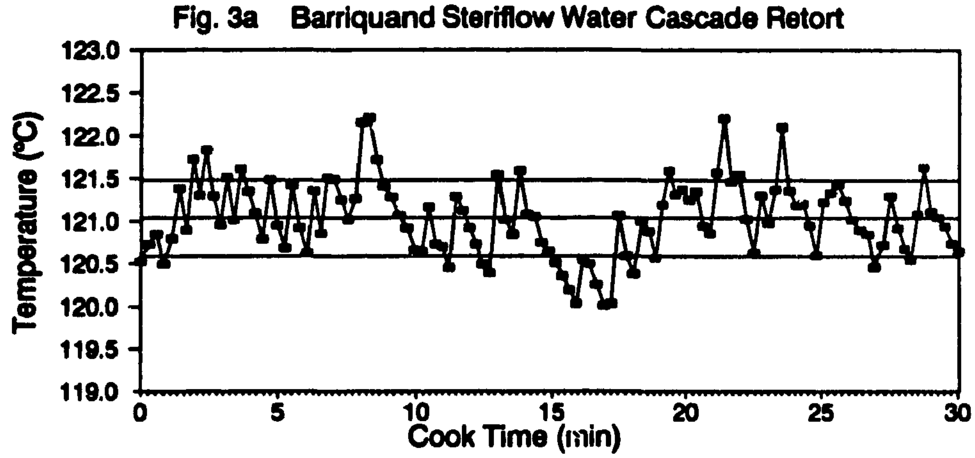
The amplitude of temperature oscillations are indicative of precision of the control system. From a safe lethality viewpoint, uniform temperature oscillations may not be a serious concern since uniform temperature oscillations around the set-point temperature are likely to result in slight over-processing of the product (discussed further in section entitled Temperature Deviation). Non-uniform or large oscillations, however, are not desirable because they can result in unpredictable processing of portions of the retort load. Very large temperature oscillations may also suggest that there is a temperature control problem.

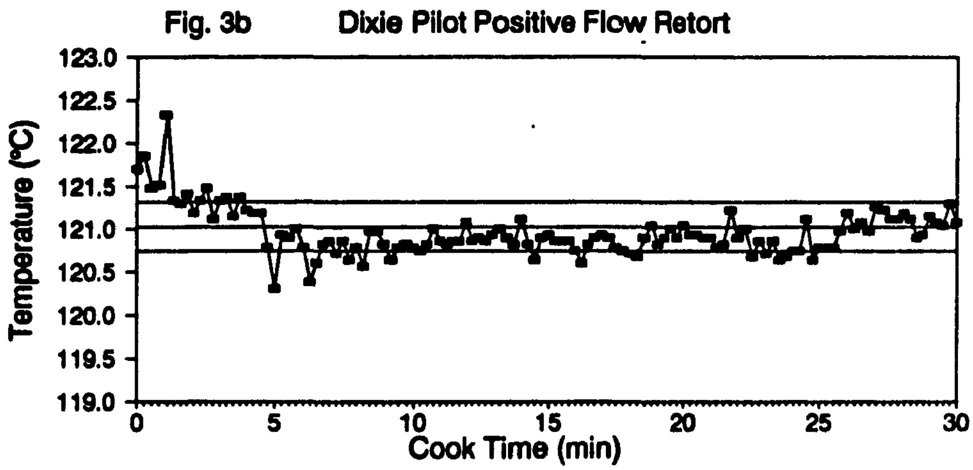
The frequency of temperature oscillations are indicative of the heat exchange rate from the medium. The heat exchange rate and hence the oscillation frequency are typically high early in the heating period due to larger heat load. This initial high heat load is due mainly to the product and the retort shell, which are usually near ambient temperature at the beginning of the process.

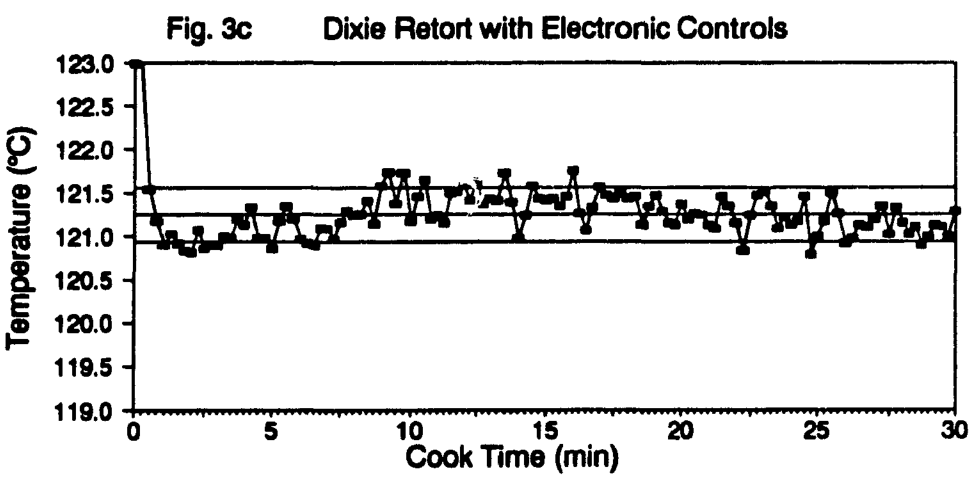
Temperature Stability in the Three Retort Systems

For each retort system, the mean retort temperatures at each time during the cook period were used to indicate temperature stability. Figures 3a,b,c are examples of these plots for each of the three retort systems. This form of presentation may be used to assess the performance of the control system in maintaining the desired operating condition. Shown in Figures 3a,b,c are three lines, the middle of which indicates the average retort temperature. The top and bottom lines represent temperatures one standard deviation above and below the average retort temperature. The standard deviation for this purpose was obtained as the overall standard deviation in temperatures during the cook-period at various locations (from below Table 1). In this analysis, since the amplitude of temperature oscillations varied from cycle to cycle, mean standard deviation

Figure 3. Mean retort temperature vs. time for sample runs in the three retort systems at 121°C and 280 kPa during 30 minute cook period.







during the cook-period was taken as an estimate of the oscillation amplitude.

Referring to the temperature stability plots (Figures 3a,b,c), the cook temperature standard deviation of a typical cook cycle in the Barriquand retort (Table 2, Figure 3a) was 0.71°C. This was much larger than the low (0.47, 0.31°C) cook period standard deviations from Figures 3b and 3c, which were observed in sample runs of the positive flow retort with the pneumatic or electro-pneumatic control systems respectively. However, on examination of data from several replicate runs, the average temperature oscillation (estimated by the overall standard deviation) associated for the three retort systems were similar.

Referring to Figure 3a, the frequency of temperature oscillations during cook period in the Barriquand retort was initially about 1.5 cycles/min, which was attributed to the initially high heat load. After about 5 minutes, the oscillation frequency in the Barriquand retort dropped to result in an average frequency of about 1 cycle/min for the cook period. For the pneumatic and electro-pneumatic control systems on the positive flow retort (Figure 3b,c), the frequency of temperature oscillations averaged about 1 cycle/min, and was constant, indicating that the temperature oscillations were not dependent on the product.

Temperature Distribution

It is important to recognize that even when the retort is operating at a particular overall average temperature, the average temperatures at different locations could be different, indicating poor temperature distribution. The process lethality achieved in containers at various locations would be influenced in a way similar to operating the retort at these deviant temperatures. This results in products receiving varied heat treatments which could range from under-processing to over-processing. This may not pose a serious safety concern since

Table 2. Typical temperature performance characteristics during cook period of the three retort systems; Barriquand Steriflow retort and Dixie positive flow steam-air retort operating with pneumatic, and electro-pneumatic control systems

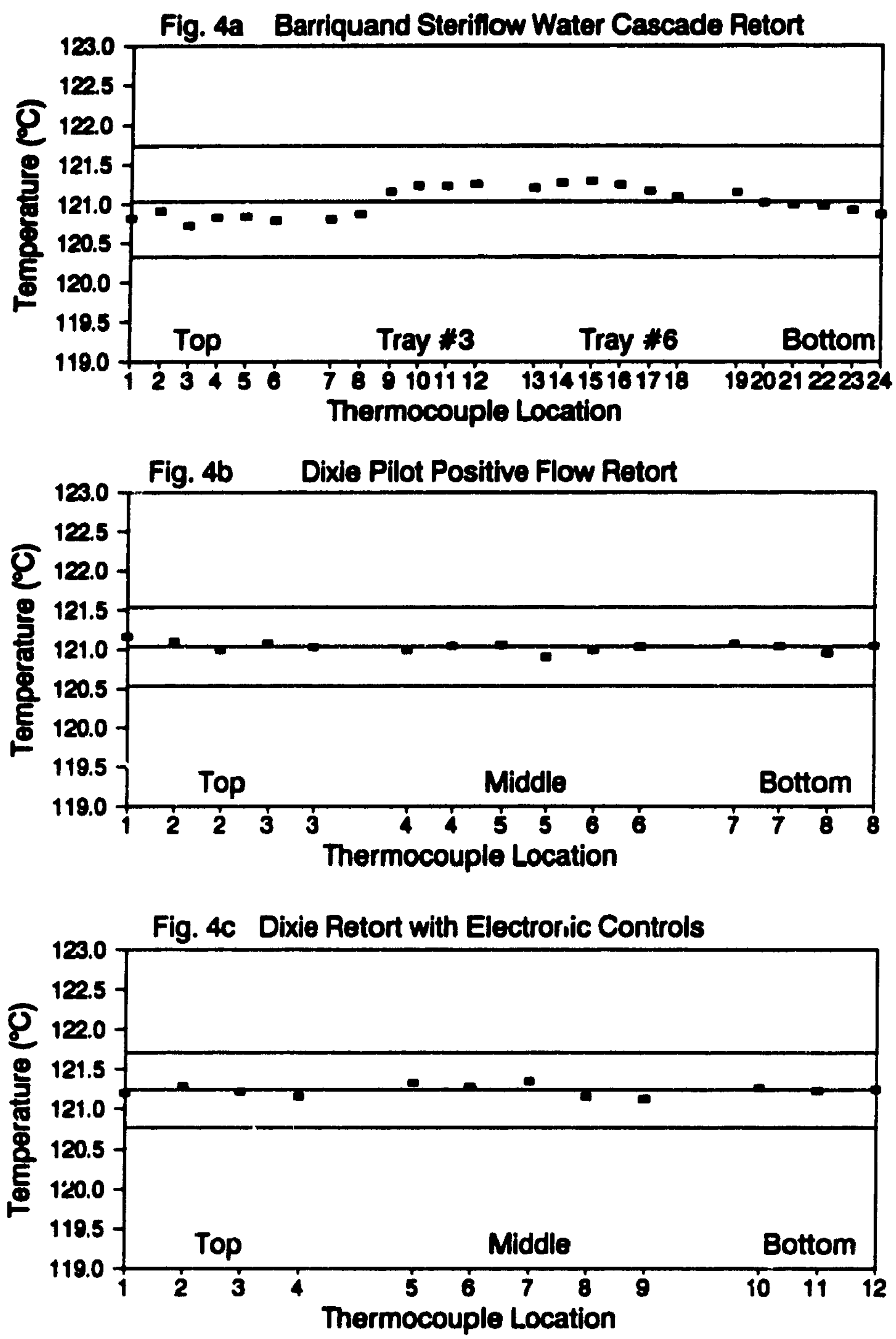
Parameter	Barriquand	Pneumatic	Electro-Pneumatic
Mean cook temperature (°C)	121.03	121.06	121.25
Std. dev. of mean temperature (°C)	0.71	0.47	0.31
Max. locational temperature deviation in the retort (°C)	3.53	1.94	2.73
Mean locational temperature deviation in the retort (°C)	1.89	1.05	1.18
Max. locational mean temperature deviation from R_T (°C)	.30	.12	.11
Max. range of locational mean temperature deviation(°C)	0.57	0.26	0.22
Frequency of temp. oscillations	1/min	1/min	1/min

the process may be redesigned to be adequate at the minimal temperature or alternatively, the retort could be operated at an appropriately higher temperature. This, however, will result in overcooking of part of the retort load.

Temperature Distribution in the Three Retort Systems

Figures 4a,b,c are plots of mean temperatures during the cook-period at various locations within each retort. Any temperature non-uniformity within the retort caused by inadequate circulation of the heating medium or inappropriate rack design and loading pattern would be seen as scattered local mean

Figure 4. Mean temperatures during 30 minute cook period at various locations in the retort systems operating at 121°C and 280 kPa.



temperatures around the average retort temperature. Persistent low or high temperatures at identifiable locations would indicate poor distribution of the heating medium and warrant design modifications of the racking system and/or distribution devices to alter the flow pattern of the heating medium (N.F.P.A., 1985). Improper container size, orientation and load could also be factors responsible for poor temperature distribution. For the purpose of gathering time-temperature data for designing a safe process, the identified location of lowest temperature offers the most conservative choice.

The temperature distribution data for the Steriflow retort are shown in Figure 4a, where the first six thermocouple locations (1-6) were positioned on the top tray (#1), with the next six on Tray #3, followed by six on Tray #6 and the last six on the bottom tray (#8). Data for the pneumatic and electro-pneumatic system are presented in Figures 4b and 4c respectively, with several thermocouples placed on each of the three locations from top to bottom of the retort. The horizontal lines in each figure indicate the mean retort temperature and temperatures one overall standard deviation above and below the mean. Figures 4a,b,c show that average temperatures at different test locations and tray levels in the typical runs were only slightly different from the average retort temperature (0.3°C for the Barriquand, and 0.1°C for the two positive flow systems), indicating good temperature distribution. The maximum variation in mean temperatures at various locations during the cook period was 0.57°C for the Steriflow and less than 0.3°C for the two positive flow systems (Table 2).

Temperature Deviation

Influence of Temperature Deviation on Process Lethality

To illustrate the effect of a ± 0.5°C deviation in retort temperature, Stumbo's method (Stumbo, 1973) and the Lethality Equation method (Equation 3) (based on instantaneous heating) were used to generate both lethality for a given process time, and process time for a given lethality. The results, for set-point temperatures ranging from 115 to 130°C, are summarized in Table 3. The process parameters employed were typical of what might be expected with processing of foods in thin profile packages. Using Stumbo's method, the calculated process times for an F_0 value of 5.0 min varied from 13.5 min at 130°C to 37.1 min at 115°C. The change in process time due to a +0.5°C temperature deviation increased from 1.6% at 130°C to 5.6% at 115°C. The corresponding change due to a -0.5°C temperature deviation was -1.8% to -6.6%. For retort temperatures from 115 to 130°C, lethality changes due to a +0.5°C, and -0.5°C temperature deviations ranged from 11 to 12% and -10 to -11% respectively. The slightly larger relative magnitude (1%) in the resulting lethality due the due to the +0.5°C temperature deviation is due to the logarithmic influence of temperature on lethality. A cyclic retort temperature with an amplitude of ± 0.5°C can thus be expected to result in a slightly higher lethality than a steady temperature controlling at the same mean value.

Assuming instantaneous heating conditions, the lethality changes as determined by the Lethality Equation Method were + 12% and -10.8% due to a +5 and -0.5°C temperature variation, respectively. These values are similar to those obtained from the rather more complex method of Stumbo. This indicates that the simple lethality relationship can be used to obtain approximate estimates of changes in lethality due to variations in retort temperatures.

Table 3. Influence of a ± 0.5 °C temperature deviation from retort setpoint temperature (RT) on process time and process lethality.

	Temperature Particulars (T), °C			
	130	125	120	115
Stumbo's Method				
A. Process Time for a given F_0 (5 min)				
1. Calculated process time at RT	13.5	16.5	22.9	37.1
2. Calculated process time at RT+0.5°C	13.3	16.1	22.1	35.1
3. % change in process time	+1.6	+2.3	+3.5	+5.6
4. Calculated process time at RT-0.5°C	13.8	16.9	23.8	39.5
5. % change in process time	-1.8	-2.4	-3.8	-6.6
B. Process Lethality for a given process				
1. Calculated process lethality at RT	5.00	5.00	5.00	5.00
2. Calculated process lethality at RT+0.5°C	5.55	5.57	5.59	5.60
3. % change in process lethality	+11.00	+11.40	+11.80	+12.00
4. Calculated process lethality at RT-0.5°C	4.50	4.49	4.47	4.46
5. % change in process lethality	-10.00	-10.20	-10.60	-10.80
Lethality Equation Method (Instantaneous Heating)				
C. Process Time for a given F_0 (5 min)				
1. Calculated process time at RT	0.64	2.04	6.44	20.37
2. Calculated process time at RT+0.5°C	0.57	1.82	5.74	18.15
3. % change in process time	+10.90	+10.90	+10.90	+10.90
4. Calculated process time at RT-0.5°C	0.72	2.29	7.23	22.85
5. % change in process time	-12.20	-12.20	-12.20	-12.20
D. Process Lethality for a given process				
1. Calculated process lethality at RT	5.00	5.00	5.00	5.00
2. Calculated process lethality at RT+0.5°C	5.60	5.60	5.60	5.60
3. % change in process lethality	+12.00	+12.00	+12.00	+12.00
4. Calculated process lethality at RT-0.5°C	4.46	4.46	4.46	4.46
5. % change in process lethality	-10.80	-10.80	-10.80	-10.80

Temperature Deviation in the Three Retort Systems

Figures 5a,b,c are plots of the maximum temperature difference between the various test locations at each recorded time interval. N.F.P.A. (1985) guidelines recommend that all points in the retort should be at or above the desired temperature within one minute after the retort reaches processing temperature. In addition, all thermocouple readings after the first minute should have a maximum range of 3°F (1.7°C) and should be within 1.5°F (0.9°C) of the reference temperature device. N.F.P.A. (1985) recommends that if these conditions do not exist, then changes in the retort or its loading configuration should be considered. In cases where such changes are not feasible, it will be essential to design the actual process to be adequate for containers located in lowest temperature in the retort (N.F.P.A., 1985).

The maximum temperature difference after come-up, between locations in a characteristic run in the Barriquand retort, as illustrated in Figure 5a, is 3.5°C. This is nearly twice as large as the N.F.P.A. guideline of 1.7°C, and conflicts with the tight distribution pattern shown earlier (Figure 4a). Even the average temperature deviation during the cook-period in the Barriquand retort was quite high (1.9°C). The positive flow retort systems performed slightly better (Figure 5b,c) with maximum temperature differences of 1.9 and 2.7°C, and average deviations of 1.1 and 1.2°C for the pneumatic and electro-pneumatic systems respectively.

A closer examination of individual temperature profiles in the three systems revealed that although temperature oscillations at different locations were similar, they were generally out of phase as shown for two locations in each retort system (Figures 6a,b,c). Because of the out-of-phase cyclic oscillations, temperature differences between certain locations in the retorts were relatively

Figure 5. Maximum temperature difference between various locations vs. time for the three retort systems operating at 121°C and 280 kPa.

Fig. 5a Barriquand Steriflow Water Cascade Retort

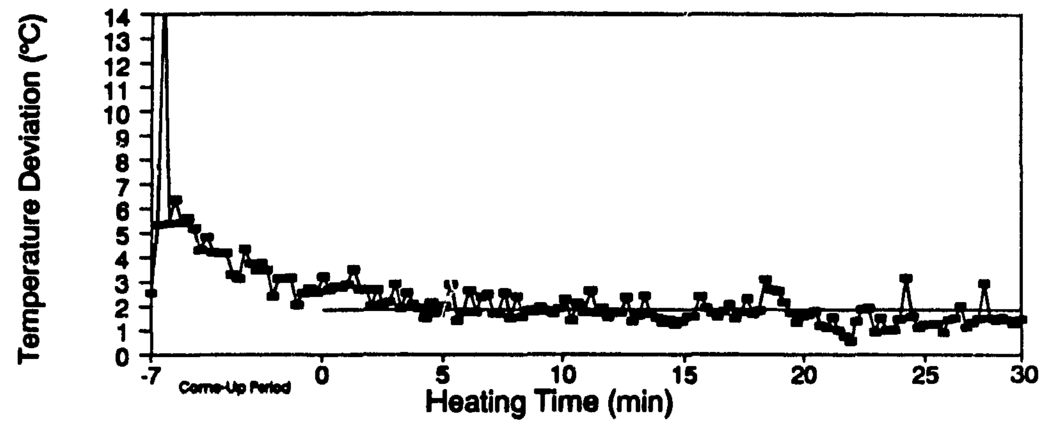


Fig. 5b Dixie Pilot Positive Flow Retort

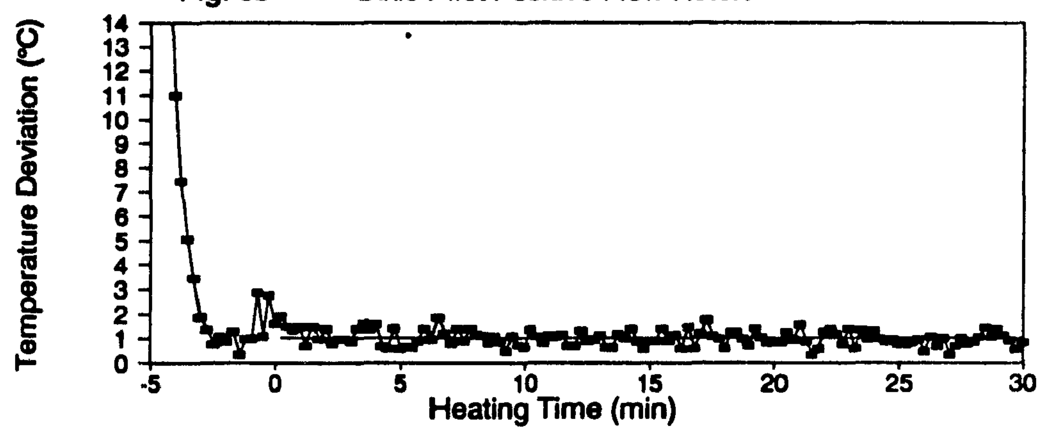


Fig. 5c Dixie Retort with Electronic Controls

Figure 6. Temperature response for two locations during sample runs in the three retort systems operating at 121°C and 280 kPa.

Fig. 6a Barriquand Steriflow Water Cascade Retort

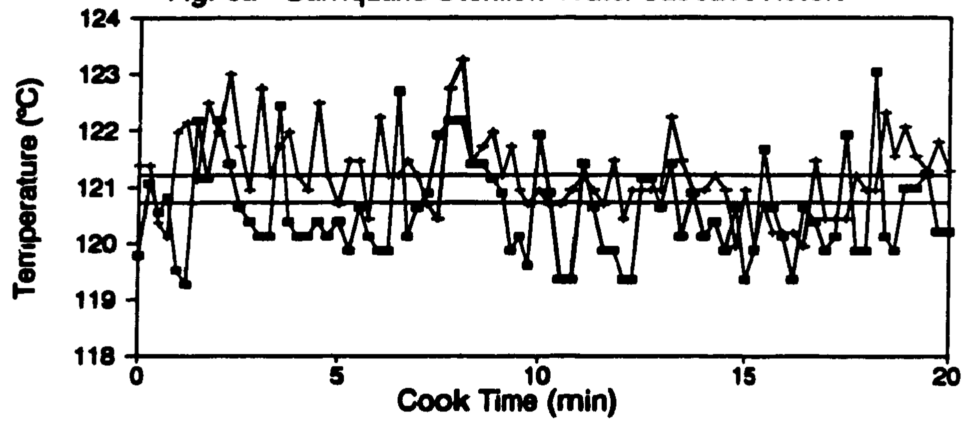


Fig. 6b Dixie Pilot Positive Flow Retort

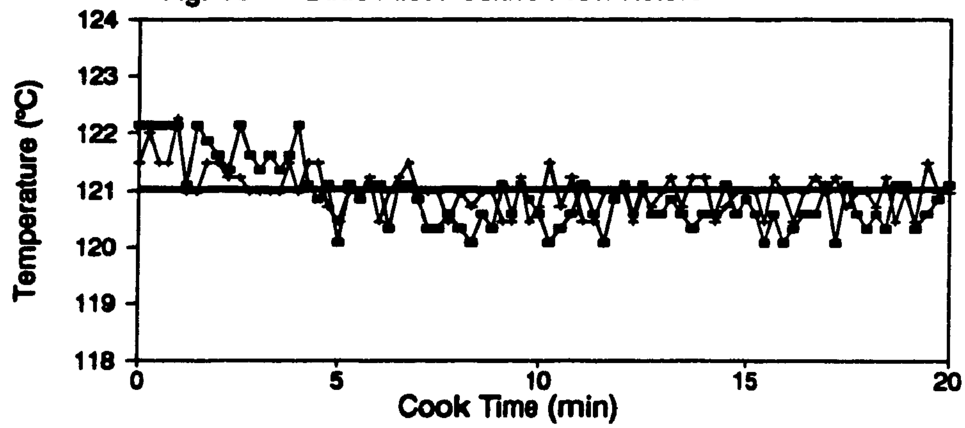
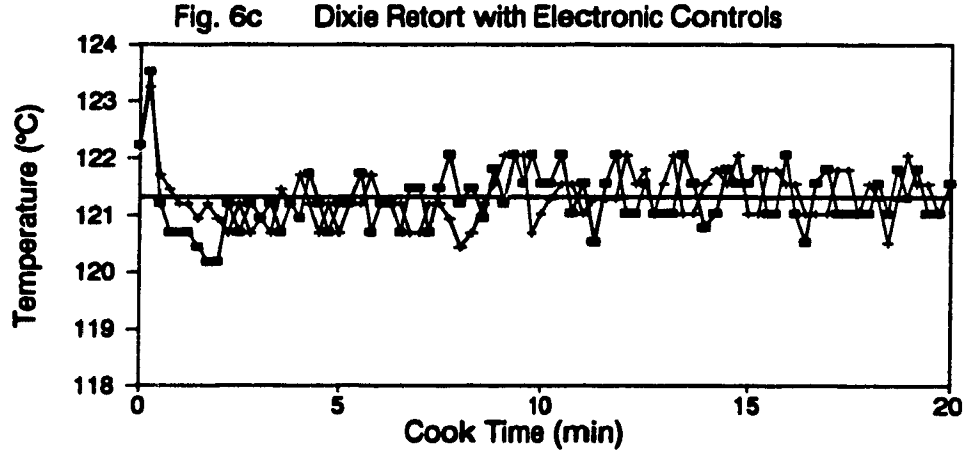


Fig. 6c Dixie Retort with Electronic Controls



large at any given time although their mean values during the entire cook period were only slightly different. Cyclic variations should not be of serious concern, as discussed previously, since they can be expected to marginally increase the resulting process lethality. These results suggest that temperature distribution in the form of Figures 4a,b,c and the overall difference in mean temperatures between locations are better indicators of temperature uniformity than maximum temperature difference or the mean temperature deviations occurring in the retort at any given time.

Temperature Performance summary

Table 4 is a summary of the temperature distribution results for all the test runs from which sample runs were individually examined in the form of Figures 3-6 to monitor any unusual performance. The overall standard deviations in temperature during the cook period (indication of the amplitude of cyclic temperature oscillations) for the test runs in the Steriflow retort varied from 0.6 to 0.7°C with a mean value of 0.6°C. For the positive flow retort systems, the overall standard deviations ranged from 0.3 to 1.0°C with a mean of 0.6°C. The variation in temperatures at separate locations within the retorts were above the 1.7°C established in the N.F.P.A. guideline with variations in the Steriflow retort during the cook period ranging from 2.6 to 3.9 °C with a mean value of 3.1°C. In the positive flow retort, temperature deviations varied from 1.8 to a single high value of 6.0°C, with a mean value of 2.7°C. The high 6.0°C deviation in the positive flow retort resulted from temperature fluctuations due to unsteady steam line pressure. This was an inevitable technical problem in the Macdonald College pilot plant, where high steam demand often caused the line pressure to drop below the retort pressure, preventing steam flow into the retort. Despite the

Table 4. Summary of temperature distribution analyses in the Steriflow retort and the positive flow retort with pneumatic and electro-pneumatic control systems.

Code	Nominal Temp. (°C)	Nominal Pressure (kPa, abs)	Temperature (°C) Retort(overall) Mean	S.D.	Max. Temp. Dev.	Mean Temp. Dev.	Top Tray Mean	Middle Tray Mean	Bottom Tray Mean
Barriquand Steriflow Retort:									
211	115.6	230	115.7	0.6	3.1	1.44	115.7	115.7	115.8
212	115.6	230	115.5	0.6	3.3	1.56	115.5	115.5	115.5
211	115.6	230	115.9	0.6	3.4	1.52	116.0	115.9	115.9
212	115.6	230	116.0	0.6	3.1	1.39	116.0	116.0	116.0
211	115.6	230	115.6	0.6	2.9	1.47	115.7	115.5	115.6
212	115.6	230	115.6	0.6	3.7	1.61	115.7	115.6	115.6
221	115.6	270	115.6	0.6	3.6	1.65	115.5	115.6	115.5
222	115.6	270	115.7	0.6	3.1	1.45	115.7	115.6	115.7
221	115.6	270	115.9	0.6	2.9	1.30	115.8	115.9	116.0
222	115.6	270	116.0	0.7	3.2	1.56	116.0	116.0	116.0
221	115.6	270	115.5	0.7	3.2	1.54	115.4	115.5	115.4
222	115.6	270	115.6	0.6	2.6	1.48	115.6	115.6	115.7
111	121.1	280	121.0	0.7	3.5	1.89	120.8	121.1	121.0
112	121.1	280	120.9	0.6	2.6	1.39	121.0	120.9	121.0
111	121.1	280	121.0	0.6	2.7	1.25	121.1	121.0	121.0
112	121.1	280	120.9	0.6	3.0	1.27	120.9	120.9	120.9
111	121.1	280	121.0	0.6	3.9	1.56	121.0	121.0	121.1
112	121.1	280	120.8	0.6	3.0	1.62	120.9	120.8	120.8
121	121.1	320	121.0	0.6	3.1	1.54	121.0	121.0	121.1
122	121.1	320	120.9	0.6	2.9	1.49	121.0	120.9	120.9
121	121.1	320	121.0	0.7	3.1	1.60	121.0	121.0	121.0
122	121.1	320	121.1	0.6	3.3	1.51	121.1	121.1	121.2
121	121.1	320	120.9	0.6	2.7	1.53	120.9	121.0	121.0
122	121.1	320	120.8	0.6	2.7	1.59	120.9	120.8	120.8
Dixie Pilot Positive Flow Retort with Pneumatic Control System:									
211	115.6	230	115.8	0.7	2.2	0.9	115.8	115.8	115.8
212	115.6	230	116.0	0.6	1.8	1.0	116.0	116.0	116.0
211	115.6	230	115.8	0.6	2.7	1.3	115.7	115.8	115.7
212	115.6	230	116.0	0.6	4.0	1.1	116.0	115.8	116.0
221	115.6	270	115.5	0.6	2.5	1.3	115.5	115.3	115.6
222	115.6	270	115.6	0.6	2.9	1.1	115.7	115.4	115.7
221	115.6	270	115.5	0.7	2.3	1.1	116.0	115.4	115.5
222	115.6	270	115.3	0.5	2.8	1.1	115.4	115.2	115.2
111	121.1	280	121.1	0.6	2.2	0.9	121.1	121.0	121.0
112	121.1	280	121.4	0.6	2.2	1.2	121.3	121.4	121.4
111	121.1	280	121.7	0.5	1.9	1.0	121.6	121.7	121.6
112	121.1	280	121.0	0.4	1.9	1.0	121.0	121.0	121.0
121	121.1	320	120.9	0.7	2.6	1.2	120.9	120.8	120.9
122	121.1	320	121.4	0.6	2.0	1.0	121.3	121.3	121.3
121	121.1	320	120.7	1.0	6.0	2.5	120.4	121.0	120.6
122	121.1	320	121.3	0.6	2.5	1.1	121.3	121.2	121.2
Dixie Pilot Positive Flow Retort with Electro-pnuematic Control System (sample data):									
E_1	121.1	280	121.2	0.3	2.7	1.2	121.3	121.3	121.2
E_2	121.1	320	121.5	0.5	2.3	1.0	121.5	121.5	121.4

relatively large temperature variation at any particular time in the retorts, the maximum variations of mean locational temperatures for the cook period were considerably less, averaging 0.6°C for the Barriquand Steriflow, and 0.2 to 0.3°C for the positive flow systems. Mean cook temperatures on the top, middle and bottom trays were very close (maximum tray to tray deviation in the mean temperature during the cook period was 0.3°C for Steriflow runs and 0.2°C for positive flow runs), and did not show any particular trend.

The amplitude of the temperature oscillations in all three retort systems were relatively large throughout the cook period. The temperature oscillations in the Barriquand retort were more reproducible, ranging from 0.6 to 0.7°C than the 0.3 to 1.0°C range for the positive flow retort. It may be possible to reduce the temperature oscillation amplitudes by "fine-tuning" the controllers to operate between narrower temperature limits. Alternatively the systems may be improved through physical modification of the retorts, by modifying the design of the distribution system to increase the volume and flow rate of the heating medium, adding steam to the retort shell during cooking, or, in the Barriquand, adding water from other locations in addition to spraying from the top.

Heat Transfer/Lethality Distribution

As recognized earlier, temperature uniformity is an important consideration and a necessary criterion for the performance testing of a retort. In spite of good temperature distribution, nonuniform processing conditions can result if heat transfer rates of packages at various locations in the retort are not uniform. The heating rate index obtained as the negative reciprocal slope of the heat penetration curve has been used as indicator of the heat transfer capacity of the heating media (Ball, 1923; Pflug and Borrero, 1967). For each transducer, the process lethality, which ultimately determines the efficacy of a process, was calculated based on numerical integration of the lethal rate equation of Ball (1923), as performed by Patashnik (1953).

Heat Transfer and Lethality Distribution in the Barriquand Retort

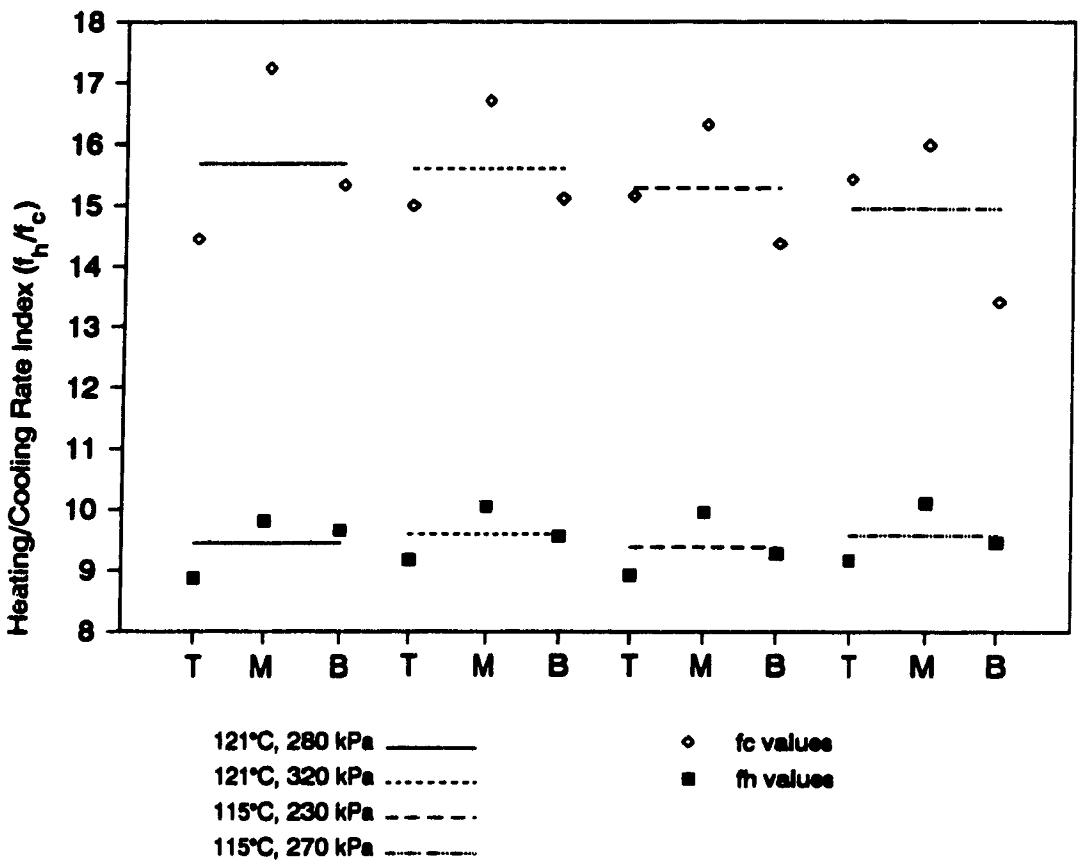
Mean values and standard deviations of heating and cooling rate indexes (f_h & f_c) and process lethality (F_o) were obtained from the Lexan test transducers. Table 5 is a summary of these parameters and their standard deviations, obtained from transducers on the top, middle and bottom trays of the loading car for each processing condition.

The f_h and f_c values for the four processing conditions at the three tray levels are presented Figure 7. From this plot, although f_c values for the 115°C processes were slightly lower than at 121°C, there were no appreciable differences in the heating or cooling rate parameters between the two temperatures and two over-pressures. Both f_h and f_c values (Table 5, Figure 7) were, however clearly influenced by their position in the retort. The f_h and f_c values were relatively low on the top and bottom trays and high on the middle tray. This indicates that products on top and bottom trays would heat (and cool) faster and those on the middle tray would heat (and cool) slower as compared with products placed on other trays. In a retort of this type, water is sprayed from the top and pumped out from the bottom. Direct contact with freshly heated water at the top tray, and submergence of the bottom tray is the most probable cause of the relatively higher heating/cooling rate indexes at these locations. The variation in f_h and f_c values may not be a serious concern since the heating and cooling rates are the same within a tray. A low heating rate index, which results in a high lethality during heating will be moderated by a low lethality during cooling due to the relatively

Table 5. Mean values (and standard deviations) of heating and cooling rate indexes (f_h and f_c), and process lethality (F_o) on different trays for centre-point of Lexan bricks processed in the Barriquand retort, and for centre-point of the silicone bricks in the positive flow retort operating on pneumatic controls.

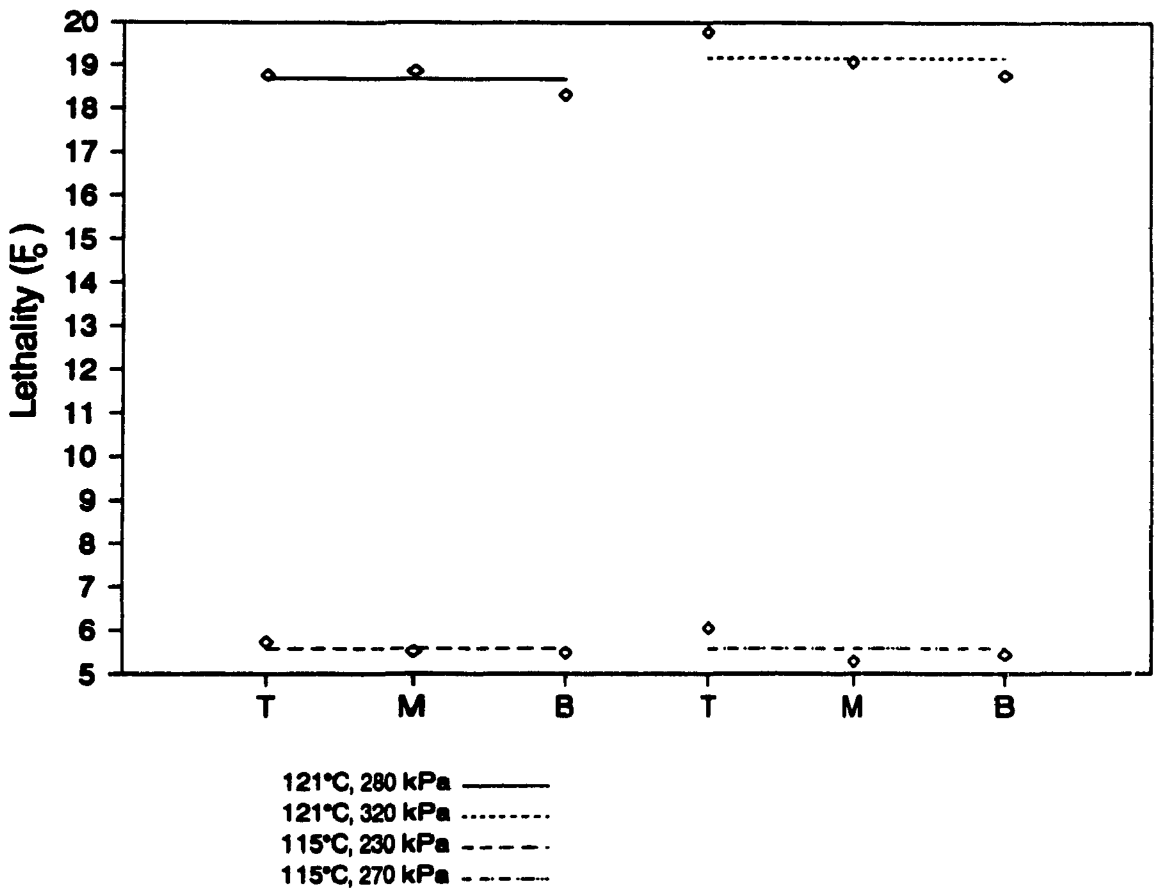
Tray Level	f_h Mean (s.d.) (min)	f_c Mean (s.d.) (min)	F_o Mean (s.d.) (min)
Barriquand Steriflow Water Cascade Retort:			
121.1°C, 320 kPa			
Top	9.2(0.22)	15.0(0.54)	19.8(0.67)
Middle	10.1(0.45)	16.7(0.85)	19.0(0.84)
Bottom	9.6(0.34)	15.1(0.50)	18.7(0.58)
121.1°C, 280 kPa			
Top	8.8(0.24)	14.4(1.20)	18.8(0.74)
Middle	9.8(0.45)	17.2(0.84)	18.9(1.44)
Bottom	9.6(0.37)	15.3(0.67)	18.3(0.77)
115.6°C, 270 kPa			
Top	9.1(0.27)	15.4(1.69)	6.0(0.24)
Middle	10.1(0.47)	16.0(0.79)	5.3(0.17)
Bottom	9.5(0.39)	13.4(0.77)	5.4(0.22)
115.6°C, 230 kPa			
Top	8.9(0.33)	15.2(0.34)	5.7(0.22)
Middle	10.0(0.31)	16.3(0.87)	5.5(0.14)
Bottom	9.3(0.48)	14.4(1.13)	5.5(0.14)
Dixie Pilot Positive Flow Retort with Pneumatic Control System:			
121.1°C, 320 kPa			
Top	9.6(0.79)	8.6(0.07)	13.9(0.68)
Middle	10.2(0.38)	9.4(0.33)	14.1(0.42)
115.6°C, 270 kPa			
Top	10.5(0.12)	11.2(0.84)	4.2(0.28)
Middle	10.9(1.2)	12.6(0.30)	4.4(0.23)

Figure 7. Average f_h and f_c values for the four processing conditions at top (T), middle (M), and bottom (B) trays in the Barriquand Steriflow retort.



low f_c. The converse is true for high f_h and f_c values, which result in relatively slow heating (low heating lethality) and slow cooling (high cooling lethality). This explanation is supported by the small differences in the accumulated process lethality (Table 5) which are represented graphically in Figure 8 between top, middle and bottom trays.

Figure 8. Average F_0 values for the four processing conditions at top (T), middle (M), and bottom (B) trays in the Barriquand Steriflow retort.



The f_c values of test bricks in the Barriquand Retort were consistently larger than their corresponding f_h values indicating relatively faster heating rates than cooling rates. This provides some additional safety when processes are designed by employing Ball's or Stumbo's process calculation methods which assume $f_h = f_c$. For designing processes, the bottom tray probably offers the most conservative choice.

Heat Transfer and Lethality Distribution in the Dixie Retort

The mean values and standard deviations of f_h, f_c and F_o for the centre-point of silicone test bricks are presented in Table 5. The silicone bricks were used in the top half of the positive flow retort with the pneumatic control system. The construction of the bricks is described later.

From the heating data presented at the bottom of Table 5, the bricks on the middle tray have noticeably larger heating and cooling rate indexes (f_h and f_c), but, similarly to the Barriquand retort, the locational differences between accumulated lethality are small. As with the Barriquand retort, this shows that slight variations in f_h and f_c values may not be a serious concern in terms of process lethality.

IV - EFFECT OF ENTRAPPED AIR

Introduction

The need for a detailed study related to the effect of entrapped air on heat transfer, shift in cold spot and the resulting influence on process lethality was stressed earlier. The study of the effect of entrapped gases in retort pouches was performed in the positive flow steam-air retort using the pneumatic control system.

Materials and Methods

Design of Food-Simulating Units

For the experiments conducted in the positive flow retort, heat penetration data were gathered using bricks (10 x 14.5 x 2 cm) fabricated from silicone rubber (RTV 3110, Dow Corning, Midland, Michigan). The silicone was mixed with catalyst at a 20:1 ratio, and was cured for three days in molds of polycarbonate sandwiched between two plates of glass. Before pouring the silicone into the molds, five 0.010" dia. type T thermocouples (Omega Engineering, Stamford, CT) were positioned with their thin-formed soldered junctions centrally located and spaced 2 mm apart from the middle to close to the surface of the brick (Figure 9). The silicone brick is shown in Figure 10a.

Package Construction

In order to study the effects of varying quantities of entrapped gases on heat penetration parameters of the fabricated silicone rubber bricks in a retort pouch, a packaging procedure was developed to overcome technical problems

Figure 9. Polycarbonate molds for silicone bricks with thermocouples positioned with their thin-formed soldered junctions positioned at five locations from the centre to the surface of the brick.

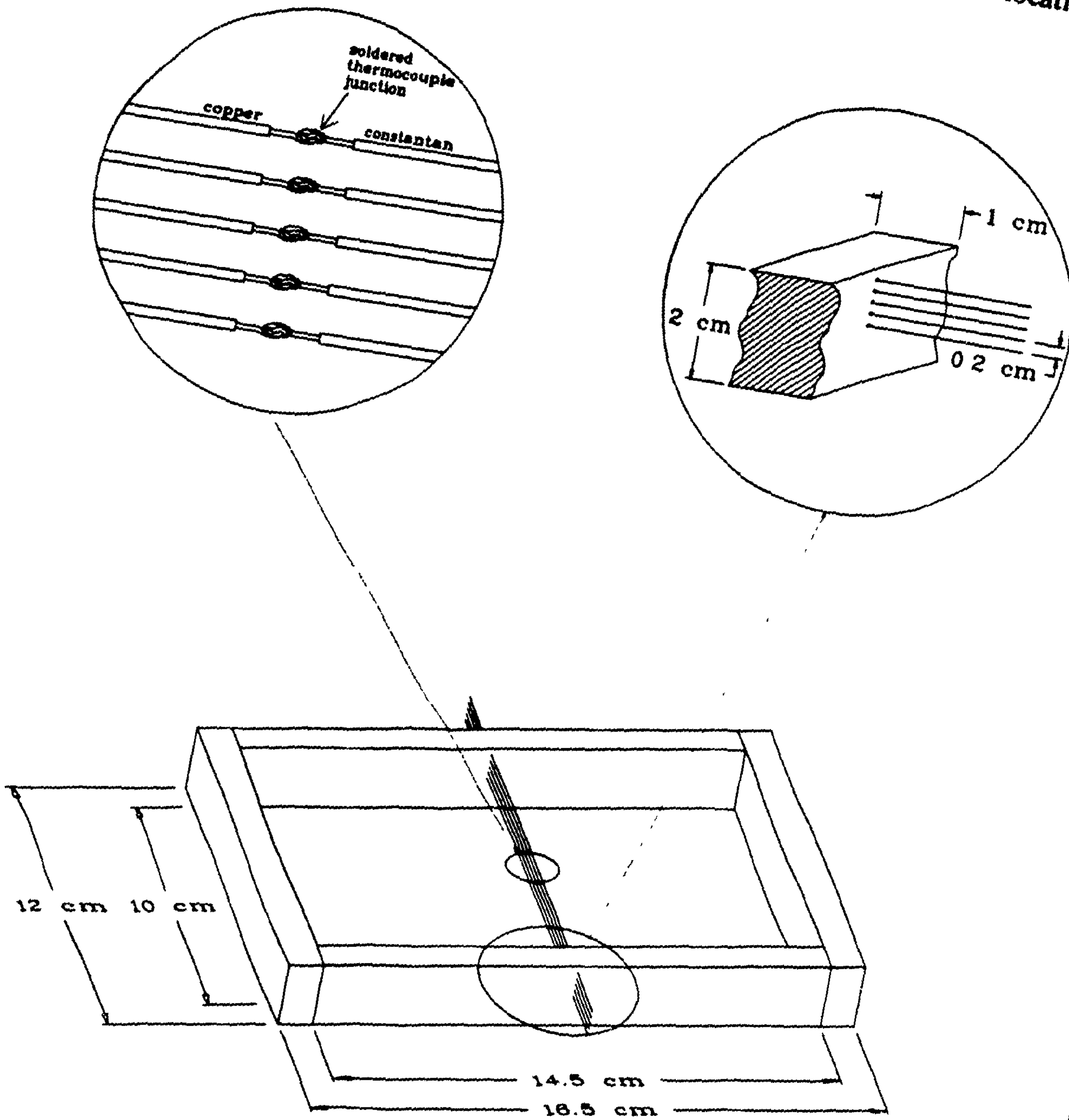
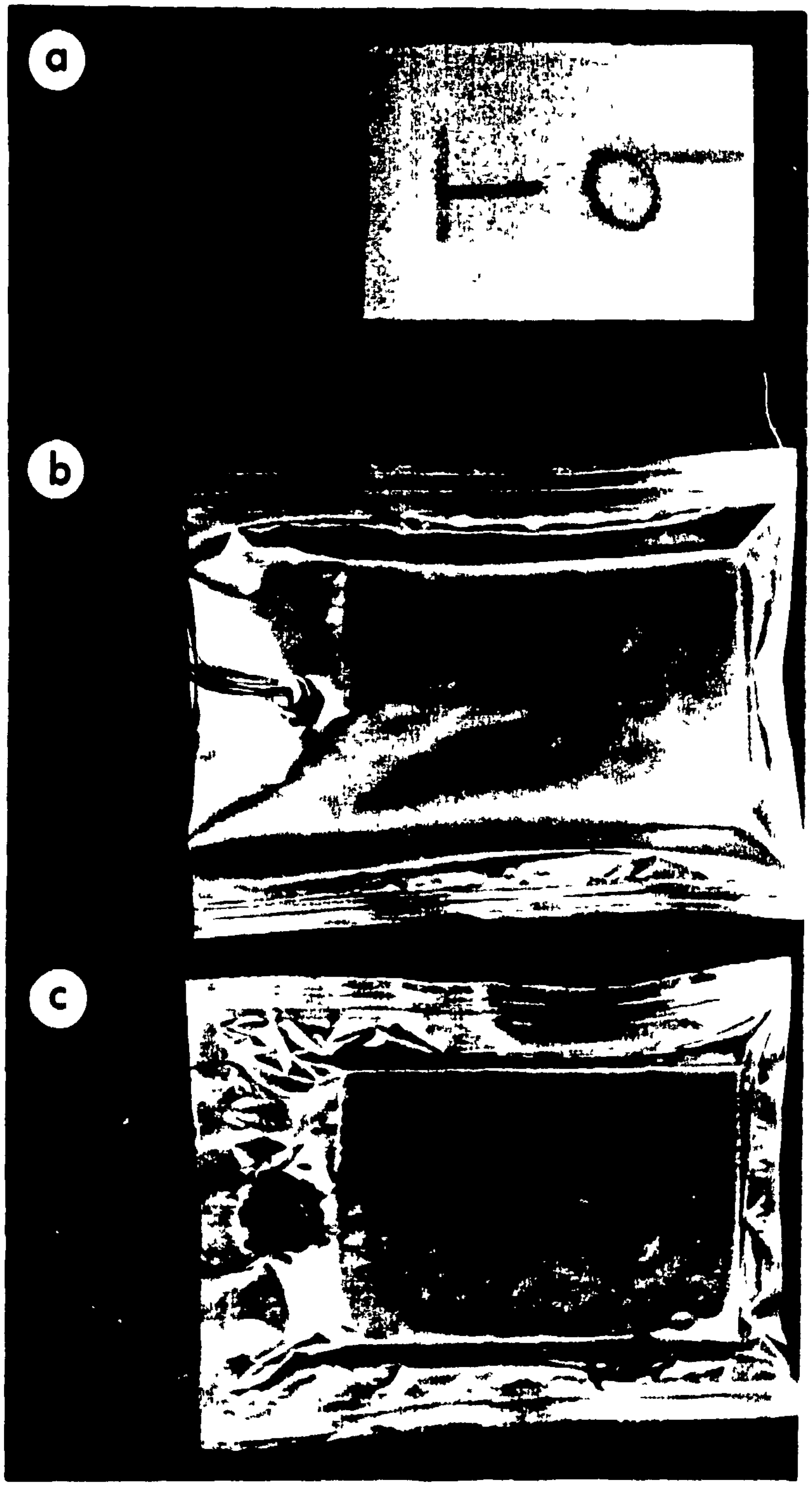


Figure 10. Test units of silicone before packaging (10a); in pouches, with the ten thermocouple wires passed through a packing gland (10b); vacuum-sealed, and with automotive silicone around packaging gland and in a blob at location of Kimwipe (10c).



associated with using 5 thermocouples inside each packaged silicone brick. The pouch material (A.C.F. Flexible Inc., Montreal; polyester/aluminum foil/polypropylene), was cut and double-sealed on three sides to form a pouch which, when sealed on the fourth side, had inside dimensions of 21 x 14 cm. Prior to sealing, a circular hole 9 mm in diameter was cut 3 cm from the open end of one layer of the pouch and the exterior polyester surface around the hole was roughened with fine emery cloth. With the silicone brick inside the package, the ten loose thermocouple wires were passed through a packing gland (O.F. Ecklund Ltd., Cape Coral, Fl.) as illustrated in Figure 10b. Automotive silicone (Gasket Maker Silicone, G.E. Canada, Mississauga, Ont.) was applied generously to all parts of the packing gland and surfaces in contact with the gland before mounting the gland on the package and securing the thermocouples within the gland. A Kimwipe (Kimberly-Clark Corporation, Toronto, Ont.) was folded to about 2 cm x 1 cm, and inserted half way down one side of the pouch, between the silicone brick and the package. The outer surface of the pouch at the location of the Kimwipe was roughened with emery cloth and automotive silicone was applied in a blob on the roughened area. In order to completely seal the packing gland and any space around the thermocouples passing therein, automotive silicone was employed to cover the packing gland from the roughened area of the pouch around the gland to about 4 cm along the thermocouple wires. The automotive silicone required about 24 hours to cure, after which thermocouple connectors (miniature, type N.M.P., Omega Engineering, Stamford, CT) were connected to each of the five thermocouples. The packaged bricks could then be stored until use (Figure 10c).

Immediately prior to processing, 10 ml of water was added to each pouch to simulate high product water activity. The package was evacuated of air, and the final edge of the package was sealed in a vacuum sealer (Röschermatic, type VM-

21, Osnabrück, W. Germany). A syringe was employed to inject the required quantity of air into the package through the silicone blob on the edge of the packaged brick. The package was then submerged in water, and the weight was determined by suspending the package from a wire attached to the bottom mount of the same analytical balance. The weight of the package in water was measured in the same manner between runs to test for any gain or loss of air in the package, which would indicate leakage.

Experimental Layout

For the various retort temperatures and pressures, both medium temperature from 8 bare thermocouples and test brick temperature at five locations in each of the 8 silicone bricks were monitored. Temperature signals for the full 48 channels of the datalogger were obtained at 15 second intervals throughout the entire process, which was continued for a minimum of 30 minutes (cook period) following retort come-up time. All thermocouples were calibrated using the last 5 minutes of process time, when all the thermocouples had reached retort temperature.

The spaces between trays on the racks was 6 cm, allowing efficient media circulation, and minimizing vertical constrainment, permitting the packages to expand freely. To simulate the fully loaded retort operation, all empty spaces in the trays, numbered 1 to 14 (top to bottom), were loaded with bricks of Lexan polycarbonate, as were employed in the previous study on the Barriquand retort. The silicone test bricks were placed on trays 3, 4 and 5. The temperatures in the vicinity of the bricks were monitored by 8 bare thermocouples positioned carefully by tying them to the perforated racks so that their tips did not touch any brick or rack material. Experiments were carried out in duplicates at two temperatures, 115.6 and 121.1°C, and two air over-pressure levels corresponding to 65/35 and 75/25 steam/air mixtures. To ensure adequate mixing of the media, a controlled flow rate of air was measured through the flow meter on the air bypass line, equivalent to the air fraction of the steam/air mixture for a constant retort vent rate of 20 scfm (0.57 m^3/min) with the pneumatic controls and 50 scfm (1.42 m^3/min) for the electro-pneumatic controls. These venting rates were equivalent to changing the processing media every 1 minute, 40 seconds and every 40 seconds, respectively. The higher venting rate was required by the electro-pneumatic system in order to hold all valves partially open, ensuring constant venting of the retort. This eliminated the necessity to overcome the inertia of the pneumatic control valves, which did not respond uniformly to the pressures effected through the electro-pneumatic converter by the proportionating electronic signal from the controller. At low venting rates, the poor valve response led to excessively large amplitude and frequency of both pressure and temperature, since the valves did not respond until the process was far from set-point values.

Data Analysis

Effect of Entrapped Gases on Heating Rate

The nature of the heat penetration curves (discussed in section IV) generated using the time-temperature data from the silicone bricks permitted determination of only the centre-point heating rate index, f_h, which was determined as detailed previously.

Lethality Profiles

Since product lethality is sensitive to even slight temperature differences, especially at processing temperature, temperature data from the thermocouples for the different processing conditions and entrapped air volumes were converted to a uniform initial temperature of 20°C and uniform retort temperatures of 115.6°C and 121.1°C by the equations developed by Schultz and Olson (1940) (Equations 5 and 6). This permitted the comparison of lethality for different conditions in spite of slight variations from one run to the next. Time-temperature data gathered every 15 seconds from the 5 thermocouples inside the silicone bricks were employed to evaluate the lethality (F_0) profile through the bricks. The lethality was determined independently for the first 30 minutes of processing (from steam-on) and for the cooling of the bricks from retort temperature. Lethalities were calculated by numerical integration using the lethal rate equation of Ball (1923) (Equation 3). The influence of the entrapped air content on the lethality at the five thermocouple locations in the bricks was assessed by means regression analysis using the S.A.S. statistical analysis software (SAS Institute Inc., North Carolina) on the McGill University mainframe computer. The analysis generated equations expressing lethality as a function of entrapped air and thermocouple location for both heating and cooling for the two processing temperatures (115.6°C and 121.1°C), and two steam contents (65% and 75%). The effect of entrapped air for the entire process (heating and cooling) was determined by summing the heating and cooling lethality equations.

Results and Discussion

Heat Penetration Analysis in Packages with Entrapped Air

Temperature-time plots were obtained for the temperature at the 5 thermocouple locations and the retort temperature. Two typical plots at 121°C, containing 0 and 40 ml of air, are shown in Figures 11a and 12a. The corresponding heat penetration curves were obtained for the five thermocouple locations in each test brick for each processing condition by plotting the logarithm of the temperature difference between the retort and temperature at the respective location within the brick (T_r - T), vs. time. These two types of plots were useful tools for qualitative interpretation of the heat transfer mechanism involved.

From the temperature-time plot (Figure 11a), it is evident that for packages with no entrapped air, the start of heating is characterized by a short heating lag within the first 2 minutes. The same lag is evident on the temperature difference plot (Figure 11b) as an initially horizontal section. Referring to the figures, the duration of this lag is a function of the depth of the thermocouples in the food, with the longest and shortest lags being displayed respectively by the thermocouples at the centre and surface of the brick. After the 2 minute lag, the heat penetration curves (Figure 11b) from the thermocouples at the various locations within the brick were essentially parallel. The constant slopes in this region indicate uniform and constant f_h values throughout the test bricks, and correspond to the theoretical heating situation, where a lag is followed by f_h values which are independent of location, indicating that heat transfer is uniform throughout the brick.

Figure 11. Temperature history of 5 thermocouple locations in test brick at 121°C and 280 kPa with 0 ml of entrapped air.

Fig. 11a Temperature vs. time plot.

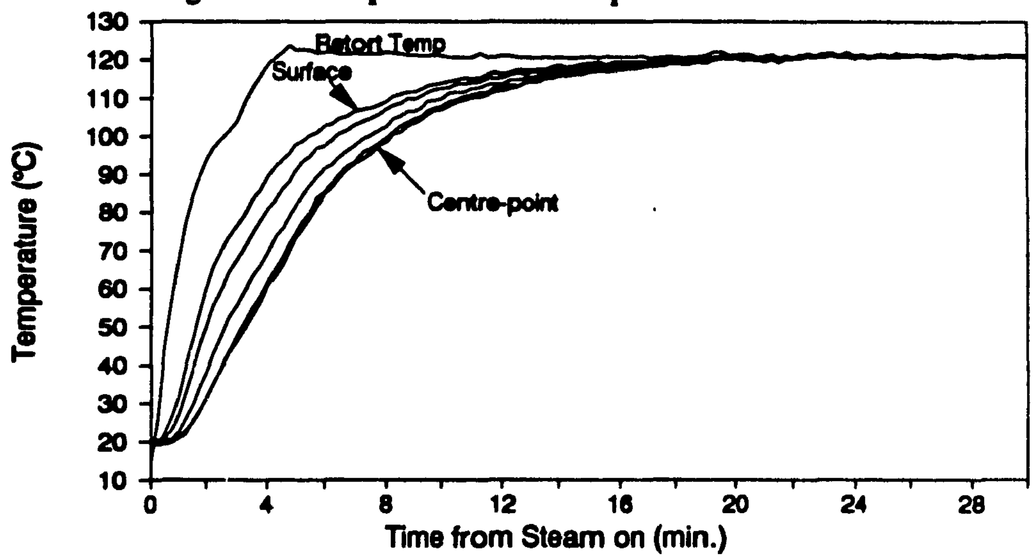


Fig. 11b Temperature difference plot.

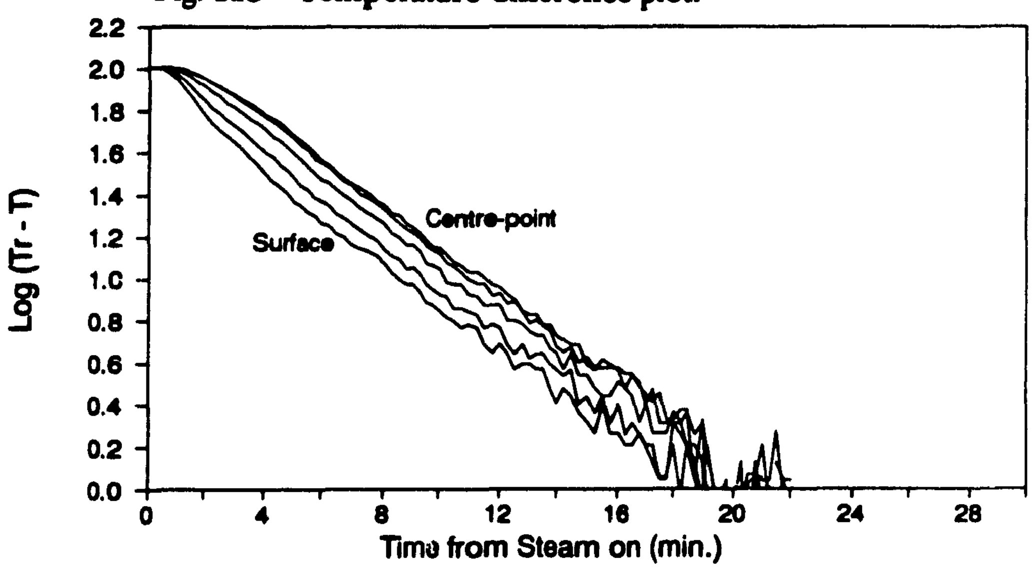


Figure 12. Temperature history of 5 thermocouple locations in test brick at 121°C and 280 kPa with 40 ml of entrapped air.

Fig. 12a Temperature vs. time plot.

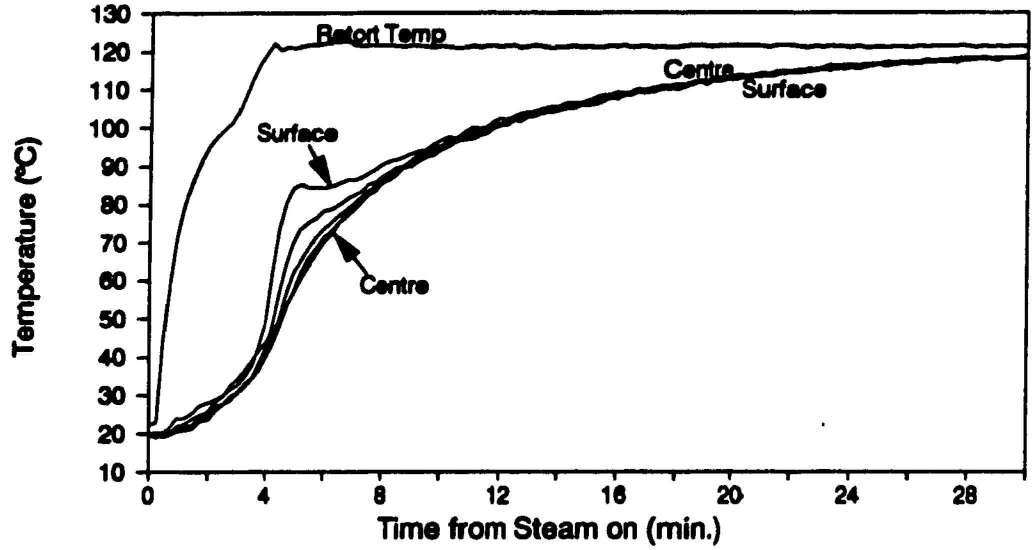
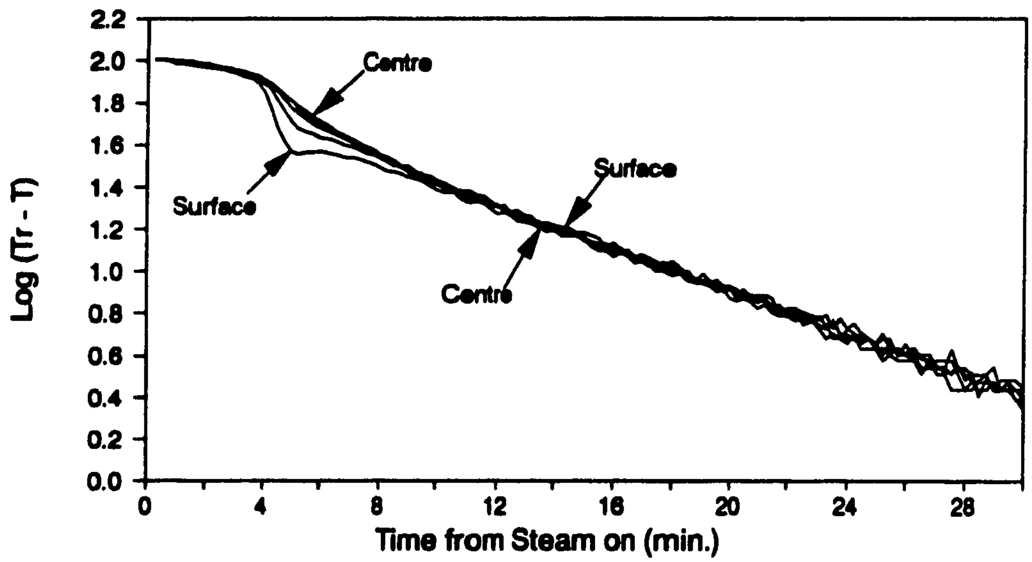


Fig. 12b Temperature difference plot.



With increasing volumes of entrapped air, as shown in Figure 12a and b, the heating lag at the centre of the brick extended to as much as 4 minutes due to the initial (<100°C) insulation effect of the entrapped air. At about 3 minutes from steam on, the retort temperature reached 100°C, at which time the manual retort vent was closed to allow the medium (mainly steam at this time) to climb in temperature and pressure. On the heat penetration and temperature-time curves at this time (Fig. 12a,b), there was a sudden increase in slope, accompanied by a noticeable spread between the 5 curves corresponding to the 5 locations within the bricks. Referring to Figures 12a and b, after about 3 minutes from steam on, the curve for the thermocouple positioned at the surface of the brick is responding most rapidly. It is probable that this behaviour was a result of both the high heat transfer coefficient associated with pure steam (the medium at this stage), and the increasing retort pressure which opposed the increasing internal pressures in the pouch and promoted heat transfer. Due to the lower lag factor, it is expected that the surface of a product will respond more quickly, as demonstrated by the package with no entrapped air (Fig. 11b), but unlike in Fig. 11b, the heat penetration curves from 3 to 9 minutes for higher volumes of entrapped air are not parallel, indicating a non-uniform and continuously changing heat transfer pattern.

At about 4 minutes from steam on, the retort reached processing temperature (see Fig. 11a, 12a), at which point the air inlet was opened, and the pressure inside the retort increased rapidly to set-point pressure. Upon opening the air inlet valve, the retort temperature remained fairly constant, as indicated in Figure 12a. Although the retort temperature at this time was fairly stable, the medium changed from pure steam to a steam-air medium, possibly lowering heat transfer coefficient. This drop in heat transfer coefficient plus possible insulating effect of the expanding entrapped gases may have resulted in the brick surface layer delivering more heat toward the centre of the brick than was could be received from the medium. The temperature at the top of the brick could thus drop to meet the net heat loss. This explanation was hypothesized because the phenomenon was observed in all test runs with packages containing large amounts of entrapped air.

After about 12 minutes from steam on, the temperature at the surface of the brick approached 100°C, and the heat penetration curves for the different positions in the brick converge, with a lower slope than for the previous region (Fig. 12b). Although it is not clear on these black and white plots, there is an air content dependent degree of reversal in the sequence of the curves for this last section (Fig 12a,b). At this time it was the centre, not the surface, which responded most quickly to the temperature gradient, and the centre of the brick was at a slightly higher temperature than the surface. Since it was this latter region of the heat penetration curve that contributed most of the lethality, the relatively higher temperature of the centre of the brick, however slight, could potentially show a higher centre-point lethality with respect to the rest of the brick (Berry, 1979; Martens, 1980).

Centre-Point Heating Rate Index (f_h)

The previously described complexity of the heat penetration curves made it impractical to evaluate the heating rate index for comparison at the various depths within the test brick, since the heat penetration curves consisted of rapidly changing slopes for all curves except those applying to the centre-point. The analysis of the effect of entrapped air on f_h value was therefore limited to the centre-point of the test bricks. Since most previous research has been conducted at the centre-point for the second region of the heat penetration curves, the centre-point f_h values for the second region of these curves provided a link to previous research. Referring once again to Figure 12b, the centre-point heat penetration curve is the top curve until about 12 minutes, at which time, the curve corresponding to the centre point of the brick is below the rest. Referring to the centre-point curve, there is clearly a change in slope at about 7 minutes from steam on. For the point of view of analysis, the curve was divided into two portions, with two different f_h values (broken heating curve). The first region of the curve, which provides the first f_h value (f_{h1}), occurs at relatively low temperatures, and thus has little direct influence on lethality. However, this first region imparts a temperature gradient in the product which may affect the heating rate and indirectly influence the lethality from the following, higher temperature region. Referring to Figure 12b, the second region of the centre-point heat penetration curve occurred from about 9 minutes, and ends as the brick temperature reaches retort temperature. This segment of the process, with it's slope of f_{h2}, occurs at a higher temperature, and imparts much more lethality than the previous region. and is therefore of substantial significance to the process lethality.

The centre-point f_h values at the initial region, f_{h1} were calculated from about 5 to 7 minutes from steam on. For the second region, the slopes of the heat penetration curves (f_{h2}) were calculated at a stable region after 10 minutes from steam on. Regression analysis was performed by S.A.S. to model the influence of entrapped air volume on f_{h1} and f_{h2} values from all four processing conditions and replicates, and f_h values as a function of entrapped air content are shown graphically in Figures 13 and 14. Due to insufficient f_{h1} data for one of the four processing conditions, models fit the data for only 3 of the 4 processing media,

Figure 13. Centre-point f_h values vs. air content for test bricks in retort pouches for first region of heat penetration curves (f_{h1}).

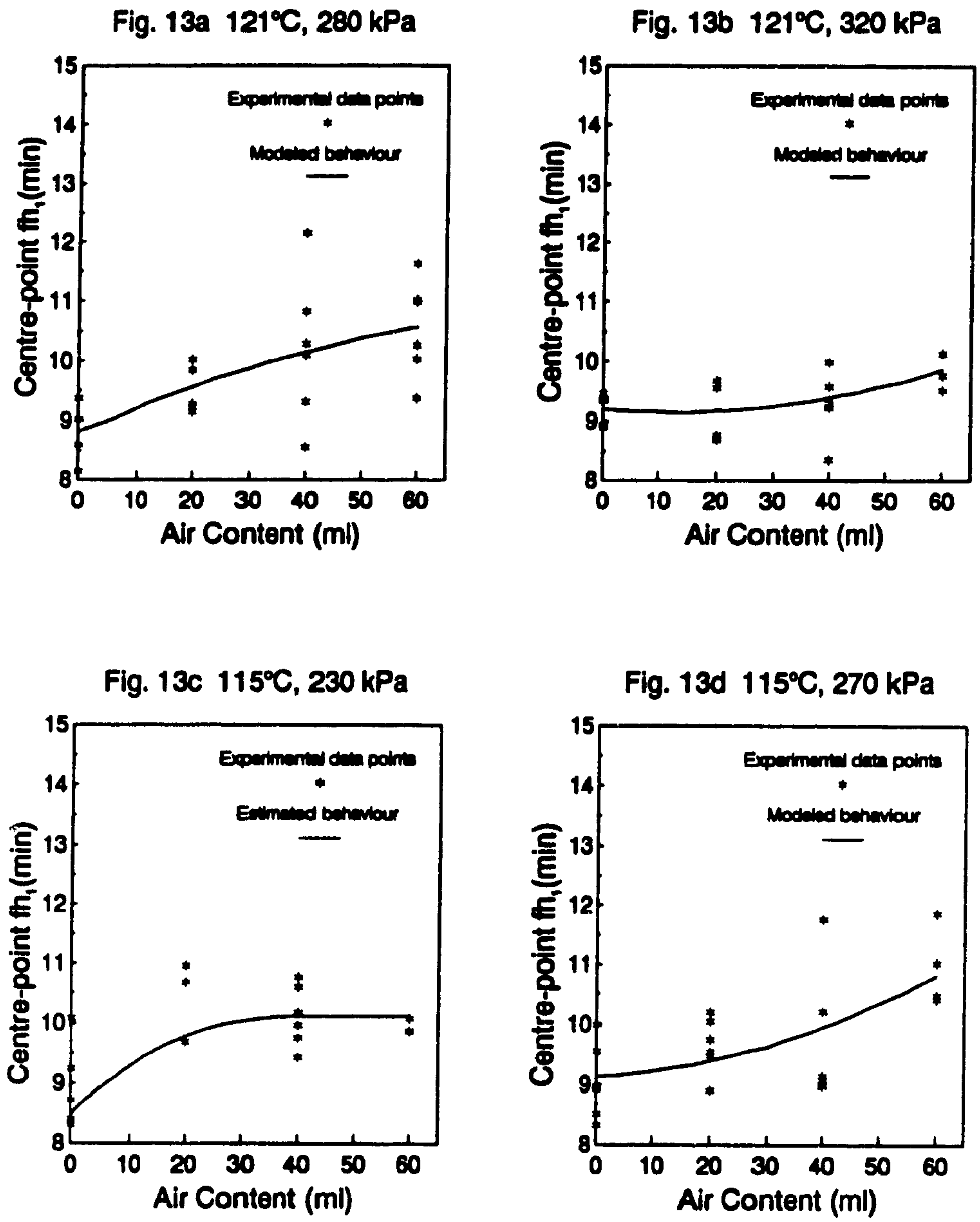
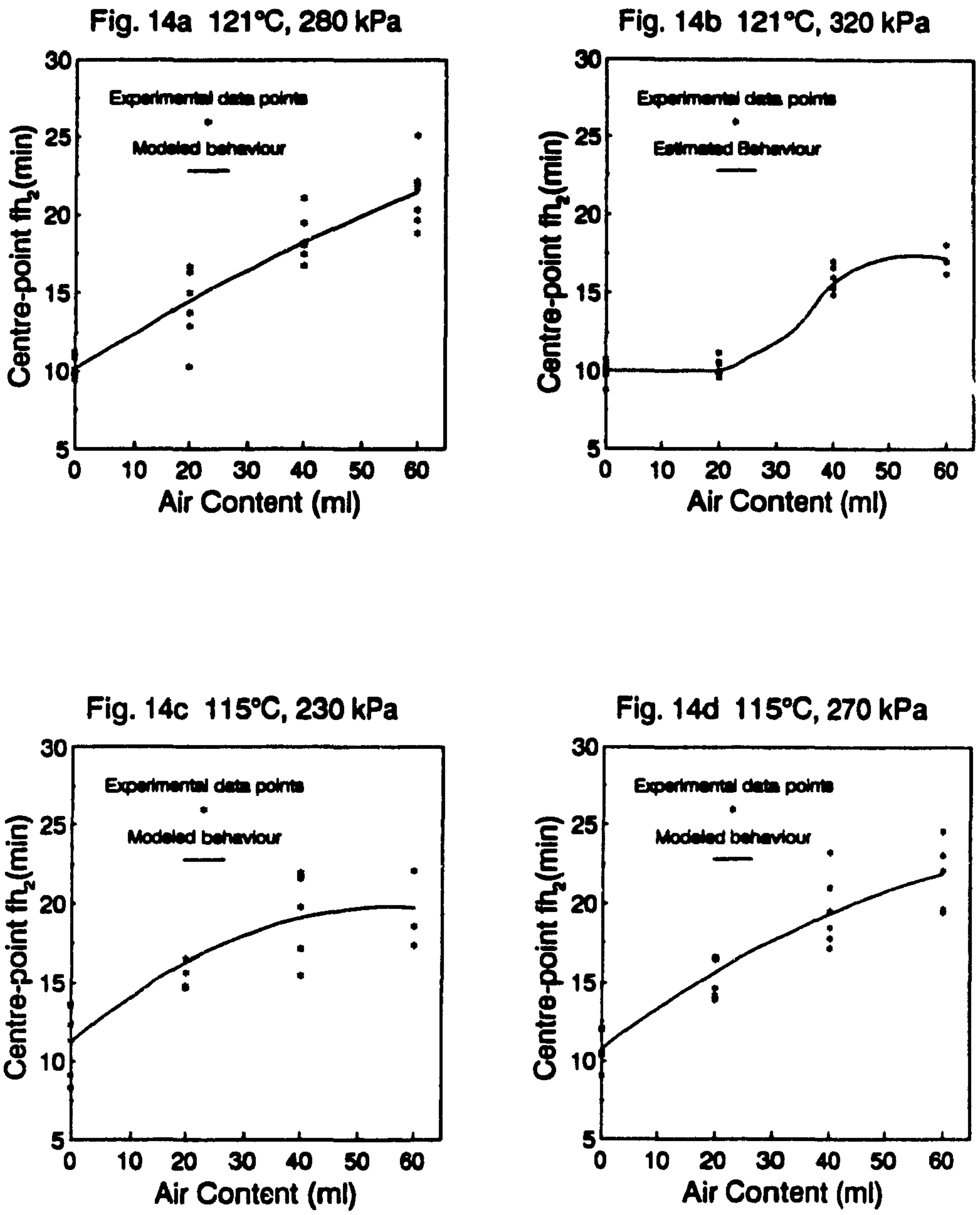


Figure 14. Centre-point f_h values vs. air content for test bricks in retort pouches for second region of heat penetration curves (f_{h2}).



and the other (115°C, 230 kPa) was analysed qualitatively. As will be explained later, for one of the four processing conditions (121°C, 280 kPa), the model did not fit the data for f_{h2} also, and a curve of best fit was added qualitatively.

Heating Rate Index for First Region of Curves (f_{h1})

The f_{h1} values as a function of entrapped air content are presented in Figures 13a,b,c,d. The effect of entrapped air on f_h values in this region of the heat penetration curves is small, with air contents from 0 to 60 ml resulting in increases in f_{h1} from about 9 to less than 11. These plots do, however, demonstrate that the effect of up to 20 ml of entrapped air on f_{h1} values was somewhat suppressed at the higher levels of over-pressure (65% steam) for both 115 and 121°C processes, but for the lower air over-pressures associated with 75% steam, 20 ml of entrapped air resulted in substantial increases in f_h values for both process temperatures. For bricks with no entrapped air, the plots depicted no substantial difference between the f_h values achieved for the use of 65 or 75% steam at either temperature set-point.

Heating Rate Index for Second Region of Curves (f_{h2})

The four plots (Figures 14a,b,c,d) of f_{h2} as a function of entrapped air demonstrate display a considerable effect of air. For two of the processing conditions, air contents from 0 to 60 ml resulted in increases in f_{h2} from about 10 to above than 20. For the processing condition with the highest level of over-pressure (Figure 14b), the effect of up to 20 ml of entrapped air on f_{h2} values was suppressed as demonstrated by the initial flat portion of the curve (for which reason no appropriate model was generated by S.A.S.). For the lower levels of over-pressure, volumes of air below 20 ml caused an increase in f_h values. In these cases, further data would have been required in the 0 to 20 ml range of entrapped air to determine the lowest entrapped air content that would initiate the increase in f_h. Such levels of entrapped air, termed "break-point values" have been determined previously by Weintraub et al. (1989).

Determination of Cold Spot

The "cold spot" has usually been determined from heating curves as the slowest heating region in a packaged product (Berry and Kohnhorst, 1983; Huerta-Espinosa 1981). This method of locating the cold spot does not account for lethality contribution during cooling, and relies on the fundamental assumption that the cold spot never reaches the processing temperature, as illustrated on Figure 15 for an institutional-size pouch 1.5" (3.8 cm) thick. If, however, the entire brick reaches retort temperature, then the contribution to lethality during cooling becomes substantial. For this study, the whole test bricks reached retort temperature in somewhere between 30 and 45 minutes, depending on the amount of entrapped gas. Since process times were not identical for all replicate runs, the determination of locational lethality was analysed for heating (30 minutes following steam-on) and cooling as two distinct regions.

Since retorting processes are designed on the basis of lethality, the cold spot in the product is best described as the region of minimum lethality, and it is with respect to this definition that the location of the cold spot was analysed for this study.

Cold Spot Location and Lethality

The lethality for the heating and cooling sections from each of the five locations in the bricks for the four processing conditions and six replicates was calculated based on numerical integration of the lethal rate. A multiple

Figure 15 Temperature vs. time plot for cold spot determination based on assumption that the cold spot never reaches the retort temperature. (from Huerta-Espinosa, 1981).

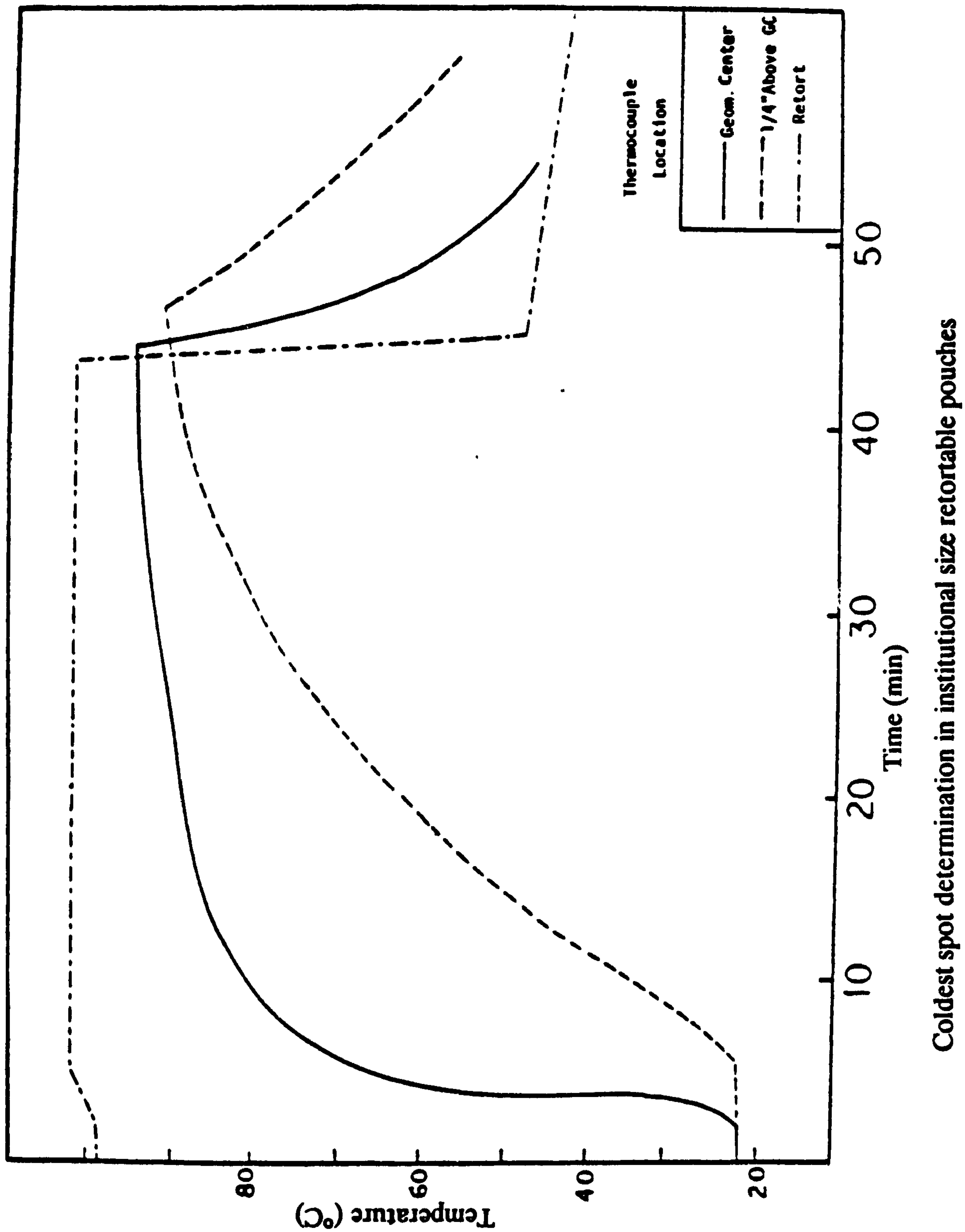


Table 6. S.A.S. modeled surfaces relating lethality to entrapped air content and location of thermocouple within the brick.

(x = air volume; y = location, 0 = center, 4 = near surface)

Heating Lethality (30 min. process, cooling excluded)

115°C, 230 kPa: $L(x,y) = 3.700 - 0.083x + 0.012y + 0.001x^2 + 0.026y^2 - 0.003xy$

115°C, 270 kPa: $L(x,y) = 3.895 - 0.067x + 0.138y + 0.013x^2 + 0.013y^2 - 0.003xy$

121°C, 280 kPa: $L(x,y) = 12.88 - 0.219x + 0.230y + 0.001x^2 + 0.142y^2 - 0.016xy$

121°C, 320 kPa: $L(x,y) = 12.53 - 0.043x + 0.233y - 0.001x^2 + 0.133y^2 - 0.007xy$

Cooling Lethality (pouch temperature close to retort temperature)

115°C, 230 kPa: $L(x,y) = 0.477 + 0.005x - 0.091y + 0.000x^2 + 0.002y^2 - 0.000xy$

115°C, 270 kPa: $L(x,y) = 0.541 + 0.002x - 0.089y - 0.000x^2 + 0.004y^2 - 0.000xy$

121°C, 280 kPa: $L(x,y) = 1.634 + 0.025x - 0.286y + 0.000x^2 + 0.019y^2 - 0.005xy$

121°C, 320 kPa: $L(x,y) = 1.777 + 0.035x - 0.401y - 0.000x^2 + 0.017y^2 + 0.002xy$

Combined Heating and Cooling Lethality

115°C, 230 kPa: $L(x,y) = 4.177 - 0.078x - 0.079y + 0.001x^2 + 0.028y^2 - 0.003xy$

115°C, 270 kPa: $L(x,y) = 4.436 - 0.065x + 0.049y + 0.000x^2 + 0.017y^2 - 0.004xy$

121°C, 280 kPa: $L(x,y) = 14.51 - 0.194x - 0.066y + 0.001x^2 + 0.161y^2 - 0.021xy$

121°C, 320 kPa: $L(x,y) = 14.30 - 0.008x - 0.168y - 0.001x^2 + 0.150y^2 - 0.004xy$

regression analysis was performed on this data using the S.A.S. For each processing condition, an equation was generated (Table 6), from which surface response curves could be obtained for lethality as a function of both entrapped air content and location of the thermocouple in the brick. The lack of fit of all of these models was insignificant ($P>0.05$).

Heating Lethality and Location of Slowest Heating Region

Using the multiple regression equations generated (Table 6), the surface response plots for the heating region lethality as a function of air content and location are shown in figure 16. These plots were used to identify the slowest heating region with respect to delivered lethality and are graphically represented in Figure 17. A summary of the lowest lethality locations (cold spots during heating) together with their associated lethalities accumulated during heating and cooling periods is provided in Table 7.

For each processing condition investigated (Figs 16a,b,c,d, & Table 7), it is evident that the effect of over-pressure on process heating lethality for packages with no entrapped air was negligible, with an increasing over-pressure resulting in an increase in heating lethality of 5% (from 3.7 to 3.9) at 115°C, and a drop in heating lethality of 3% (from 12.9 to 12.5) at 121°C. It is clear from Figure 16 that any increase in volume of entrapped gas beyond 20 ml resulted in a drop in the process lethality.

At 115°C, increasing the air content from 0 to 60 ml reduced process lethality by nearly 75% (Table 7). The effect of increasing the total pressure from 230 to 270 kPa (75 to 65% steam media) on process lethality at 115°C was nominal, with respective lethality increases from 3.7 to 3.9 with 0 ml entrapped air, and from 1.1 to 1.2 for packages with 60 ml of entrapped air. At 121°C however, increasing the total pressure from 280 to 320 kPa (75 to 65% steam media), nearly doubled the lethality of packages containing 60 ml of air (from 2.9 to 5.6), while causing a slight decrease in process lethality for packages with no entrapped air (from 12.9 to 12.5). The slight drop in process lethality with increasing over-pressure at 121°C for packages with no entrapped air was probably a result of the drop in surface heat transfer coefficient with the 10%

Figure 16. Heating lethality as a function of both entrapped air content and location of thermocouples in the test bricks at each of the four processing conditions.

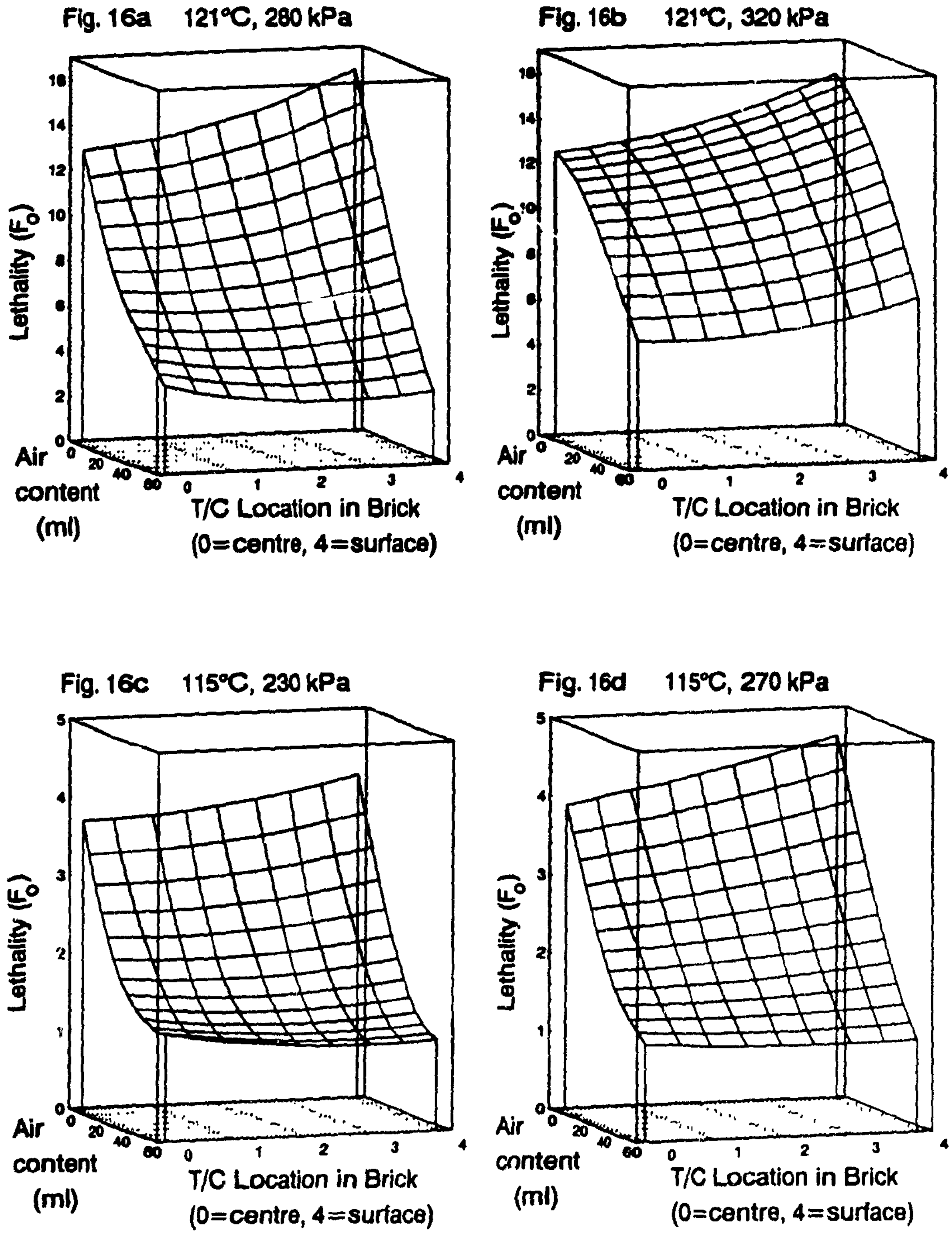
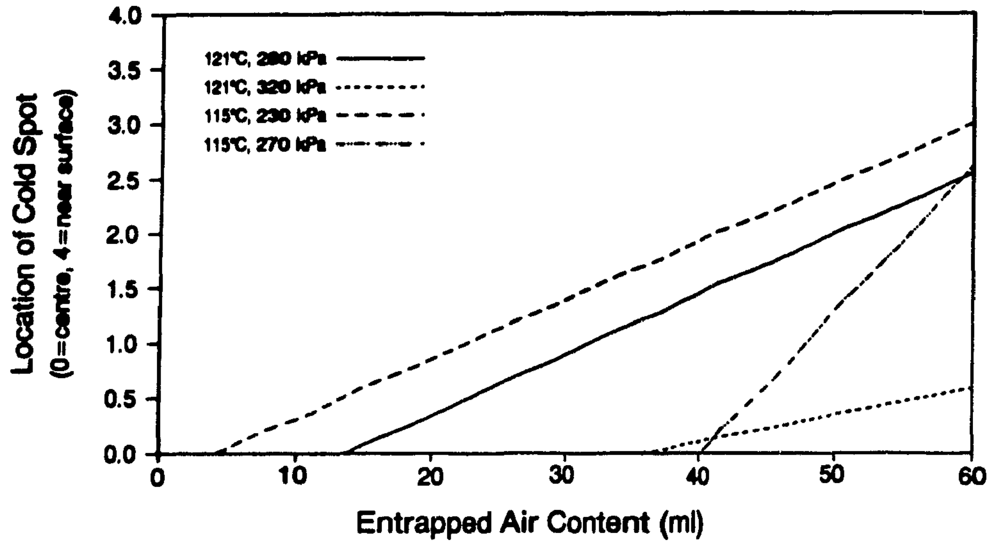


Figure 17. Location of slowest heating region as a function of entrapped air for 30 minutes of heating (cooling excluded) for the four processing conditions.



reduction in steam content of the medium. At higher entrapped air contents, the effect of the reduced surface heat transfer coefficient at higher over-pressures is outweighed by the improved heat transfer through the more compressed entrapped air.

For the 30 minutes of heating, the location of the cold spot as a function of air content is presented in Figure 17. At increasing entrapped air volumes, the region of lowest lethality shifted toward the surface of the brick in all cases. As previously mentioned, the experimental levels of over-pressure at 115°C did not have an appreciable effect on process lethality at the cold spot. However, the increase in over-pressure from 60 to 100 kPa did influence the location of the cold spot. Figure 17 shows that at 115°C, the higher level of over-pressure (corresponding to 65% steam; 270 kPa) caused no shift in the cold spot until the

Table 7. Location of slowest heating and slowest cooling regions and their respective lethalities for heating and cooling, and location and lethality at the cold spot as determined from heating and cooling lethalities.

			Location[1] and Lethality[2] (min, given in parentheses)		
			Heating	Cooling	Heating and Cooling
Temp. (°C)	Nominal pressure (kPa)	Air content (ml)	Slowest heating point [F_{oh}, F_{oc}]	Slowest cooling Point [F_{oh}, F_{oc}]	Lowest lethality point [F_o]
115	230	0	0.0 [3.7,0.15]	0.0 [3.7,0.48]	1.4 [4.1]
115	230	20	0.8 [2.3,0.24]	0.0 [2.3,0.58]	2.5 [2.7]
115	230	40	1.9 [1.5,0.34]	0.0 [1.6,0.71]	3.6 [1.9]
115	230	60	3.0 [1.1,0.45]	0.0 [1.4,0.84]	4.0 [1.6]
115	270	0	0.0 [3.9,0.26]	0.0 [3.9,0.54]	0.0 [4.4]
115	270	20	0.0 [2.7,0.26]	0.0 [2.7,0.58]	0.8 [3.3]
115	270	40	0.0 [1.8,0.25]	0.0 [1.8,0.61]	3.0 [2.3]
115	270	60	2.6 [1.1,0.23]	0.0 [1.2,0.63]	4.0 [1.4]
121	280	0	0.0[12.9,0.79]	0.0[12.9,1.6]	0.2[14.5]
121	280	20	0.3 [9.0,0.85]	0.0 [9.0,2.1]	1.5[10.8]
121	280	40	1.4 [6.0,0.89]	0.0 [6.3,2.6]	2.8 [7.6]
121	280	60	2.6 [3.8,0.90]	0.0 [4.7,3.0]	4.0 [5.0]
121	320	0	0.0[12.5,0.45]	0.0[12.5,1.8]	0.6[14.3]
121	320	20	0.0[11.2,1.31]	0.0[11.2,2.5]	0.8[13.5]
121	320	40	0.1 [8.9,2.13]	0.0 [8.9,3.1]	1.1[11.8]
121	320	60	0.6 [5.6,2.91]	0.0 [5.6,3.7]	1.4 [9.0]

[1]Location: 0 = centre, 4 = surface
[2]Lethality: F_{oh} = heating lethality; F_{oc} = cooling lethality; F_o = overall lethality

entrapped air content exceeded 40 ml., and at 60 ml, the cold spot was mid-way between the centre and the surface of the brick. At 75% steam (230 kPa), however, the cold spot was shifted at 20 ml of entrapped air, and at 60 ml., the cold spot was 2/3 of the distance from the centre to the surface. This shift is twice as large as that reported by Huerta-Espinosa (1981) with 200 to 300 ml. of entrapped air in an institutional retort pouch.

The precise air content corresponding to the initiation of lethality degradation predicted by the model may be somewhat less precise because of the large intervals of entrapped air volumes employed in the study (0,20,40,60 ml.).

Figures 18a,b,c,d illustrate the difference between the lethality at the slowest heating region and the centre-point lethality as functions of entrapped air content for the four processing conditions employed. From these figures, it is clear that higher over-pressures reduce the shift of the cold spot while causing no marked deterioration of lethality due to the reduced steam fraction.

Cooling Lethality and Location of Slowest Cooling Region

The cooling cycle of processing usually causes immediate collapse of the entrapped gases. Depending on the cooling method (ie. fresh cold water, cooling of processing water, etc.), cooling rates may vary somewhat from one retort system to the next. For the research in the Dixie retort, cooling was accomplished with cold fresh water, sprayed from two ports on the side of the retort.

As explained previously, if the slowest heating region in the pouch does not reach processing temperature at the time cooling begins, then the lethality contribution at this location during cooling may be relatively small, and determination of the cold spot as the slowest heating region during the heating section may be valid. If, however, the brick approaches processing temperature throughout, then the cooling lethality is substantial, and should not be neglected in the determination of the cold spot. Further, the lethality contribution during cooling in this situation is invariably highest at the centre-point of the brick, as illustrated on surface response curves for cooling lethality (Figures 19a,b,c,d, Table 7). Since cooling is initiated by the cold water on the package surface, location of lowest lethality during cooling is the surface of the brick.

Figure 18. Lethality at slowest heating point and geometrical centre of test brick as a function of entrapped air content for 30 minutes of heating (cooling excluded) for the four processing conditions.

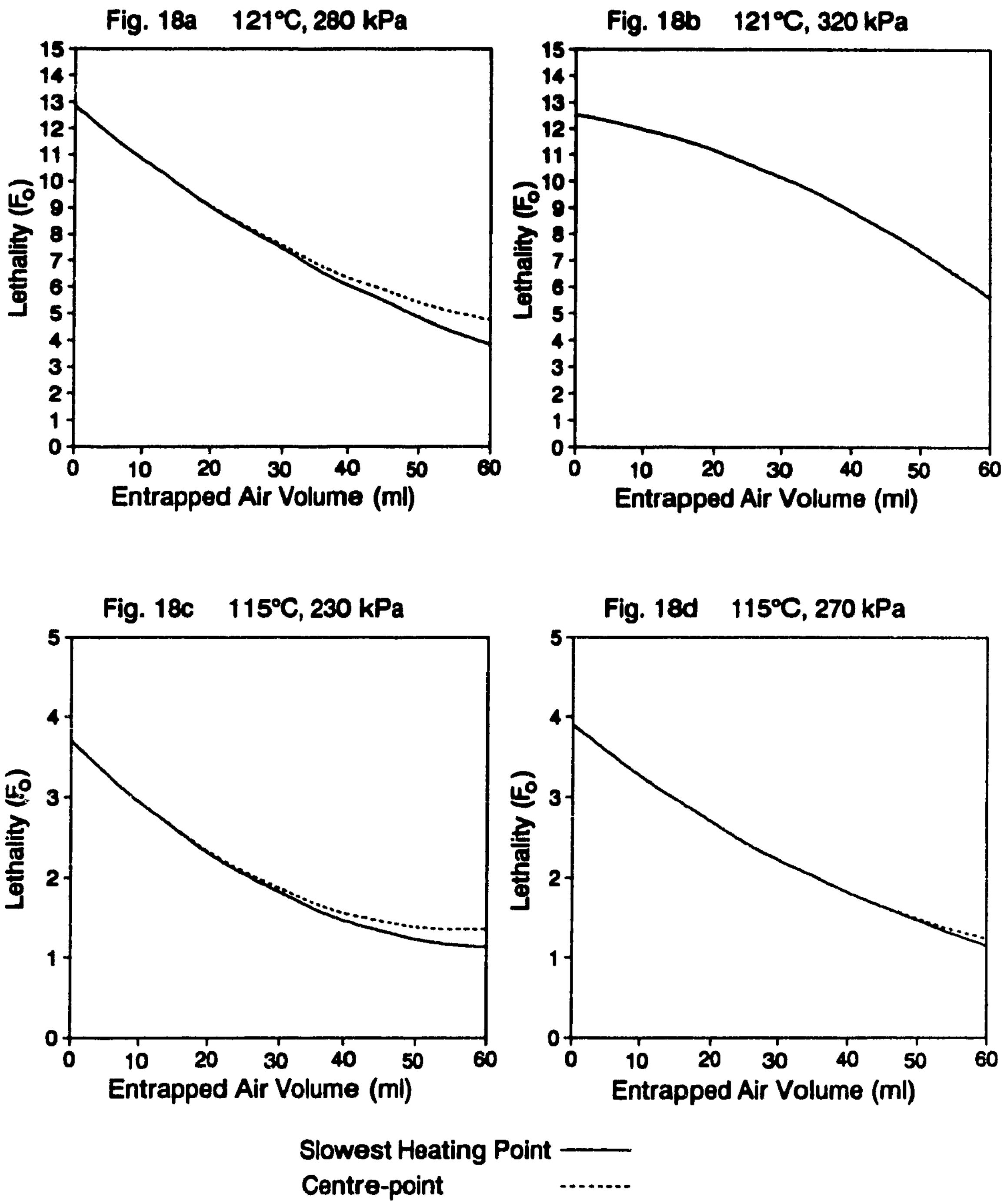
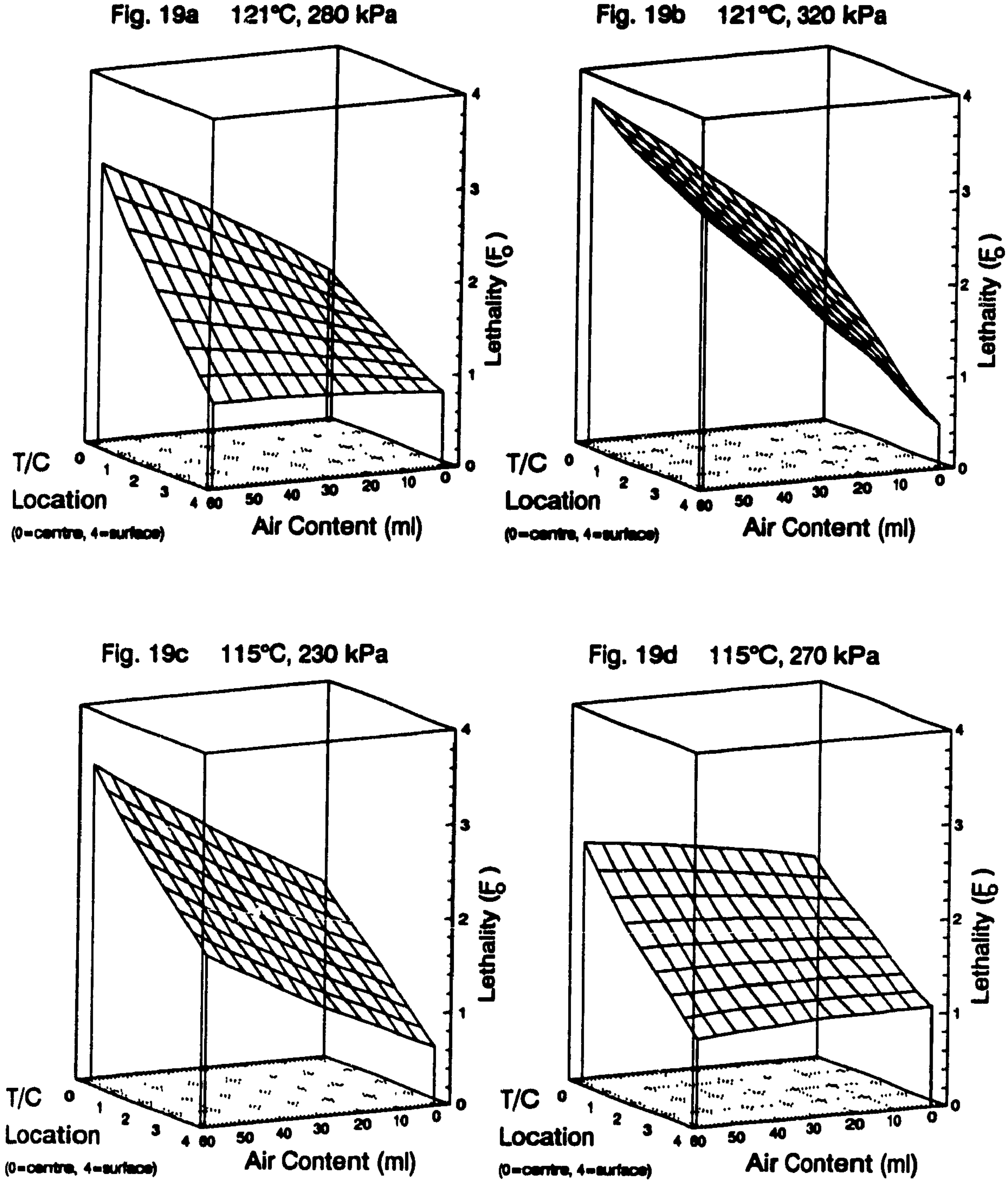


Figure 19. Cooling lethality as a function of both entrapped air content and location of thermocouples in the test bricks at each of the four processing conditions.



Referring to Figures 19a,b,c,d, increasing entrapped air contents clearly caused increased centre-point lethality, but in two of the four processing conditions (121°C, 280 kPa and 115°C, 270 kPa), increasing entrapped air had no significant effect on the lethality at the surface. No influence was evident regarding the effect of over-pressure on cooling lethality.

Combined Heating and Cooling Lethality and Location of Lowest Lethality

For processes in which the entire contents of a package approach processing temperature, the cold spot for processing is determined from the combined lethalities during heating and cooling. The 2nd order equations (table 6) from heating and cooling were combined to express the lethality as a function of location and air content in the package. These new equations were used to generate the response surface plots shown in Fig. 20, which show that the cold spot is shifted much more toward the surface than when heating lethality alone is considered (Fig. 16). Figure 21 shows the location of this new cold spot (point of lowest overall lethality) as a function of air. For all cases except 121°C and 320 kPa (the condition of highest air over-pressure), the cold spot at 60 ml of entrapped air was at the surface of the brick, and for all cases except 115°C and 270 kPa, the cold spot was slightly shifted from the centre with no entrapped air in the package. Figure 22 illustrates the lethality at the centre-point (typically assumed to be the cold spot) and at the cold spot as determined from heating and cooling lethalities. The differences between the lethalities at these two locations demonstrate the level of inaccuracy related to the assumption that the cold spot is located at the centre-point. Referring to Fig. 22, the difference between the two curves (and hence, the inaccuracy of centre-point techniques) is more significant at lower levels of processing over-pressure (75% steam).

Figure 20. Heating lethality + cooling lethality as a function of both entrapped air content and location of thermocouples in the test bricks at each of the four processing conditions.

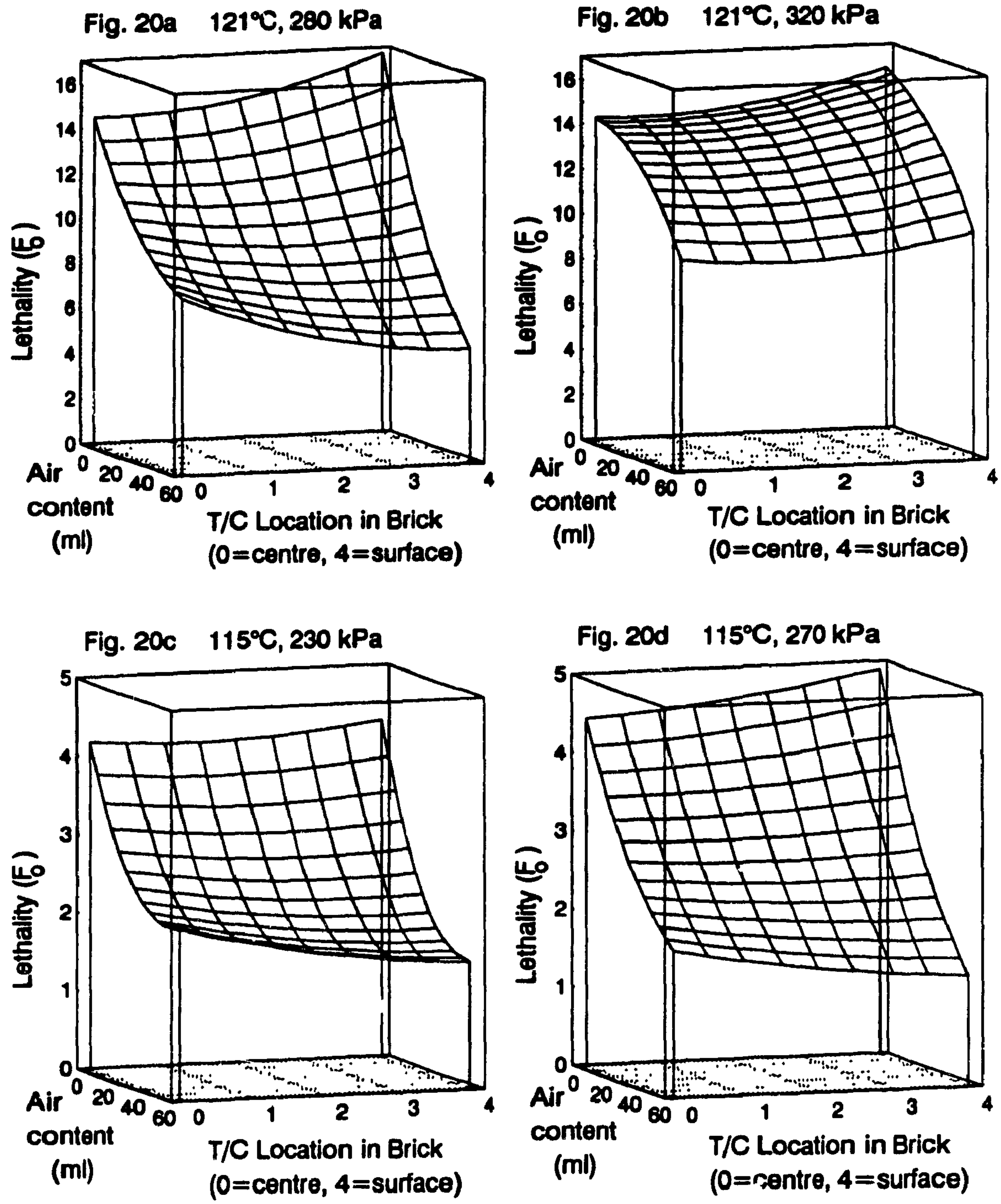
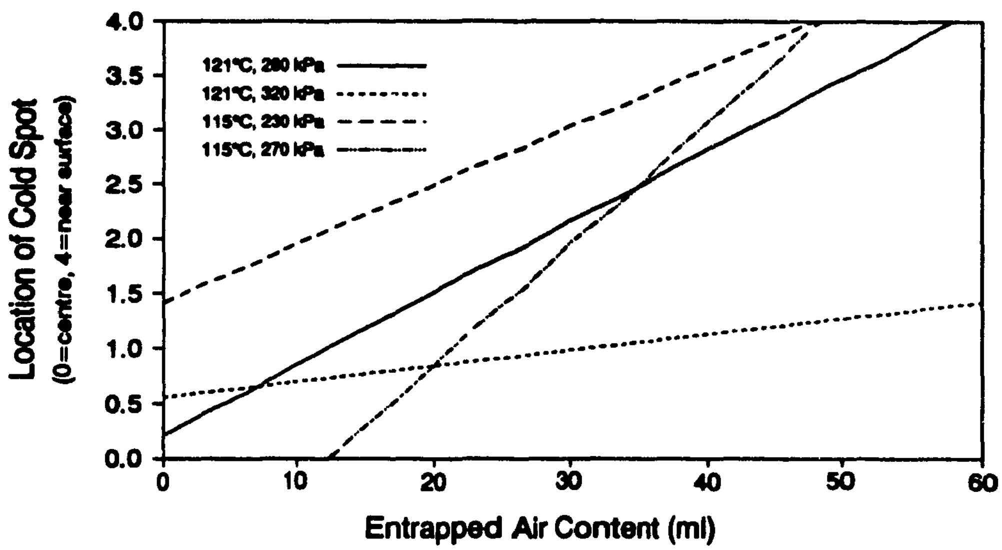


Figure 21. Location of lowest overall lethality (cold spot) as a function of entrapped air content for heating + cooling for the four processing conditions.



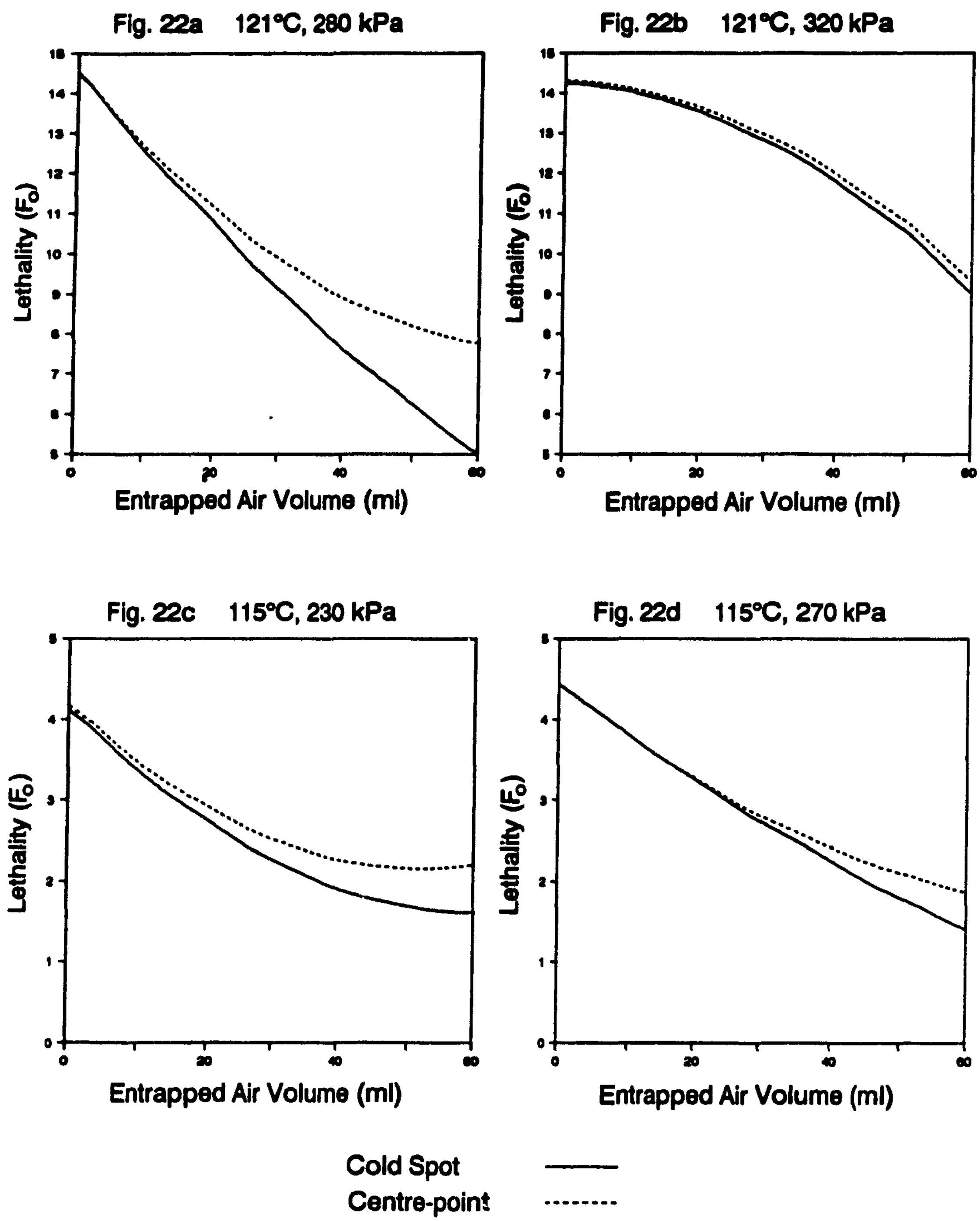
Measurement of Entrapped Gas Volume

The results of the air determination procedures (destructive and non-destructive) indicated minimal leakage of the pouches during processing, with such small average deviations from target air contents (less than 1 ml.) that they were neglected.

Determination of Effect of Gas Expansion on Pouch Thickness

By injecting a fully prepared and packaged test brick (300 ml volume) with water, the critical volume, below which no increase in package thickness will result, was determined to be 15 ml. After this volume was reached, a thin layer of water was formed at the top surface which was initially thicker around the edges

Figure 22. Lethality at cold spot and geometrical centre of test brick as a function of entrapped air content for heating + cooling for the four processing conditions.



than in the middle of the brick. From 30 to 400 ml of injected water, the centre thickness increased linearly to about 4 cm from the initial 2 cm brick thickness, with the thickness at the edge of the brick increasing to 3 cm. Beyond 400 ml of injected water, the formation of a water layer at the bottom of the package was evident. Rupture of the pouch occurred at 800 ml of injected water (1.1 liters total volume). The increase in package thickness as a function of injected water volume is illustrated in Figure 23.

Determination of Gas Volumes at Processing conditions

The behaviour of entrapped air in a flexible pouch can be estimated using the perfect gas law:

$$(P_1 \cdot V_1)/T_1 = (P_2 \cdot V_2)/T_2 \qquad (9)$$

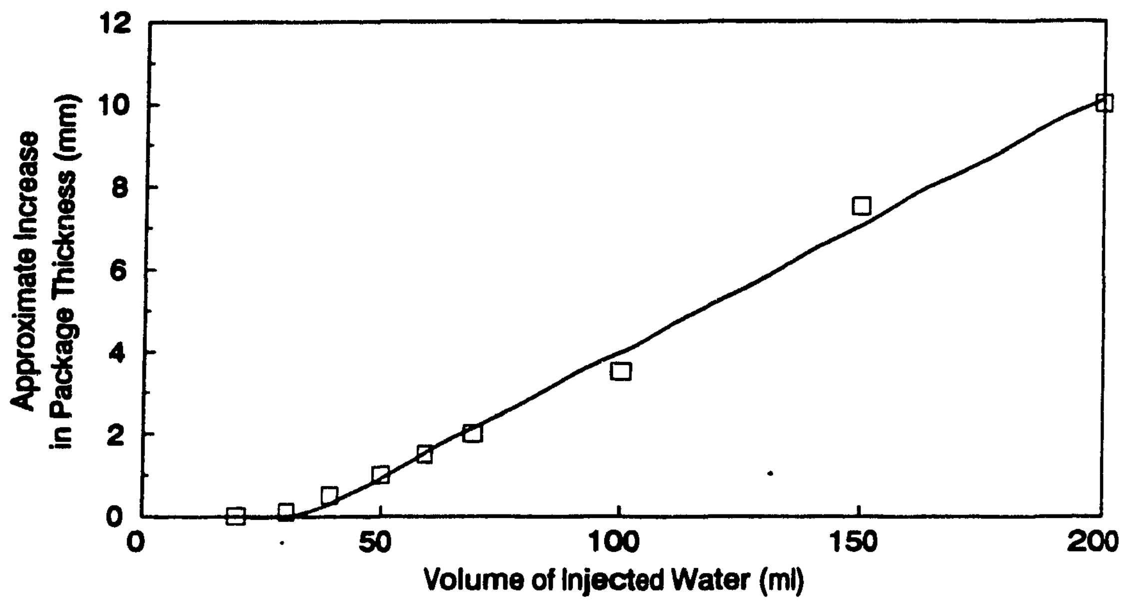
from which, the increased air volume at cook temperature and pressure can be expressed as a ratio:

$$V_2/V_1 = (P_1 \cdot T_2)/\{(P_2 - P_{2s}).T_1\} \qquad (10)$$

Where V_2/V_1 is the ratio of the volume of entrapped air at processing temperature and pressure (T_2 and P_2), to the volume at packaging temperature and pressure (T_1 and P_1). P_{2s} is the vapour pressure of water at processing temperature.

At the initiation of the cooling cycle of a retort process, there is typically a period in which the steam in the processing medium collapses, and air is supplied to compensate for this sudden pressure loss. Should their be a delay in the air supply to the retort at the time of steam collapse, it is possible that the pressure in the retort may drop to that of the air fraction of the processing media. At this time, the air inside the pouch would remain at cook temperature and the volume of this

Figure 23. Increase in package thickness as a function of injected water volume.



air would increase to a much larger volume than during the cook period of the process. Assuming complete steam collapse, no increase in air pressure in the retort, and a temperature inside the package equal to the retort process cook temperature (previously defined as T_2), this increase in volume from the volume of air at process cook conditions can be expressed as a ratio:

$$V_3/V_2 = P_2/P_3 \quad (11)$$

Where V_3/V_2 is the ratio of the volume of entrapped air at the onset of cooling to

the volume of air at processing temperature and pressure (T_2 and P_2). P_3 is the retort pressure after steam collapse (equal to the pressure of the air fraction of the process cook medium). The temperature of the contents of the pouch remain at cook temperature ($T_3 = T_2$), and can thus be disregarded.

From these two relationships, the theoretical expansion of the experimental volumes of the entrapped air, both at processing conditions and at the onset of cooling, were determined. Table 8 is a summary of the factors affecting the expansion of entrapped air during processing, and the expanded volumes (V_2 and V_3). From Table 8, the maximum theoretical expansion volume of the entrapped air during the cook period (V_2) was 128 ml. Referring to Figure 23, this corresponds to an increase in package thickness at the centre of the brick of slightly greater than 5 mm, and presents no danger of rupture. Further, it is unlikely that a significant volume of air had formed below the brick, since this was not observed with water injection below volumes of 400 ml. The last column of Table 8 is the theoretical expansion volume of the entrapped air at the onset of cooling (V_3). The maximum volume is 467 ml, an almost eight-fold increase from the initial 60 ml air that was injected at ambient temperature and pressure. Referring again to figure 23, this volume corresponds to a greater than 2 cm increase in thickness. At such levels, a gas layer below the brick is probable, since this was observed at injection volumes above 400 ml. The effect of a layer of gas at the bottom surface of the package would be to insulate from below. However, since expansion to such levels are quickly reduced by increasing air pressure in the retort and cooling of the package contents, the primary concern is package rupture. For the packages used for this study, rupture did not occur until 800 ml of water was injected into a retort pouch. It is unlikely that, even at elevated temperatures, air volumes below 500 ml would cause rupture of the pouch.

Table 8. Initial volumes injected into test packages and their corresponding volumes at processing conditions and at the end of cooling.

Temp. (°C)	Steam (%)	Nominal Press. (kPa)	Vapour Press. (kPa)	Air Press (kPa)	V_1 Experimental (ml)	V_2 Cook (ml)	V_3 Cool (ml)
115.6	65	270	167	103	0	0	0
115.6	65	270	167	103	20	26	69
115.6	65	270	167	103	40	52	137
115.6	65	270	167	103	60	79	206
115.6	75	230	167	63	0	0	0
115.6	75	230	167	63	20	43	156
115.6	75	230	167	63	40	86	311
115.6	75	230	167	63	60	128	467
121.1	65	320	204	116	0	0	0
121.1	65	320	204	116	20	24	65
121.1	65	320	204	116	40	47	130
121.1	65	320	204	116	60	71	196
121.1	75	280	204	76	0	0	0
121.1	75	280	204	76	20	36	133
121.1	75	280	204	76	40	72	266
121.1	75	280	204	76	60	108	398

Practical Considerations Involving the Effect of Entrapped Gases

In order to make use of research performed using food-simulating products instead of real food products, certain fundamental differences must be recognized. In this study, the use of a solid brick may simulate the behaviour a brick-shaped food product packaged without added sauce or brine, but a distinction must be made between the behaviour of fluid and solid food products. In a fluid food product, or a solid packaged in sauce or brine, any gases contained in the package will tend to form a layer at the top of the product. For a solid brick, as used in this experiment, gases in the package may form pockets around the edges of the brick, underneath the brick, or around obstacles such as the thermocouples or the packing gland. Similarly, a pouch-packaged piece of meat may permit air to gather at it's perimeter or around stray pieces of product. These pockets of air will not hinder heat transfer as much as a surface layer, and as such, an equal volume of entrapped air may more significantly hinder the processing of fluid foods or foods packed in brine.

V - CONCLUSIONS

The study indicated a good temperature distribution pattern for the Barriquand Steriflow retort. However, the amplitude of temperature oscillations during the cook period was somewhat large resulting large temperature deviations within the retort. Variations in process lethalities at different locations within the retort were small. Temperature distribution in the Dixie positive flow retort was slightly better than for the Barriquand retort, while the small lethality variations were similar to those encountered in the Barriquand retort.

The retorts used for these tests were respectively, a Barriquand standard 1-basket model with a "universal" loading car, and a Dixie pilot scale single basket model. Temperature distribution in full-sized commercial retorts having a tighter loading pattern could be somewhat different. Similar tests by qualified thermal process experts are recommended on commercial retorts under practical loading patterns for verification of the operating performance.

The effect of entrapped air volume on the heating rate index (f_h) at the centre-point of the test bricks was substantial, with increases in f_h values at all levels of entrapped air (20, 40, 60 ml) except the highest air over-pressure (121°C, 320 kPa), where the effect of 20 ml of entrapped air was suppressed. With the exception of this highest level of over-pressure, 60 ml of entrapped air caused the f_h value to double. Further data would have been required to determine the exact levels of entrapped air that were suppressed at other levels of air over-pressure.

This study indicated much larger shifts of the point of least lethality of the test brick (cold spot) from the centre than has previously been reported. At the highest level of entrapped air (60 ml) and the air over-pressures associated with 75% steam, the slowest heating region, which is usually employed to indicate the cold spot, was shifted to a height equivalent to 3/4 of the brick thickness, slightly above the 2/3 height previously reported (Berry and Kohnhorst, 1983; Huerta-Espinosa, 1981). For corresponding processing conditions and 60 ml of entrapped air, the location of the least processed region as determined from the combined lethality of heating and cooling was shifted to the location of the thermocouple nearest the surface of the brick. This suggests that the least processed region of the brick was probably the surface of the test brick. Such a shift in cold spot indicates that the insulating effect of entrapped air at the top of the package contents evident during heating, did not persist for long during the cooling of the brick, thereby initiating surface cooling.

The Dixie positive flow retort performed equally well with both the standard pneumatic control system and the electro-pneumatic conversion. The only drawback of the electro-pneumatic control system is the higher venting rates required by the electro-pneumatic system in order to ensure constant venting of the retort. This problem could be solved by the use of electronic control valves, which would respond more accurately than the pneumatic control valves. The electro-pneumatic system has the advantage of being programmable, and can communicate for both input and output with a microcomputer.

In order to supply thermally processed foods to meet both the required safety standards and the quality demanded in today's food marketplace, it is increasingly important to be able to design processes that minimize over-processing. The quality losses associated with over-processing are a result of large safety factors required due to lack of understanding concerning thermal processing. Both performance of retort systems, and the determination of the least processed region in foods under various conditions are major areas of concern.

The results of this study indicate that the present industry-standard of using time-temperature data from the geometrical centre of the container may not be the most conservative approach in arriving at a safe process. Assurance of adequate processing should be based on the location receiving the least cumulative lethality (during both heating and cooling) rather than on the coldest point during heating alone. The study indicates that the two locations differ considerably when thin profile containers with entrapped air are subjected to thermal processing, and in such cases, consideration should be given to the re-design of processes that are presently based on the geometrical centre.

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