THERMAL STERILIZATION OF FLEXIBLY PACKAGED FOODS

by

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SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

(May 12, 1967)

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ABSTRACT

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ChoKyun Rha

Submitted to the Department of Nutrition and Food Science on May 12, 1967, in partial fulfillment of the requirement for the degree of Doctor of Science.

Procedures for the prediction of the microbial sterility of flexibly packaged heat processed foods were investigated to examine the applicability of existing thermal process calculations. Food systems with different heating characteristics selected for this study were: ground beef, chicken broth and carrot slices in chicken broth.

Heat penetration in these three types of foods at the slowest heating point were studied for the cases when the pouches were placed for processing in a vertical position or in a horizontal position. Another variable investigated was the amount of air left in the pouches. Heat penetration data obtained from the geometric center of ground beef pouches showed generally a conduction-heating behavior, but the magnitude of the overall heat transfer coefficient was lower than expected. There was a significant effect of position during processing on the heating rate. Heat penetration data obtained with chicken broth and with carrot slices in chicken broth showed generally a convective heating behavior, but the overall heat transfer coefficient was lower than expected. Consideration of possible reasons for the slower heat penetration in all cases studied led to postulation of additional heat resistance due to gas films at the surface or within the lamination composing the pouches.

With data obtained in the thermal resistance studies on Clostridium sporogenes (PA 3679), the decimal reduction times at various temperatures and the slope of the decimal reduction times curves in beef puree and chicken broth were determined.

From the heat penetration data and thermal resistance data above, the lethality of thermal processing was predicted for ground beef and chicken broth, and these were compared with experimental results obtained from the inoculated packs. Similar studies were carried out for a more severe process to evaluate the sterility of the product. The agreement between the predicted and experimental effects of thermal process, and sterility were satisfactory.

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May 12, 1967

Professor Nevin S. Schrimshaw
Head, Department of Nutrition
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Cambridge, Massachusetts

Dear Professor Schrimshaw:

A thesis entitled "Thermal Sterilization of Flexibly Packaged Foods" is hereby submitted in partial fulfillment of the requirements for the degree of Doctor of Science in Food Science and Technology.

Respectfully submitted,

ChoKyun Rha

ChoKyun Rha

ACKNOWLEDGEMENTS

The author wishes to express her sincere gratitude to her thesis advisor, Professor Marcus Karel, for offering her his superb guidance, his constructive advice and criticism, his thorough understanding and above all his unchallengeable patience during the experimental phase and especially writing of this thesis.

The author is appreciative to Professor John T. R. Nickerson for his advice in microbiological aspects of this study.

Without the help of Janusz M. Zak in the heat penetration experiments and Edith Ritter in thermal death time determinations, this work would not have been accomplished in such a limited time.

The author is most grateful to her son, TaeMinm, for managing to be a good and healthy boy while he was away from his mother during this study.

Needless to say the author is aware that she owes everything to her parents, Dr. and Mrs. Sea Zin Rha, whose gearing have always led her in every aspect of her life and who have always provided her with the very best of everything.

This study was supported by U. S. Army Natick Laboratory, Contract No. DA 19-129-AMC 606(N), Project No. 1K643324D587.

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INTRODUCTION

THERMAL STERILIZATION OF FLEXIBLY PACKAGED FOODS

I. INTRODUCTION

Thermal-processing of foods in flexible films was proposed as early as 1940 (Geisman, 1963), but actual commercial application did not follow immediately because the existing flexible films could not withstand the stresses of normal commercial processes. Since then material developments resulted in the production of various types of laminated plastic films which possess higher resistance to mechanical impact, pressure bursting, mass transfer, and chemical attack. Peter and Robe (1963), Geisman et al. (1963), Long (1962), Pflug et al. (1963) as well as others have reported that several commercially available flexible films can withstand the commercial thermal processing. Also production of laminated plastic films and laminated foil has greatly increased the possibility of utilizing flexible films for thermally processed foods.

If the flexible films which are suitable for packaging foods can withstand the stresses of commercial processing and storage as well as rigid containers, the advantages of these films over rigid containers are numerous. The advantages include:

1. Considerable weight reduction and cubic volume reduction for same quantity of foods (Keller, 1959).

2. Small weight and volume of the empty package which decreases costs of shipping, storage and disposal and increases convenience.

3. Greater ease of opening the flexible packages.

4. Less chance of corrosion of container made with flexible films because of relatively inert plastic layers.

5. Adaptability of package to product shape and quantity which may decrease the number of various sizes of containers necessary for packaging different sizes and quantities of foods.

6. Greater flexibility in use of sealing machines for different sizes of containers.

7. Easier portion control for institutional feeding.

8. Possibility of reheating in the pouch and reheating several different pouches in one heating vessel at the same time by consumers.

9. Possibility of imprinting labels in between lamination and plastic coating therefore eliminating labeling cost as well as labeling defects.

10. Use of more easily available raw materials in the flexible films compared with the raw material such as tin commonly used for rigid cans.

11. Easier removing of some viscous food materials from flexible packages due to their squeezability.

Because of those numerous distinct and significant advantages, as flexible packages become more refined, it is only natural that they would be used more for heat preserved foods. As yet no work has been done on the systematic analytical evaluation of thermal processing of foods in flexible containers.

Work done to date included only:

a) Sterilization test (Long, 1963).

b) Comparison of the process with that of rigid cans (Keller, 1959).

c) Heating characteristics in limited number of food (Pflug, 1963).

d) Heat penetration in bentonite clay (Suzuki, 1966).

Utilization of flexible packages for thermal processing of foods, requires that the methods for calculating process time for a given sterility be developed. In this study, the applicability of the traditional method for determining thermal process for flexibly packaged foods was examined and verified. The method and procedures for prediction of the microbiological sterility of flexibly packaged heat-processed foods were investigated for a characteristic conduction-type heating solid food, a convection-type heating liquid food, and of a food containing solid pieces in a liquid substrate. The slowest heating points of these foods contained in flexible packages were determined and heat penetration characteristics at these points were determined. The thermal death times of Cl. sporogenes PA 3679 in pureed solid food, and in the liquid food were determined experimentally. The process lethalities were calculated using heat penetration curves and the thermal death times of Cl. sporogenes PA 3679.

LITERATURE SURVEY

II. LITERATURE SURVEY

A. Thermal Sterilization of Foods:

1. Development of thermal sterilization

Long before history had any record, it has been known that food substances were subject to deteriorative and putrefactive change with age. Until the middle of the nineteenth century, destructive and objectionable changes in food material were ascribed to the natural tendency of foods to decompose, and the probability of the change being due to attack by living cells would have been ridiculed and was not recognized as significant or perhaps even possible (Prescott, 1932).

However, it has been observed that the food kept longer when cooked. In 1809, Nicholas Appert applied this knowledge and was able to preserve various kinds of foods in containers by heating in boiling water. Interestingly, Appert thought the elimination of air from the food products by heating was the reason for the preservative effect, and concluded that air was the causative spoilage factor in food materials.

Pasteur's discoveries of the activity of living organisms in fermentation, putrefaction, and in causing diseases were the first recognition of the activities of living cells in these systems. Eventually, these discoveries led to Koch's postulates recognizing that a particular disease is caused by the growth and activity of a specific organism (Nickerson, 1962). Koch's postulates and Pasteur's recognition of microorganisms as a causative agent to food spoilage

made possible to find correlation between microbial population and wholesomeness of foods (Goldblith et al., 1961). From this it became evident that the microorganisms must be inactivated or prevented from growth if any food material is to be preserved for an extended period of time.

2. Thermal inactivation of microorganisms

One of the most important physical conditions affecting microorganisms is temperature, which therefore became the most important means of preservation of food.

Following Russell's (1895) discovery of decrease in can spoilage upon increase in processing temperature and time and isolation of microorganisms from food by Prescott and Underwood (1897 and 1898), more systematic studies on the behavior of microorganisms to heat were carried out by several investigators.

Bigelow and Esty (1920) investigated the thermal death point of thermophilic organisms. By thermal death point they meant the length of time at different temperatures necessary to completely destroy a definite concentration of speres in a medium of known hydrogen ion concentration. For the presentation of thermal death point data, they reported both the longest heating time which resulted in growth and the shortest heating time after which growth did not occur. They presented the data as plots in Cartesian coordinates, of temperature versus heating time.

a. Logarithmic rate of microbial death

The recognition that generally the number of viable cells re-

duces exponentially with time of exposure to a lethal temperature, (Rahn, 1945; Chick, 1910; and Watkin, 1932), led to the use of logarithmic plots in which the log of the number surviving is plotted against time. This practice allows the calculation of single value parameters characterizing resistance and allows the comparison of resistances of different organisms at a given temperature. It is general practice to designate the time required for 90% of destruction at a given temperature by D, called decimal reduction time.

It is only natural that different microorganisms or the same microorganisms cultured in different manner or heated in different media exhibit varied decimal reduction time even at the same lethal temperature.

b. Thermal death time of microorganisms

In 1921, Bigelow recognized the logarithmic nature of thermal death time curves and reported that straight lines resulted when logarithm of thermal death time was plotted against temperature. These discoveries have stimulated many workers in the field and resulted in extensive studies on the thermal death time at different conditions, of various organisms such as Bacillus coagulans (Amaha and Ordal, 1957; Reynold et al., 1952; and Stumbo et al., 1950), putrefactive anaerobe PA 3679 (Esselen and Pflug, 1956; Reynold et al., 1952, and Stumbo et al., 1950), Clostridium botulinum (Stumbo et al., 1950; Sugiyama, 1951; and Esty and Meyer, 1922) and many others. These studies showed that different types of microorganisms have different resistivity to temperature. Prescott (1932) found bacteria which survived 10 hours of boiling, and others showed highly heat re-

sistant endospores. Development of pure culture techniques for diagnosis of food spoilage led to the discoveries of heat resistant bacilli and micrococci by Prescott and Underwood (1898), mold, cocci and bacilli which include the spore-formers: B. subtilis, B. mesentericus, non-spore-formers similar to B. proteus vulgaris and Bact. thermo. by Vaillard (1900), and Cl. botulinum which has already been recognized as a potent causative agent of food poisoning due to processed food by Dickson (1917).

Although Bigelow (1921) has taken the arithmetic average of the thermal death points of four different organisms, A. alkaligenes, B. coli, B. aerogenes, and B. proteus, and from these average values constructed a thermal death time curve which he considered applicable to all these four organisms, it became evident that different microorganisms have different resistivity to heat. Therefore it became necessary to have some means of comparing the thermal resistivities of different organisms as well as obtaining the knowledge of thermal resistance of many organisms. Since the thermal death time curve reflects the relative resistance of bacteria to different lethal temperatures, the comparison of thermal death time curves of different organisms gave a good indication of the relative heat resistance of different organisms. Therefore, the use of the thermal death time curve in thermobacteriology became accepted and wide spread.

The thermal death time curves are constructed by plotting the logarithm of time required to decrease a number of organisms to a given fraction (usually to 10%) on the ordinate against the exposure temperature in the abscissa. It is often a practice to report a point, usually destruction time at 250°F refered as F_o and the slope

of thermal death time curve. More often the term Z, which is the reciprocal of the slope of the curve, numerically equal to the number of degrees Fahrenheit required for the thermal death time curve to traverse one log cycle of time is used in place of the slope as the indication of the thermal resistivity of an organism.

c. Devices for measuring the thermal resistance of bacteria

There are many devices developed for measuring thermal resistivity of bacteria. They belong to one of the following major categories or their modifications.

1. "Thermal Death Time Tube" method developed by Bigelow and Esty (1920).

2. "Thermal Death Time Can" methods developed by American Can Company (1943).

3. "Tank" method developed by William et al. (1937).

4. "Flask" method developed by Levine et al. (1927).

5. "Thermoresistometer" method developed by Stumbo (1948).

6. "Capillary Tube" method developed by Stern and Proctor (1954).

Each of the above methods has its advantages and disadvantages which are discussed by Stumbo (1965). However, all of these devices have a similar principle in that the microorganism suspended in media of interest is heated at various temperatures for various time intervals and microbial counts are made to obtain enough data to construct thermal death time curves. The methods vary in the types of vessels and heating methods used.

d. Treatment of thermal resistance data

According to Stumbo (1965), there are two general methods for treating thermal resistance data:

1. Construction of survivor curves, by plotting the logarithm of survivors against time at constant temperatures from which D values may be taken directly.

2. Assuming the logarithmic order of death, and calculating a D value from "initial" number and number surviving after some one heating time at each temperature studied.

For the first method, it is necessary to obtain thermal resistance data at several different heating times for each temperature. This method is satisfactory if the log of number surviving is linear with time.

The second method needs thermal resistance determinations only for two different heating times for each temperature. For the purpose of thermal sterilization of foods, it is generally considered justifiable on the basis of available evidence to assume the logarithmic order of death although some exceptions to this have been reported. Therefore, logarithmic death is assumed, and a straight line is drawn between these two points.

To obtain initial counts for the second method, the spore suspension is diluted and heated to result in less than one spore per milliliter. This is to give assurance that most of the colonies developed in subculture are from a single surviving spore. The second point is chosen at a heating time that will reduce the number of survivors to very low level compared with the number of spores initially present. Stumbo et al. (1950) calculated most probable number of sur-

viving spores per milliliter by the equation:

$$\bar{N} = \frac{2.303}{v} \log \frac{S}{q}$$

where,

$\bar{N}$ = most probable number of surviving spores per milliliter

v = volume of each heated sample in milliliter

S = total number of replicate samples subject to a given time-temperature treatment

q = the number of which show negative growth on subculture among the above n samples

With the most probable number of surviving spores for "initial" and "after heating for time t" obtained in the manner described above, D may be calculated by:

$$D = \frac{t}{(\log a) - (\log b)}$$

Where,

a = initial number of organisms

b = number of organisms after heating for time t

Schmidt (1954) also used two point techniques to determine D values. He employed probability paper to determine the time at which 50% of the subculture tubes were sterile (LD_{50}). Therefore, he obtained D by the equation:

$$D = \frac{LD_{50}}{(\log a) - (\log b)}$$

It was reported (Schmidt, 1957) that the methods of Stumbo et al. (1950) and Schmidt (1954) gave good agreement.

Other methods for calculating D values have been suggested; however, the present precision in thermal resistance determination does not justify the increased complexity in calculation of D to attain improved precision.

3. Heat transfer through food material

In 1898, Prescott and Underwood first called attention to the importance of the rate of heat penetration into canned food material during processing. Following that, undoubtedly many have studied some aspects of heat transfer in food products because of the unavoidable necessity in food industry, but no significant work was published until Thompson (1919) published his work.

a. Time-temperature relationship

Thompson (1919) developed an equation for obtaining temperature at any point in a food product heated by conduction in a cylindrical can:

$$T = C_r - (T_i - T_r) \sum_{\mu} \sum_{m=1}^{\infty} A_{\mu m} e^{\frac{-k}{C_p \rho}(\mu^2 + \lambda^2)t} J_o(\mu r) \sin \lambda (Z + l)$$

where,

T = temperature at any time t and in any point r and Z

$(T_i - T_r)$ = difference in initial temperature of can and bath

r & Z = cylindrical coordinate of a point in a can (at the

center of the can, r = 0, Z = 0)

ℓ = half length of the can

μ = a root of $J_o(\mu a)$

$\lambda = m\pi/2\ell$

$A_{\mu m}$ = constant depending on the initial temperature distribution in a can:

$$\frac{4\ (1 - \cos m)}{\pi(\mu a)\ J_1(\mu a)}$$

C_r = centigrade temperature of bath or retort

$\frac{k}{c_p \rho}$ = diffusivity, $\frac{\text{conductivity}}{\text{specific heat x density}}$

For all practical purpose, the first term of the above equation is adequate. This simplifies to:

$$T = C_r - A_1(T_i - T_r)\ e^{\frac{-k}{c_p\rho}(\mu_1^2+\lambda_1^2)t}\ J_o(\mu_1 r)\ \sin\lambda_1\ (Z + \ell)$$

These equations can also be applied for cooling if the contents of can were heated to practically uniform temperature before cooling started.

At the center of the can where r = 0 and Z = 0, Bessel function,

$$J_o(\mu r) = 1 - \frac{(\mu r)^2}{2^2} + \frac{(\mu r)^4}{2^2 4^2} + \frac{(\mu r)^6}{2^2 4^2 6^2} + \text{-------}$$

of zero'th order is $J_0(\mu r) = J_o(0) = 1$, and also,

$$\sin \lambda \ (Z + \ell) = \sin \frac{m\pi}{2} = \pm 1$$

$$\cos \lambda \ Z = \cos (0) = 1$$

Therefore the equation expressing the temperature at the center of the foods in a cylindrical container becomes:

$$T = C_r - A_1(T_i - T_r)\, e^{\frac{-k}{C_p \rho}(\mu_1^2 + \lambda_1^2)\, t}$$

Thompson (1919) presented a table of $(\mu_1^2 + \lambda_1^2)$ for different containers, a table of thermal diffusivities for some food products as well as the chart of temperature versus time as $(k/C_p\rho)(\mu_1^2 + \lambda_1^2)$ to facilitate the calculations for obtaining heat transfer informations. Besides giving the mathematical equations, charts and tables, he presented experimental temperature-time data of some food products in rectangular coordinate paper. This gave an easy visible means of predicting time-temperature relationship of food products in containers during the processing.

In 1920, Bigelow et al. studied heat penetration during processing of canned foods. They observed that the fastest possible heat penetration in canned foods is similar to that of water or slightly less. This maximum heat penetration occurs when the food is in the form of a dilute solution and heats by convection. They also noticed that the slowest heat penetration in canned foods is similar to the

heat penetration in water due to conduction alone. This is common to food materials which consists of many cells each containing cellular water and cell walls preventing the formation of convection currents. Good examples are fruits and vegetables. Bigelow et al. (1920) developed heat penetration data for many individual products, as well as conversion factors from one size cans to the other size cans to be used for heat penetration calculations. However, perhaps the most significant contribution in heat penetration study was their presentation of time-temperature data in semilog coordinate paper with temperature in logarithmic scale. When the semilog paper was turned 180° and the top line labeled one degree below retort temperature, a straight line has resulted.

Magoon and Culpepper (1921) showed heat penetration curves of distilled water, brine, sugar solution and starch solutions, as well as several food products. They also (1922) studied the relation of initial temperature to pressure, vacuum, and temperature changes in the container during canning operations.

In further heat penetration studies by Jackson and Olson (1940) the slowest heating point in the products which heat by convection was found to be located on the can axis at the point near the bottom of the container. For No. 2 cans the point is about 3/4 inch (19 mm) above the bottom and for No. 10 can, about 1½ inches (38 mm) above the bottom when the cans are processed in an upright position. Long before this, it was generally accepted that the slowest heating point in the conduction heating product was located at the geometric center.

In a more recent study (Pflug et al., 1965), it was reported

that in general the slowest heating point is determined by the relative heat transferred by convection flow versus conduction. According to this study when conduction heat transfer dominates, the slowest heating point is near the geometric center, as convective flow increases, the point will move toward the bottom of the container, and the displacement of the cold zone from the geometric center is proportional to the rate of convection heat transfer. However, the numerical relationship between the distance of cold-point shifting and convection heat transfer was not established.

b. Devices for obtaining heat penetration data

It was not known who exactly was responsible in starting to use Tell-Tale thermometer (a maximum thermometer) in the measurement of the temperature of food during processing; nevertheless, it appears to be the first mechanism used for this purpose. The thermometer was placed in a metal frame that was adapted to the screw top of test can. (Later, it was modified so that the thermometer was sealed into an ordinary can and fastened to a splinter of wood that fits the can diagonally).

In 1912, Bitting used a chemical thermometer which is sealed in a can by means of a stuffing box soldered to the top.

In 1919, Thompson, and Bovie and Bronfenbrenner (1919) used copper-constantan thermocouples to measure the temperature of food during processing. These were the first successful attempts to obtain temperature history of food during process. Bigelow et al. (1920) improved the thermocouple system by attaching it to a can by means of a stuffing box that is soldered to the top of the can, and using ice-

water as a cold junction. They used a Leeds and Northup's potentiometer to measure the voltage which was converted to temperature. This made it possible to record the temperature of canned foods during actual commercial processing conditions. The use of a Bakelite tube (Ford and Osborne, 1927) as a protective tubing for thermocouples eliminated one important source of error namely, the flow of heat along the tube.

Ecklund (1949) developed a thermocouple unit in which the thermocouple is sealed to the receptacle and the receptacle to the can by means of rubber gaskets. The heat penetration thermocouple, in addition to having the connector feature, was so designed that the thermocouple and the receptacle which holds it did not project from the side of the can. This permitted normal closure of the can on commercial closing equipment. Now the complete specialized heat penetration equipment which could be conveniently used was available to any investigators.

Alstrand and Ecklund (1952) gave the equipment necessary for heat penetration measurement as follows:

1. Thermocouple capable of being mounted in a can in such a manner that the hot junction is on the can axis.

2. Compensated lead wires made into a cable of several duplex leads depending on the number of cans to be tested simultaneously.

3. A stuffing box so that the lead cable can be brought through the retort wall.

4. A selector switch.

5. Potentiometer for indication of the can temperature.

c. Treatment of heat penetration data

Depending on the method of thermal process calculation (discussed in the section immediately following) to be employed, the heat penetration data can be treated as follows:

1. Time-temperature data can be plotted in rectangular coordinate paper if the lethality is later to be found from each corresponding temperature and summed up graphically.

2. Time and the temperature corresponding to that heating time can be left in a tabular form if lethality at each corresponding temperature for a given time interval is to be summed up to give a total lethality of a specified process.

3. Time-temperature data can be plotted directly on lethal-rate paper to obtain a lethality curve the area beneath which will be proportional to the lethality of the process.

4. Finally, the difference between retort temperature and food temperature may be plotted on the log scale against time on the linear scale on upside down semilog paper with the top line labeled one degree below retort temperature for the heating curve. For the cooling curve, the data also plotted on normal semilog paper, with the bottom line labeled one degree above cooling water temperature. This is convenient when mathematical method is going to be used.

4. Thermal process calculations

The inadequacy of trial and error methods led to more systematic study of the thermal processing. An obvious object of thermal processing as mentioned before is inactivation of microorganisms which cause spoilage in canned food and more importantly of bacteria which cause disease. In order to do this, it was necessary to have some microbiological standard. Since

the beginning of the nineteenth century, it was known that Cl. botulinum caused food poisoning. It was later found that this organism also is extremely heat resistant; therefore Cl. botulinum was considered to be the proper microbial-standard for determining the degree of the sterility of processed foods.

Esty and Meyer (1922) determined an "ideal" thermal death time curve for spores of Cl. botulinum in neutral phosphate buffer. This curve was designated by the values F = 2.78 minutes and Z = 18°F. Since then no one was able to observe higher thermal resistance for Cl. botulinum than the above value. Because of the lack of knowledge concerning the types of bacteria occurring in various foods prior to their being processed, concerning the concentration of the more resistant types which might be encountered, and concerning thermal resistance of bacteria as they occur in foods, the maximum resistance values mentioned above for spores of Cl. botulinum have been and still are used as the basis for establishing safe commercial processes throughout the canning industry. According to Stumbo (1965), in view of the concept that bacterial death is logarithmic in order, this procedure is justifiable, and quite possibly imperative to the establishment of safe commercial processes. Consequently, processes having an F_o value of at least 2.78 minutes have been considered absolutely necessary for all non-acid canned foods unless well-checked evidence indicates that the chemical or biochemical nature of the product necessitates a revision.

While in high acid foods, Cl. botulinum does not grow, there are other high heat resistance organisms such as B. thermoacidurans, B. stearothermophilus which cause spoilage of canned foods, and these

differentiated the equations, multiplied by lethality expressed in terms of semilogarithmic straight line, and integrated between the limits. Combining these three resultant equations, he obtained,

$$A = \frac{f_h}{t}\left\{ e^{\frac{g}{Z}}\left[E_i\left(-\frac{80}{Z}\right) - E_i\left(-\frac{g}{Z}\right)\right] + \left[\frac{.33172}{e^{\frac{.343m}{Z}}}\right.\right.$$

$$\left. + e^{\frac{.300m}{Z}}\ \frac{.58338}{m}E\right] + \frac{1}{e^{\frac{m}{Z}}}\left[E_i\left(\frac{.657m}{Z}\right)\right.$$

$$\left.\left. - E_i\left(\frac{m+g-80}{Z}\right)\left(\frac{m+g-80}{Z}\right)\right]\right\}$$

or,

$$A = \frac{f_h}{t} C$$

where,

A = total lethal value of the process

m = temperature difference in °F between the maximum temperature reached at the center of the can and cooling water

g = °F below retort temperature of the maximum temperature reached by the center of the can

E_i = universally convergent series

f_h = reciprocal of the slope of heat penetration curve, or time required to trasverse one log cycle of temperature, or time in minutes required for the straight line heating curve to trasverse one log cycle

C = an arbitrary constant depending on m, g, and Z

From the heating curve, f_h can be found. A value of g corresponding to a certain value of t (time in minutes) on the thermal death time curve can be found and a given value of C from the C versus g curves published by Ball. This value of g, which satisfies the above equation when applied to the heating curve, gives the length of process. The above equation can be solved either entirely by graphs or by combination of equations and graphs. (See Ball (1923) for detailed method for obtaining solution).

Ball has presented, in the same paper, series of tables and graphs of C for different values of Z, g and m+g to simplify the calculations.

Ball (1923) published simplified equations for the process calculation for the case of straight semilogarithmic heating curves. From the heat penetration curve an equation for a straight line can be written as:

$$B = f_h \log \frac{(T_R - T_{pih})}{(T_R - T)} = f_h \log \frac{(T_R - T_{pih})(T_R - T_{ih})}{(T_R - T_{ih})(T_R - T)}$$

$$= f_h \log \frac{J_{ch} I_h}{g_c}$$

where,

B = process time, in minutes, when retort reached processing temperature instantaneously

J_{ch} = heating lag factor, $(T_R - T_{pih})/(T_R - T_{ih})$

T_R = temperature of retort

T_{ih} = initial food temperature when heating is started

T_{pih} = pseudo-initial food temperature when heating is started, or the temperature indicated by the intersection of the extension of the straight-time protion of the heating curve and the vertical line representing beginning of heating

I_h = difference in degrees Fahrenheit, between retort temperature and initial food temperature, that is: $I_h = T_R - T_{ih}$

g_c = difference in degrees Fahrenheit, between retort temperature and maximum temperature reached by the food at the geometric center of the container

F_c = the equivalent of minutes at 250°F of all lethal heat received by the geometrical center of a container of food during process; the relationship of it to other parameters are given by: $U = F_c F_i$

where,

U = number of minutes required to destroy the organisms at retort temperature

$F_i = \log^{-1} (250 - T_R)/Z$

From published charts of f_h/μ versus g (Ball, 1923) and the above equations, the processing time for a given lethality or the lethality for a given process can be found.

Ball (1923) experimentally determined that about 42% of the "come-up" time should be considered as process time at retort temperature. Therefore, the process time after the retort reaches the processing temperature, P_t becomes, $P_t = B - 0.42\ell$, where ℓ = come up time.

c. Nomographic method

Nomographs were constructed by Olson and Stevens (1939) to provide graphical means of carrying out the computation required in the Ball's formula method for specific applications. This nomograph decreases the computation required for calculation of processing time and makes possible for persons without mathematical knowledge to obtain processing time.

The nomograph incorporates the following variables: R.T.; f_h, F_o, j, RT-IT and B. In the same report, they give f_h conversion factors for different can sizes and correction factors for different R.T.-C.W.

d. Summation of lethality throughout whole container

Stumbo (1948) considered the thermal processing based on the lethality at the point of greatest temperature lag does not necessarily give the sufficient process for whole container. He showed the difference between the actually obtained lethality by thermal processing and the lethality required to reduce the probability of survival to a desired level at each imaginary cylindrical layer inside the container of food being processed. In some cases, especially in convection heating product, the highest probability of survival occurred at locations definitely away from the center of the can and rather more close to the side wall of the can. On this bases he claimed, that the accurate evaluation of thermal process can be accomplished only if all points in the container are considered, since the sterility of the whole container is the sum of lethal effects at all points throughout the container.

Later in another publication, Stumbo (1953) used the concept of iso-F regions for the integral estimation of the lethal effect in whole container. Normally these are identical with the iso-j, or constant lag regions. He described iso-j regions by using Olson and Jackson's (1942) concept:

$$j = j_c J_o(R_1 \frac{r}{a}) \cos \frac{\pi y}{2l}$$

where,

j = lag factor at any designated point in the container

j_c = j at the geometrical center of the container

$J_o(X)$ = zero-order Bessel function of X

R_1 = the first positive root of $J_o(X) = 0$, or a constant which is 2.4048

r = distance, along the container radius, of a designated point from the vertical axis of container

a = radius of the container

y = distance of the designated point above or below a horizontal plane bisecting the container midway between two ends

$2l$ = container height or length

The volume of iso-j region is:

$$v = 2 \int_o^{y_{max}} r^2 dy \text{ from geometry}$$

where,

y_{max} = one-half length of the solid revolution

dy = infinitesimal element of y

r = radii of dy element

As already given earlier the bacterial death is described by:

$$t = D (\log a - \log b)$$

or,

$$F_o = D_r (\log a - \log b)$$

or,

$$b/a = 10^{-F_o/D_r}$$

where,

t = time of heating

D = decimal reduction time

a = viable cell present in some given volume

b = viable cell present in some given volume after heating

F_o = lethal effect equivalent in minutes at 250°F

D_r = decimal reduction time at retort temperature (or 250°F)

When the difference between the treatment received by any iso-j region, F_λ, and the treatment received at the center of container, F_c, was plotted against fraction of total can volume enclosed by any iso-j region, v, a straight line was obtained up to v = 0.4. Therefore using the equation for straight line, $F_\lambda - F_c = mv$.

Above equations with some substitutions, rearrangements and

simplifications lead to:

$$F_s = F_c - D_r\left\{(\log D_r + \log v) - \left[\log 2.303 + \log (F_\lambda - F_c)\right]\right\}$$

giving the equivalent of all heat received by the entire container, F_s. By using $v = 0.19$ for convenience, this equation is further simplified to:

$$F_s = F_c + D_r\ (1.084 + \log \frac{F_\lambda - F_c}{D_r})$$

Hicks (1951) and Gillespie (1951) suggested similar integral approaches for the evaluation of thermal processing.

e. Selection of process calculation method

The graphical method, while tedious, is classical in the sense that it could be used for any type of heating curve and does not require mathematical manipulation nor any information other than temperature at the slowest heating point as a function of time, and the heat resistance of the organism.

Some products show heating curves deviating from linearity. One of the common deviations is a "broken heating curve" in which two straight line portions may be fitted to the data. For the products exhibiting such broken heating curves, processes can be most accurately and easily evaluated by the graphical integration procedure. Although mathematical procedures were developed (Ball, 1928; Ball and Olson, 1957), they are rather time-consuming, and accurate transformation of

data for process calculation may be difficult.

The graphical method is also satisfactory for evaluating processes for convection-heating products. However, the formula method is less time consuming for the same degree of accuracy in results.

Another point of view, represented in particular by Stumbo (1948) is that it is more desirable to integrate the lethal effects at different positions in the container, especially when there exists considerable gaps in lag times within the container.

B. Thermal Sterilization of Foods In Flexible Packages

Successful application of flexible packages for dehydrated, frozen, refrigerated, high sugar and high salt, and high acid products stimulated the application of flexible packages further for the food materials to be heat-sterilized.

1. Utilization of flexible packages for thermal sterilization

In 1956, Nelson et al. used mylar-polyester film and Trithene film in processing apple sauce and tomato juice in boiling water and potato-meat stew and club steaks at 250°F. Their experiments indicated that these flexible films were not suitable for the thermal-processing because of the high incidence of leakage, high water vapor permeability and color changes of the products upon storage.

Keller (1959) processed meat at 250°F, and peach slices in boiling water in vinyl-foil-polyester pouches. According to the author, his results demonstrated the general feasibility of using foil-laminated packages for thermal processing.

In 1962, Mayer and Robe reported that great numbers of foods in foil-film-laminated pouches were processed commercially with some products having excellent shelf life. They claimed leak incidence and shipping damage were comparable to or lower than cans. However, products studied were limited only to those processed in an atmospheric cooker.

In 1963, Geisman et al. processed snap beans, sweet corn and tomato products at 250°F under water for the purpose of investigating the product quality. Their work was primarily concerned with the effect of flexible packaging to quality of the food products rather than the performance of packaging material itself.

In 1964, Luh and co-workers processed tomato paste in mylar-saran-polyethylene and saran-coated-cellophane-polyethylene-aluminum-polyethylene pouches at 208°F for 15 minutes. Although this experiment showed improved acceptability of the flexible pouches for thermal processing, still short storage life of the products was reported. The incidence of leakage of the pouches was not mentioned in their work. Using the same packaging materials, Luh and Tsiang (1965) processed tomato ketchup in a water bath at 200°F. Concluding that the plastic laminate was less desirable than aluminum-foil lamination pouches, they considered that more work was needed to improve the property of the aluminum-foil pouches. Same packaging materials were again used in processing boysenberry puree by Dirdjokusumo and Luh (1965) in a water bath at 200°F. This work was also concerned mainly with quality factors.

More recently, Suzuki (1966) processed a curry product, soft spaghetti, Subuta (Japanese pork dish), and Yakimeshi (fried rice) at

120°C, beef yamatoni (Japanese beef dish) at 113°C, rolled tangle (Chinese food) at 110°C. His study was more diversified and included some heat transfer studies as well as storage studies.

2. Requirement characteristics of the flexible packaging materials for thermal processing of foods

The minimum requirements for materials for heat-processible packages can be outlined as follows:

A. Low permeability to gases and vapors.

B. Adequate physical properties in the temperature ranges -40 to 250°F.

C. Heat-sealability at wide range of temperatures.

D. Chemical inertness:

1. Lack of toxic extractables

2. Lack of off-flavor or odor problems

E. Resistance to fat, oil, or other food component penetration.

F. Resistance to stress cracking, and storage durability.

Of course, besides the above requirements, it is necessary that the flexible package form a barrier for microbial penetration.

Data obtained by Proctor and Nickerson (1956-1958) indicated that plastic films more than 1/2 mil thick, including polyethylene, were not permeable to bacteria.

Ronsivalli et al. (1966) studied the bacterial permeability of plastic films. Of 133 tests made, 15 showed the possible permeability to bacteria among which only five showed no visible material defect of film. They reported that plastic films appear to be imper-

meable to bacteria, that nylon-11 and polyethylene coated polyester are 100% reliable, saran-coated nylon-11, polypropylene, and polyester were more than 95% reliable and nylon-6 and polyethylene were less reliable.

Some quantitative figures for the limitations are given by Long (1962). He gives the permeability to O_2 as less than 1 cc/100 sq. in. in 24 hours for one atmosphere differential, and water vapor permeability less than 0.05 gm /100 sq. in. in 24 hours of packaging materials for most application. For a flexible packaging material to make a successful retortable package, he considered that it must also be economical, hydrophobic, stable with regard to dimension, sufficiently strong to resist tearing, corrosion, pin-holing, fatigue, impact and abrasion during production, processing and distribution cycles. It is also necessary for this material capability of being handled on automatic fabricating and filling equipment, and good printability with inks that will withstand thermal processing.

Considering all these factors, Long (1962) concluded that only aluminum-foil lamination, but not yet the plastic lamination, was suitable for heat-processing purpose. Keller (1959) also reported the greatest potential of foil lamination and coating, and he went one step further by recommending non-oriented films or films not subject to shrinkage (probably he meant expansion as well) for the lamination or coating to control the delamination of the film. Several other workers (Mayer and Robe, 1963); Luh and de la Hoz, 1964; Luh and Tsiang, 1965), besides the above mentioned consider aluminum lamination acceptable or desirable on the basis of their experiment.

On the other hand, many workers agreed that plastic laminations are not acceptable for the packaging of thermal processed foods on the basis of high moisture transmission across the film (Keller, 1959; Nelson et al., 1956; Luh and de la Hoz, 1964; Suzuki, 1966; Davis et al., 1962), high gas permeability (Nelson et al., 1956), color change of the products (Geigman et al., 1963; Luh and de la Hoz, 1964; Luh and Tsiang, 1965; Davis et al., 1962), and off-flavor of the products (Luh and de la hoz, 1964; Luh and Tsiang, 1965; Mannheim et al., 1957a and 1957b).

Incorporation of aluminum between the plastic lamination greatly decreases the moisture and gas transmission and foil can also improve the appearance of the film. Polyethylene, vinyl, and pliofilm are desirable for the inner lamination. Polyethylene has good sealing ability, and inertness which gives freedom from taste impartation and off-flavor. Vinyl also has good sealing ability and it can be applied in a very thin layer. Pliofilm has good sealing ability, and ability to withstand oil and fats. For the outer layer cellulose acetate and mylar were considered desirable. Cellulose acetate has clarity, dimensional stability, superior printing surface and ability to withstand sealing temperature used to seal the inner ply. Mylar gives strength, support and maximum protection of foil, clarity, and has an ability to stand sealing temperature as well.

3. Sealing methods for flexible film

a. Ultrasonic sealing

In this process, two pieces of plastic are sandwiched be-

tween a solid anvil and a continuously hammering tool. According to the manufacturer (Ultrasonic Seal, Incorporated, 1961), the hammering tool, moving at the rate of 20,000 blows per second or faster, produces a natural molecular bond without deforming, distorting or changing the properties of the material. They claim this invention not only seals, but welds quickly, economically and permanently, and better yet, right through contaminants such as food. If this were true, it would be a desirable sealing process for food packaging with flexible films; however, no additional literature or information was available on this matter.

b. Heat sealing

This process involves fusion of thermo-plastic layers by supplying the necessary heat. The methods of heat application include heated jaws, dialectric heating and impulse heating. Heating can be accomplished either from both sides or from only one side. The jaws or platens can be either flat or rounded. Christie (1961) found that the rounded jaw heat sealer gave seal efficiency of 80% or better, in comparison with 50% or less for the flat-jaw sealer. Many mechanical modifications of the basic reciprocating heat sealer have been developed to improve speed and continuity of sealing. Such examples are rotary and continuous belt-type sealers used commonly in industry.

There are more than one set of optimum conditions to be used for heat-sealing a specific film, because of the variability depending on three variables (temperature, pressure and time) on the sealing unit as well as the type of film to be sealed. The

optimum conditions have to be found by trial and error by using the particular sealer to be used for the experiment.

Modern Packaging Encyclopedia (1963) gives some information in heat-sealing as follows:

Type of film	Pressure	Temperature	Dwell Time
Polyethylene (H.D.)	20 psi	300	1/2 sec
Polyethylene (L.D.)	10 psi	300	1/2 sec
Polyproplene	20 psi	350	1/2 sec
Cellulose acetate	50 psi	450	1/2 sec

From this table, it can be observed that the variable which is maintained constant is time, and this varaible could be different depending on the investigator. The optimum sealing conditions found, therefore, could differ greatly depending on the variables which investigators choose not to vary and of course depending on the machine used.

4. Some thermal processing methods for flexibly packaged foods

References concerning the thermal sterilization of flexibly packaged foods so far mentioned have experimented with one or more of the many thermal processing methods yet developed for canned foods. Those include processing in boiling water, heating with steam, steam air mixture, and steam in water. However, for cooling, generally water with over-riding air pressure is employed and considered most desirable for preventing bursting of the pouches caused by pressure differential during cooling (Davis et al., 1960).

5. Devices for obtaining heat penetration data during the processing of flexibly packaged foods

The same thermocouples and temperature recording devices used for the measuring of the temperature change of canned foods during processing can be used also for flexibly packaged foods. The problem arises in employing in the flexible pouch the metal thermocouple receptacles developed for measurement in cans. Because of the flexible nature of the flexible packaging material, heavy receptacles can severely distort the natural shape of the flexible packages, changing the heat transfer characteristics of the pouch, and giving meaningless heat transfer data.

Nevertheless, Nelson et al. (1956) used conventional thermocouple receptacles generally used for measuring the center temperature of food processed in a tin can. Keller (1959) used the Armour-piercing thermometer which cannot be considered improvement over the above. Wornick et al. (1960) fitted thermocouple probe through a slit in one heat-sealed edge, and clamped it in place with two small circular rubber gaskets and a screw clamp, which maintained the thermocouple at the center of the pouch. Gould (1962) reportedly used a metal packing gland, a wax seal, and a coiled duplex lead with the thermocouple on the inside of the coil. According to Pflug et al. (1963), this led to development of the all-flexible-gusset and lead and positive metal packing-gland-type thermocouple system.

In the above systems, the thermocouple was stripped of all insulation, cleaned with solvent, coated with 3-5 layers of a lacquer that will heat-seal to the inside laminate of the pouch then inserted through the seal of the pouch and heat-sealed to the inside

lamination of the pouch. Pflug (1963) used V-shaped gusset heat-sealed to the pouch to maintain the thermocouple tip in desired position. When metal packing-gland was used for inserting the thermocouple and when necessary, plastic saddle maintained the position of the tip of the thermocouple.

Eckland-type metal glands specifically designed to be used for heat-penetration experiment in flexible packages are commercially available from Continental Can Company, Chicago, Illinois. These receptacles still have the disadvantages of the original receptacles.

6. Heat penetration and thermal sterilization studies in flexible packages

The rate of heat penetration into a container may influence the processing time required for sterilization of the product. Wornick et al. (1960) studied this aspect by investigating the rate of heat conduction into flexible plastic containers. The containers used were made of 0.001 inch mylar polyester film, 0.001 inch, 0.002 inch and 0.003 inch high-density polyethylene and 0.00125 inch polypropylene. The heating curves obtained for pouches made from different films and containing same food product did not differ significantly. They concluded that the heating lag in the pouch containing water was no larger than could be expected for water alone. Plastic films used regardless of type or thickness (up to 0.003 inch) had a negligible heat resistance compared with that offered by surface films, and these packaging materials could be interchanged without appreciably altering the heating time. A table of heating times for various food items (water, corn, spinach,

tomato puree, and cream of mushroom soup) in plastic film bags of several sizes and film thickness was presented. They pointed out that, in considering the heating time of foods in flexible plastic bags, the heating time would be more a function of the conductivity of the food and the shape of the container, with the plastic film offering little resistance.

Keller (1959) obtained heating curves for flexibly packaged 5.5 ounce beef steak during steam process at 250°F, 240°F and 230°F followed by pressure cooling. Pressure cooling was employed to prevent expansion and possible bursting and to insure proper heat transfer. The process time required to obtain F_o value of 6 were 15 minutes, 35 minutes, and 60 minutes for 250°F, 240°F and 230°F process respectively. He also showed that the heat penetration into the flexibly packaged beef steak was considerably more rapid than for an equivalent can, and anticipated similar reduction in process time for other products. He used the formula method for calculating the process time, found process time at 250°F for 5.5 ounce of beef steak in a 300 x 200 can to be 55 minutes compared to 15 minutes in the flexible package.

Pflug et al. (1963) calculated processing time to obtain various sterilizing values (F_o) for different thicknesses of conduction heating food having a thermal diffusivity of 0.014 sq. in. per min. at condition of RT - IT = 100°F, RT - CW = 160°F, and j = 1.27. They showed the critical nature of pouch thickness on the process time required to deliver several sterilizing (F_o) levels, and the necessity of basing the sterilization-process design on the

maximum thickness. The heating characteristic: f_h and j were determined experimentally for tomato puree, for water, for chicken a la King, and for beef slices in barbecue sauce in mylar-foil-vinyl flexible packages. Their data indicated a trend for the tomato puree to heat fastest and the beef slices to heat the slowest. The ranges in heating rates for each of the three products, however, overlapped the means for the other two products. Ranges of f_h values for tomato puree were 8.0-10.4, for water 1.9-2.4, for chicken a la King 6.4-10.7, and for beef slices in barbecue sauce 8.9-11.3 minutes. There was a close agreement between values calculated from thermal diffusivities of 0.014 sq. in./min. as 0.750 inch thick infinite plate and experimental values of f_h.

Suzuki (1966) obtained heat penetration curve for 22.5% bentonite clay in a flexible package (thickness 1.2 inch) and found f_h to be 16 minutes compared with 28 minutes for a No. 6 can (7.4 x 5.9 can) when processed at 250°F.

THEORY

III. THEORY

A. Mechanisms of Heat Transfer In Thermal Sterilization:

1. General theory on heat transfer

Whenever temperature gradient exists, energy transmission occurs from higher temperature region to lower temperature region. The eventual effect of energy- or heat-transfer is the equilization of the temperatures of all regions. The mechanisms by which energy transfer takes place can be divided generally into three groups, radiation, conduction and convection heat transfer.

Radiation heat transfer takes place when bodies with temperature gradients are separate in space. All bodies emit radiant heat continuously, and the intensity of the emission depends on the temperature and the nature of the surface. Heat transfer by radiation becomes increasingly important as the temperature of an object increases. In the thermal processing of food in retorts, the heat transfer by radiation can be neglected since the contribution by this mechanism is negligible compared with that by conduction or convection. This is more so in processing food under water as done in this study.

Conduction is a process by which heat flows from a region of higher temperature to a region of lower temperature within a medium or between different media in direct physical contact. In conduction heat flow, the energy is transmitted by direct molecular communication without appreciable displacement of the molecules. The absolute temperature of an element of matter is proportional to the mean kinetic energy of its constituent molecules. When molecules in one region acquire a mean

kinetic energy greater than that of molecules in an adjacent region, the molecules with higher energy will transmit some of their energy to the other. Conduction is the only mechanism by which heat can flow in opaque solids, and this is the major mechanism to be considered in the thermal processing of solid food.

Convection is a process of energy transport by the combined action of heat conduction, energy storage, and mixing motion. Convection is most important as the mechanism of energy transfer between a solid surface and a liquid or a gas. The transfer of energy by convection from a surface whose temperature is above that of a surrounding fluid takes place in several steps. First, heat will flow by conduction from the surface to adjacent particles of fluid. The energy thus transferred will serve to increase the temperature and the internal energy of these fluid particles. Then the fluid particles will move to a region of lower temperature in the fluid where they will mix with, and transfer a part of their energy to, other fluid particles. A flow of fluid as well as energy flow will occur. The energy is actually stored in the fluid particles and is carried as a result of their mass motion. This mechanism does not depend for its operation merely on an energy propagation but also mass motion, however, the transport of energy occurs in the direction of a temperature gradient as in the other mechanisms. The convection heat transfer takes place within food materials in the thermal processing of liquid food or less viscous food materials, also it is the principle mechanism of heat transfer from the heating medium, such as steam or water, of the retort to the food container.

In most of the actual heat transfer processes, usually some

combination of these three mechanisms exists. However for engineering purposes, often the consideration of only one dominant mechanism could approximate numerical solution to the desired accuracy.

The heat transfer process is either steady, that is, rate of heat flow does not change with time, or unsteady, that is, rate of heat flow changes with time. The heat flow in a system is transient, or unsteady, when the temperature at various points in the system changes with time.

In thermal processing, foods to be processed are heated to desired temperature and held at that temperature. Therefore, the process involved of major interest is unsteady or transient heat transfer.

2. Mechanisms of heat transfer to flexibly packaged foods

When a package of food is placed in a retort to which steam or water of higher temperature is supplied, as a result of the temperature difference there is a flow of heat from the heating medium to the food.

a. Heat transfer to the package wall from heating water

The major mode of heat transfer from heating water to the outside wall of the package film is free-convection although conduction heat transfer also takes place. As a result of heat transfer, the temperature of the fluid near the package changes toward the temperature of the food in the package. The change in temperature causes the change in the density of fluid. This change in density in turn leads to the mass downward flow of cooled-heavier fluid near to the package and upward flow of hotter or lighter fluid. This body force responsible for convection current is buoyancy. When the food is processed under water

in a still retort, no external agency is used to induce mixing motion of water, the flow of steam used to heat the water causes only negligible mixing, and the mixing motion takes place merely or mostly as a result of density differences of the fluid caused by temperature gradients. Therefore it is reasonable to consider that mainly free convection heat transfer takes place.

The instantaneous amount of heat transferred, dQ, by free convection from the heating water to the outside wall of the package can be expressed as

$$dQ = h_{out} dA (T_s - T_\infty)$$

where,

h_{out} = convective heat transfer coefficient outside of the food package

dA = infinitesimal area

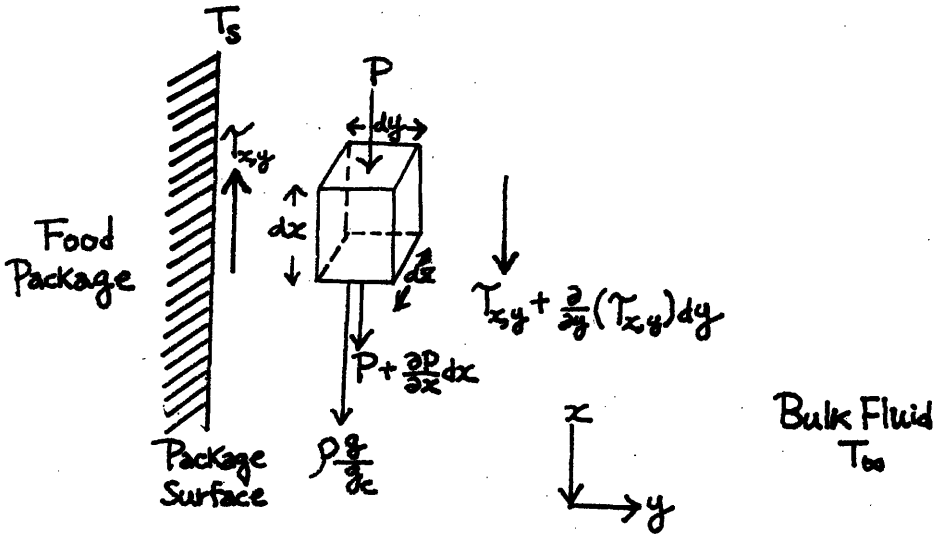
T_s = temperature at surface of the package

T_∞ = temperature of the bulk heating fluid

Infinitesimal area is used since heat transfer coefficient may not be uniform throughout the surface area.

The heat transfer coefficient, h_{out}, depends on the thickness of the laminar layer at the boundary, thermal conductivity of the heating medium and the rate of flow of convection current. The thickness of the laminar layer at the boundary is often the limiting factor in convective heat transfer, since at the boundary layer the heat transfer is mainly restricted to conduction.

In order to derive the equations governing the flow in the boundary layer, the forces acting an elementary volume of this layer are considered.



Forces Acting On A Volume Element of Heating-Water Near the Package In Free Convection Flow

The forces acting on the volume element of heating-water near the package, dx dy dz in the positive x direction consist of

1. The force due to the pressure gradient

$$P\ dy\ dz - (P + \frac{\partial P}{\partial x})\ dy\ dz = -\frac{\partial P}{\partial x}\ (dx\ dy\ dz)$$

2. The body force

$$\rho \frac{g}{g_c}\ (dx\ dy\ dz)$$

3. The frictional shearing forces due to the velocity gradient

$$-\tau_{yx}\,(dx\,dz) + \left(\tau_{yx} + \frac{\partial}{\partial y}(\tau_{yx})dy\right) dx\,dz$$

$$= \frac{\partial(\tau_{yx})}{\partial y}\,(dx\,dy\,dz)$$

In free convection, especially near the boundary the flow of fluid by density gradient is laminar. In laminar flow the shearing force is expressed as

$$\tau_{yx} = \frac{\mu}{g_c}\left(\frac{\partial u}{\partial y}\right)$$

where,

μ = absolute viscosity (16-m/sec.-ft.)

u = linear velocity in x direction (ft./sec.)

Therefore, net shearing force on the volume element becomes

$$\frac{\partial(\tau_{yx})}{\partial y}\,(dx\,dy\,dz) = \frac{\mu}{g_c}\left(\frac{\partial^2 u}{\partial y^2}\right)(dx\,dy\,dz)$$

Considering an elementary control volume having the shape of a parallelepiped with dimensions dx, dy, dz, fixed in the flow field and for the case when the flow is two-dimensional, the fluid is incompressible, the

pressure is constant throughout the flow field, the flow is steady with respect to time, and the mass of fluid entering the volume, dx dy dz, during a time interval dt must be equal to the mass leaving the system, the mass of fluid entering through the face of the control volume during dt is

$$(\rho u)\ (dy)\ (dz)\ dt$$

The mass of fluid leaving through the bottom plane during this time is

$$\left(\rho u + \frac{\partial(\rho u)}{\partial x}\,\partial x\right)\ (dy)\ (dz)\ dt$$

The mass of fluid entering through the left face during dt is

$$(\rho v)\ (dx)\ (dz)\ dt$$

and the mass of fluid leaving through the right face during dt is

$$\left(\rho v + \frac{\partial(\rho v)}{\partial y}\ dy\right)\ (dx)\ (dz)\ dt$$

From the continuity or conservation of mass, the mass entering the system must be equal to the mass leaving the system. Therefore,

$$\rho u\ dy\ dz + \rho v\ dx\ dz = \rho u\ dy\ dz + \frac{\partial(\rho u)}{\partial x}\ dx\ dy\ dz$$

$$+ \rho v\ dx\ dz + \frac{\partial(\rho v)}{\partial y}\ dy\ dx\ dz$$

Simplification of the above equation yields the following or the continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

According to Newton's second law, the summation of forces acting on the control volume of the fluid is equal to the time rate of change of its momentum or mass times velocity. In an equation form

$$\Sigma F = \frac{1}{g_c} \frac{d(mV)}{dt}$$

where,

F = force

m = mass

V = linear velocity

The mass of the fluid particles entering through the top face per unit time is $\rho u\, dy\, dz$. The velocity of these particle is u. Therefore, the x momentum per unit time entering from the top is

$$(\rho u\, dy\, dz)\, u = \rho u^2\, dy\, dz$$

Fluid particles flow into the control volume through the left face at the rate of $\rho v\, dx\, dz$. Also these particles have a velocity component in the x direction, and their contribution to the x momentum entering per unit time is

$$(\rho v\, dx\, dz)\, u = \rho v u\, dx\, dz$$

The momentum per unit time leaving through the bottom face is

$$\left(\rho u + \frac{\partial(\rho u)}{\partial x} dx\right)\left(u + \frac{\partial u}{\partial x} dx\right) dy\, dz$$

Carrying out the multiplication and discarding the higher order term

$$\frac{\partial(\rho u)}{\partial x}\,\frac{\partial u}{\partial x} dx^2\, dy\, dz$$

yields,

$$\left[\rho u^2 + \rho u \frac{\partial u}{\partial x} dx + u \frac{\partial(\rho u)}{\partial x} dx\right] dy\, dz$$

Similarly, the momentum per unit time leaving through the right face is

$$\left[\rho v u + \rho v \frac{\partial u}{\partial y} dy + u \frac{\partial(\rho v)}{\partial y} dy\right] dx\, dz$$

The net increase of momentum per unit time of the fluid in the control volume is the difference between the momentum leaving and the momentum entering during that time. Therefore,

$$\left\{\rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial y} + u\left[\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y}\right]\right\} dx\, dy\, dz$$

This should be equal to the summation of all the forces, body force, gravity force and shearing force. But from the continuity or conservation of mass:

$$u\left[\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y}\right] dx\, dy\, dz = 0$$

Therefore,

$$(\rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial y}) \, dx \, dy \, dz = (-g_c \frac{\partial P}{\partial x} - \rho g + \mu \frac{\partial^2 u}{\partial y^2}) dx \, dy \, dz$$

Cancelling dx dy dz results

$$(\rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial y}) = -g_c \frac{\partial P}{\partial x} - \rho g + \mu \frac{\partial^2 u}{\partial y^2}$$

The heating fluid far away from food package is in hydrostatic equilibrium, or

$$g_c (\frac{\partial P_e}{\partial x}) = -\rho_e g$$

where the subscript e denotes equilibrium conditions. At any elevation the pressure is uniform therefore,

$$\frac{\partial P}{\partial x} = \frac{\partial P_e}{\partial x}$$

Substituting $\rho_e g$ for $-\frac{\partial P}{\partial x}$ gives

$$\rho (u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y}) = (\rho_e - \rho) g + \mu \frac{\partial^2 u}{\partial y^2}$$

Assuming that the density of fluid depend only on the temperatures, the buoyant term can be written

$$g (\rho_e - \rho) = g (\rho_\infty - \rho) = -g \rho \beta \cdot (T_\infty - T)$$

where, β is the coefficient of expansion of the heating fluid, and defined as

$$\beta = \frac{\rho_\infty - \rho}{\rho(T - T_\infty)}$$

Substituting the buoyant term in the force balance equation yields

$$\rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = g\rho\beta\,(T - T_\infty) + \mu\frac{\partial^2 u}{\partial y^2}$$

For all free convection systems, the velocity of heating fluid is both zero at the surface and a distance far removed from the surface, therefore the boundary conditions are same. In order to determine the conditions for which the velocity field in one free-convection system is similar to the velocity field in another, consider a system A where the above equation holds.

The system A is to be related to system B whose conditions can be defined as

$$U_B = C_V U_B$$

$$V_B = C_V V_B$$

$$x_B = C_L x_A$$

$$y_B = C_L y_A$$

$$g_B = C_g g_A$$

$$\beta_B = C_\beta \beta_A$$

$$(T - T_\infty)_B = C_T (T - T_\infty)_A$$

$$\mu_B = C \mu_A$$

$$\rho_B = C \rho_A$$

The equation of motion for the system B is

$$\rho_B \left(U_B \frac{\partial U_B}{\partial x_B} + v_B \frac{\partial U_B}{\partial y_B}\right) = \rho_B g_B \beta_B (T - T_\infty)$$

$$+ \mu_B \frac{\partial^2 U_B}{\partial y_B^2}$$

This equation can be expressed in terms of the quantities pertaining to system A, that is

$$\frac{C_\rho C_v^2}{C_L} \left[\rho_A \left(U_A \frac{\partial U_A}{\partial x_A} + v_A \frac{\partial U_A}{\partial y_A}\right)\right]$$

$$= C_T C_\rho C_g C_\beta \left[\rho_A g_A \beta_A (T - T_\infty)_A\right]$$

$$+ \frac{C_\mu C_v}{C_L^2} \left[\mu_A \frac{\partial^2 U_A}{\partial y_A^2}\right]$$

This equation of motion for system B, is identical to the equation of motion of system A if the coefficients of each of the terms are identical, that is

$$\frac{C_\rho \, C_V^2}{C_L} = C_T \, C_\rho \, C_g \, C_\beta = \frac{C_\mu \, C_V}{C_L^2}$$

Then the solutions of the equations of motion for both systems A and B (the boundary conditions being similar) will be the same and the systems are dynamically similar. When V is the significant velocity and L is the significant length the above equation becomes

$$\frac{\rho_B V_B^2 / L_B}{\rho_A V_A^2 / L_A} = \frac{\rho_B g_B \beta_B (T - T_\infty)_B}{\rho_A g_A \beta_A (T - T_\infty)_A} = \frac{\mu_B V_B / L_B^2}{\mu_A V_A / L_A^2}$$

Combining the first and the last term of the above equation yields

$$\left(\frac{\rho V L}{}\right)_B = \left(\frac{\rho V L}{}\right)_A$$

which are Reynolds number having physical significance of the ratios of inertial forces to frictional forces being identical. Combining the second and the third term of the same equation yields

$$\frac{\rho_B g_B \beta_B (T - T_\infty)_B L_B^2}{\mu_B V_B} = \frac{\rho_A g_A \beta_A (T - T_\infty)_A L_A^2}{\mu_A V_A}$$

that is, the ratio of buoyant to frictional forces are equal. According to the physical aspects of the problem, the velocity of the fluid is not an independent quantity, but depends upon the buoyant force. Therefore, eliminating V from the above equation and substituting in terms of $\mu/\rho L$.

$$\frac{\rho_B^2 g_B \beta_B (T - T_\infty)_B L_B^3}{\mu_B^2} = \frac{\rho_A^2 g_A \beta_A (T - T_\infty)_A L_A^3}{\mu_A^2}$$

The above dimensions modulus is usually defined as Grashof number, G_r, and represents the ratio of buoyant to viscous forces.

When the buoyancy is the only driving force, such as in free convection, the fluid motion is governed entirely by the quantities contained in the Grashof modulus and Reynold number becomes superficial. Therefore when Grashof numbers are equal, there are dynamic similarities between the system.

Considering the same control volume dx dy dz according to the conservation of energy, the energy balance for the system can be expressed as

Influx of enthalpy and kinetic energy	+	rate of heat inflow by conduction	+	rate at which work is done by frictional shear on the fluid in control volume

= Efflux of enthalpy and kinetic energy + rate of heat outflow by conduction + rate at which work is done as a result of frictional shear by the fluid in control volume

or,

$$\rho u \left(h + \frac{u^2 + v^2}{2g_c J}\right) dy + \rho v \left(h + \frac{u^2 + v^2}{2g_c J}\right) dx - K \left(\frac{\partial T}{\partial x}\right) dx$$

$$+ \frac{1}{J}\left[u \frac{\mu}{g_c} \frac{\partial u}{\partial y} dx + \frac{\partial}{\partial y} \left(u \frac{\mu}{g_c} \frac{\partial u}{\partial y} dx\right) dy\right]$$

$$= \rho u \left(h + \frac{u^2 + v^2}{2g_c J}\right) dy + \frac{\partial}{\partial x}\left[\rho u \left(h + \frac{u^2 + v^2}{2g_c J}\right) dy\right] dx$$

$$+ \rho v \left(h + \frac{u^2 + v^2}{2g_c J}\right) dx + \frac{\partial}{\partial y}\left[\rho v \left(h + \frac{u^2 + v^2}{2g_c J}\right) dx\right] dy$$

$$- K \left(\frac{\partial T}{\partial y}\right) dx + \frac{\partial}{\partial y}\left[-K \left(\frac{\partial T}{\partial y}\right) dx\right] dy$$

$$+ \frac{1}{J}\left[\left(u \frac{\mu}{g_c} \frac{\partial u}{\partial y}\right)\right] dy$$

where J is a dimensional conversion factor defined as W = JQ, where W =

work done by the system, Q = heat added to the system, and J = 778.161 ft.-lb/BTU in the British Thermal Unit system. In the above energy balance equation, the frictional work terms represent the work done by shearing forces on the surface of the control volume as faster fluid particles slide over slower ones. At the lower surface, the fluid inside the control volume exerts a force on the fluid outside because the former moves faster. The force times distance per unit time or velocity $u(\mu/g_c)(\partial u/\partial y)$ represents the rate at which work is done by the fluid in the control volume. Similarly, the last term in square brackets on the left hand side of the equation represents the rate at which work is done on the fluid in the control volume.

Conduction along the x direction has been neglected because $-K\frac{\partial T}{\partial x}$ is insignificant compared to $-K\frac{\partial T}{\partial y}$ and convection term in the boundary layer.

For the fluid having constant specific heat, the term $h + (u^2 + v^2)/2g_c J$ can be written as $C_p T_o$ where T_o is the stagnation temperature. In natural convection, the flow of fluid is usually slow and kinetic energy of the flow is negligible, therefore, $\Upsilon = T_o$.

Simplifying, rearranging and neglecting the higher order differential terms of the energy equation yields

$$\rho C_p u \frac{\partial T_o}{\partial x} + \rho C_p v \frac{\partial T_o}{\partial x} = K \frac{\partial^2 T}{\partial y^2} + \frac{\partial}{\partial y}\left(u \frac{\mu}{g_c} \frac{\partial u}{\partial y}\right)$$

But the increase in internal energy due to friction is negligible, therefore the energy equation reduces to

$$\rho C_p u \frac{\partial T_o}{\partial x} + \rho C_p v \frac{\partial T}{\partial y} = K \frac{\partial^2 T}{\partial y^2}$$

or simply

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \frac{K}{\rho C_p} \frac{\partial^2 T}{\partial y^2}$$

Therefore for the systems to be identical, $K/\rho C_p$ of the systems also must be identical. The velocities in these energy equations, u and v, have the same values at any point (x,y) as in the dynamic equation.

In the case of forced convection when the kinematic viscosity, γ or μ/ρ is identical to the thermal diffusivity, the velocity distribution is same as temperature distribution of the system. In other words, the momentum equation and energy equation in forced convection are identical when $\gamma = K/\rho C_p$. Therefore, for similarity of temperature fields in forced convection, $C_p \mu/K$ or Prandtl number must be equal. This is also true for free convection (Kreith, 1963). Therefore, when G_r and P_r are equal at corresponding points, both the velocity and temperature fields are same in free convection heating. The definition of Nusselt number, $h_c L/K$, permit to express the functional relationship in free convection heating as

$$Nu = \phi(G_r)\, \psi(P_r)$$

or when the velocities are sufficiently small so that inertial forces can be neglected:

$$Nu = \phi\ (G_r\ P_r)$$

In agreement with the above approach, for the heat transfer calculation in the natural convection to a vertical plate or cylinder, King (1932) recommended the following dimensionless equation

$$\frac{h_c\ L}{K_f} = C\left[\left(\frac{L^3 \rho_f^2 g_c \beta\ (T_s - T_\infty)}{\mu_f^2}\right)\left(\frac{C_p \mu}{K}\right)_f\right]^n$$

$$\frac{h_c\ L}{K_f} = C\ X^n$$

when $X = 3.5 \times 10^7$ to 10^{12}, $C = 0.13$ and $n = 0.333$

when $X = 3.5 \times 10^4$ to 10^7, $C = 0.55$ and $n = 0.25$

where,

h_c = heat transfer coefficient

L = length of plate or diameter of cylinder

ρ_f = density evaluated at temperature T_f

$T_f = \frac{T_s + T_\infty}{2}$

K_f = thermal conductivity at T_f

μ_f = viscosity of fluid at T_f

In many standard heat transfer text books (Kreith, 1963; McAdams, 1954), it is usual practice to present the graphs of $h_c L_o/K$ versus $C_p \rho^2 g \beta \Delta T L_o^3/\mu K$ to facilitate calculations.

b. Heat transfer to the solid food in the flexible package

The rate of heat transfer to the food package is proportional to the driving forces, temperature gradient, heat transfer area, and overall heat transfer coefficient between the food and the heating medium.

$$q = \frac{dQ}{dt} = UA\,(\Delta T_m)$$

where,

Q = total amount of heat transferred

t = time

q = instantaneous rate of heat transfer dQ/dt

U = overall heat transfer coefficient

A = area of heat transfer

ΔT_m = instantaneous mean temperature difference between the heating medium and food

Overall heat transfer coefficient is reciprocal of sum of the all the resistances.

In the case of heating the packaged solid food is

$$U = \frac{1}{\frac{1}{h_{out} A_p} + \frac{x_p}{K_p A_p} + \frac{1}{h_{in_1} A_p} + \frac{1}{h_{in_2} A_s} + \frac{x_s}{K_s A_s}}$$

where,

A_p = heat transfer area of the package

h_{out} = heat transfer coefficient to the package wall from heating medium

x_p = thickness of the package film

K_p = heat conductivity of the package film

h_{in_1} = heat transfer coefficient inside of the package between package inner wall and the inside space

h_{in_2} = heat transfer coefficient between the inner space of the pouch and the solid object

x_s = thickness of solid object

A_s = area of heat transfer in solid food

The heat transfer in the space between the inside wall of the package and the solid food can be eliminated from consideration when the package is vacuum-sealed to allow the direct contact between the inside wall and the solid food and $A_s = A_p$, therefore

$$U = \frac{1}{\frac{1}{h_{out} A_p} + \frac{x_p}{K_p A_p} + \frac{x_s}{K_s A_s}}$$

The order of magnitude of heat transfer coefficient of water heating is 300~9,000 Btu/hr.-ft.^{2}-$^\circ$F (McAdams, 1954) and 500-10,000 Btu/hr.-ft.^{2}-$^\circ$F (Kreith, 1963).

In the case when heating medium is water at 250°F, temperature of the wall is 150°F and for the plate having 4.5 inch length,

$$P_r = 1.88$$

$$g\beta\rho^2/\mu^2 = 1.11 \times 10^9/°F\text{-ft.}^3 \quad \text{(Kreith, 1963)}$$

$$\log_{10} \left(\frac{g\beta\rho^2}{\mu^2}\right)(\Delta T\, L^3)\left(\frac{C_p\mu}{K}\right) = \log_{10} (1.11 \times 10^9)$$

$$\times \left(100 \left(\frac{4.5}{12}\right)^3\right) (1.88)$$

$$\log_{10} (1.1 \times 10^{10}) = 10.04$$

From this value and the extrapolation of the Nu versus (G_r) (P_r) graphs for horizontal plate (Kreith, 1963, page 305) gives

$$\log_{10} \left(\frac{h_c D_o}{K_f}\right) \approx 2.24$$

$$\frac{h_c D_o}{K_f} \approx 370$$

$$h_c = 370 \frac{K_f}{D_o} = 370 \frac{0.394 \times 12}{4.5} = 389$$

For vertical plate, when

$$G_r = (G_r)(P_r) = 1.1 \times 10^{10}$$

$$Nu = 2.7 \times 10^2 \text{ from a similar graph (Kreith, 1963, page 306)}$$

therefore

$$h = 282$$

Therefore the experimental condition imposed in the thermal processing of food gives the convective heat transfer coefficient in the same order of magnitude of lower values (McAdams, 1954; Kreith, 1963; Perry, 1950). Therefore,

$$\frac{1}{h_{out}A_p} \approx \frac{1}{300A_p} \approx \frac{1}{A_p}(3.3 \times 10^{-3})$$

The flexible packaging film used in this experiment is a lamination of 0.5 mil mylar/0.35 mil foil/3.0 mil H. D. polyethylene. Therefore, the thermal resistance term for the packaging film can be further expended to

$$\frac{x_p}{K_p A_p} = \frac{x_{mylar}}{K_{mylar}A_{mylar}} + \frac{x_{foil}}{K_{foil}A_{foil}} + \frac{x_{polyethylene}}{K_{polyethylene}A_{polyethylene}}$$

but,

$$A_p = A_{mylar} = A_{foil} = A_{polyethylene}$$

$$\frac{x_p}{K_p A_p} = \frac{1}{A_p}\left(\frac{x_{mylar}}{K_{mylar}} + \frac{x_{foil}}{K_{foil}} + \frac{x_{polyethylene}}{K_{polyethylene}}\right)$$

Thermal conductivity of aluminum is given as

119 Btu/hr.-ft.-°F

at 212°F, and

117 Btu/hr.-ft.-°F

at 32°F (Kreith, 1963).

Thermal conductivity of H. D. polyethylene, $K_{polyethylene}$, is given as 11 x 10^{-4} gm-cal/sec-cm^2-°C/cm (Modern Plastics Encyclopedia, 1963), or 0.267 Btu/hr.-ft.-°F. The thermal conductivities of the majority of the polymer films range between 1.0 x 10^{-4} to 15 x 10^{-4} cal/sec.-cm.-°C (Modern Plastics Encyclopedia, 1963) or 0.0242 to 0.363 Btu/hr.-ft.-°F.

The thermal conductivity of mylar (polyester polymer of ethylene glycol and teraphthalic acid) is 3.63 x 10^{-4} cal./sec.-cm.-°C (Amborski and Flierl, 1953) or 0.0878 Btu/hr.-ft.-°F. The resistant term due to aluminum foil is negligible compared with the plastic layers and can be neglected. Therefore, the combined resistant of flexible term becomes

$$\frac{x_p}{K_p A_p} = \frac{1}{A_p}\left(\frac{x_{mylar}}{K_{mylar}} + \frac{x_{polyethylene}}{K_{polyethylene}}\right)$$

$$= \frac{1}{A_p}\left(\frac{0.5}{(1000)(12)(8.78 \times 10^{-2})} + \frac{3}{(1000)(12)(0.267)}\right)$$

$$= \frac{1}{A_p}(0.473 \times 10^{-3} + 0.937 \times 10^{-3})$$

$$= \frac{1}{A_p}(1.400 \times 10^{-3})$$

In the case when the food to be processed is solid, if the conductivity of the food material is assumed same as that of water, 0.364 Btu/hr.-ft.-°F at 100°F and 0.394 Btu/hr.-ft.-°F at 200°F, then the overall heat transfer coefficient can be expressed as

$$U = \frac{1}{\frac{1}{h_{out}A_p} + \frac{x_p}{K_p A_p} + \frac{x_s}{K_s A_s}}$$

$$= A_p \frac{1}{(3.3 \times 10^{-3}) + (1.4 \times 10^{-3}) + (5.3 \times 10^{-2})} \text{ Btu/hr-°F}$$

when the thickness of solid food is 0.5 inch. The above equation indicates that the heat transfer during the thermal processing of food is limited by the heat flow within the solid food itself, and also for all practical purposes the resistant terms for the convection outside of the package film can be neglected, leaving only the resistant term for conduction through solid food material. Therefore, in processing solid food or conduction heating food

$$U \approx \frac{A_s K_s}{x_s}$$

c. Heat transfer to the liquid food in the flexible package

For packaged liquid product, the liquid is mostly in direct contact with the packaging film, hence

$$U = \frac{1}{\frac{1}{h_{out} A_p} + \frac{x_p}{K_p A_p} + \frac{1}{h_{in_1} A_p}}$$

where,

h_{in_1} = heat transfer coefficient for liquid food inside the package

The above argument shown numerically for solid food also applies to liquid or convection-heating food and the term $x_p/K_p A_p$ can be neglected.

However, in this case because of the similarities in the mechanism of heat transfer outside and inside of the pouch, if the physical properties of the fluid food do not differ greatly from that of heating medium such as in the case of this study, that is, chicken broth and water, heat convective transfer coefficients outside and inside of the pouch are likely to be of the same order of magnitude, and one of the two resistance terms cannot be easily neglected.

B. Mechanisms of Thermal Inactivation of Microorganisms

1. Rate constant of microbial inactivation

When the logarithms of the experimentally obtained numbers of microorganisms surviving are plotted against heating time at a constant temperature, generally a straight line results. The equation for this straight line is

$$- \ln N = k t + \text{constant}$$

or, in differential form

$$\frac{dN}{dt} = -k N$$

where

N = number of microorganisms surviving

k = proportionally constant or rate constant

t = time of heating

But when t = 0, the number of microorganisms surviving is same as the initial number of organisms, Therefore

$$\ln \frac{N_o}{N} = k\,t$$

or

$$\log \frac{N_o}{N} = \frac{k\,t}{2.303} \quad - - - - - - - - (1)$$

These equations indicate that the rate of bacterial destruction is directly proportional to the number of surviving microorganisms. This equation is also similar to the mathematical description of an unimolecular or first-order bimolecular chemical reaction. In an unimolecular reaction only one substance reacts, and its rate of decomposition is directly proportional to its concentration. In a first-order bimolecular reaction one reactant is in great excess that variation im its concentration is negligible, and the rate of decomposition of the second reactant is directly proportional only to its concentration. Although this equation with experimental data suggests first-order reaction, it is important to realize that this does not necessarily support implied physical significance. However, some physical significances have been attempted to be attached to this first-order reaction phenomena.

Rahn (1945b) explained this apparent unimolecular reaction by the loss of reproductive power of a bacterial cell which is caused by the denaturation of single molecule. Also, the denaturation of a particular single protein molecule and description of a single bond in genetic code

has been suggested as the reasons for the apparent first-order reaction.

Reaction constant k can be correlated with Decimal reduction time D, since

$$\log \frac{N_o}{N} = \frac{k\,t}{2.303} \quad - - - - - - - - \quad (1)$$

and

$$\log \frac{N_o}{N} = \frac{1}{D}\,t$$

therefore

$$D = \frac{2.303}{k}$$

2. Kinetics of microbial inactivation

According to Deindoerfer (1957), the velocity constant k for the spores of a particular species at given media is function only of temperature, and can be expressed by empirical Arrhenius equation as

$$k = A\,e^{-E_a/RT} \quad - - - - - - - - \quad (2)$$

or

$$\log k = (-E_a/2.3\,RT) + \log A$$

where

k = velocity constant

A = frequency factor

E_a = activation energy for thermal destruction of spores

R = gas constant

T = absolute temperature

Arrhenius equation indicates that molecules must acquire a certain critical E_a before they can react, the Botzmann factor $e^{-E_a/RT}$ being the fraction of molecules that manages to obtain the necessary energy (Moore, 1960). The analogy of bacterial inactivation with the kinetic effect theory was presented (Charm, 1958), by explaining the fraction of water molecules surrounding the sensitive-volume of the cell gaining a certain level of energy upon heating and the energy being imparted to the cell to cause the inactivation, however, this explanation does not depend on any actual physical basis and is considered perhaps an over-simplification of a complex biological reaction. The activation or inactivation energy, E_a, obtained from the slope of log k versus 1/T curve may be compared with the activation energy of the various organic molecules if desired.

3. Correlation between the heat transfer and thermal inactivation

As it is shown experimentally and further by derivation of Arrhenius equation, based on experimental data, the reaction rate constant shows logarithmic relationship with the reciprocal of the temperature, increasing logarithmically as the reciprocal of temperature decreases. On the other hand, the temperature of the system depends on the heating time, increasing logarithmically. Therefore, the rate constant or the number of microorganisms inactivated can be related to heating time.

The equation showing the analytical relationship between the number of organisms surviving and the time of heating can be derived by assuming E_a is independent of temperature, k depends only on the temperature, and heat penetration curve is linear in semilogarithm graph. From heat penetration curve

$$\log \frac{(T_R - T)}{(T_R - T_{pi})} = - \frac{t}{f_h}$$

$$T = T_R - (T_R - T_{pi})\, e^{-\frac{t}{f_h}} \quad - - - - \quad (3)$$

Rearranging equation (1)

$$k = (\log \frac{N_o}{N}) \frac{2.303}{t} \quad - - - - - - \quad (4)$$

and substituting equations (3) and (4) into Arrhenius equation yields

$$(\log \frac{N_o}{N}) \left(\frac{2.303}{t}\right) = A\, e^{-\frac{E_a}{R\left[T_R - (T_R - T_{pi})\, e^{-\frac{t}{f_h}}\right]}}$$

EXPERIMENTAL PROCEDURE

IV. EXPERIMENTAL PROCEDURE

A. Procedure For Heat Penetration Study

1. Preparation of sample food materials

a. Ground beef

Ground beef was prepared by trimming off all excess fat from the eye of the round and grinding the lean part to obtain ground beef with fairly constant fat content (2.7 - 3.9% except in one case of 4.9%) and moisture content (71-75%).

b. Chicken broth

Chicken broth was prepared by placing 5 commercial chicken bouillion cubes per 1000 ml. distilled water and dissolving them by steaming in a retort at atmospheric pressure.

c. Carrot slices in chicken broth

Carrots were sliced to a thickness of 1/6 - 1/8". 50 gm. of sliced carrots per 100 ml. of chicken broth were used for the food system having the mixed physical characteristics of solid and liquid.

2. Preparation of pouches from flexible film

Pouches were prepared from an olive drab lamination of 0.5 mil mylar/0.35 mil foil/3.0 mil H. D. polyethylene manufactured by Dow Chemical Company. All the pouches were made to give a final inside dimension of 6.25 x 3.75". The sealing was accomplished with an air-operated jaw sealer (ROBOT, Pack-Rite Machines) at 300°F, 40 psi and dwell time of 2 sec. This

sealing condition was experimentally determined to be optimum for this lamination by trial and error.

The lamination was cut and sealed on two adjacent sides for the experiment with ground beef.

For chicken broth and carrot slices with chicken broth, the thermocouples were sealed in the mid-point of one of the 3.75" sides for runs in vertical position. For runs in horizontal positions thermocouples were sealed to mid-point of two 3.34" sides of the pouch by extending polyester tape containing the couples from one side of the pouch to the other. In each case, three sides were sealed before filling. 50 gm. of carrot slices were placed when desired and the last side was partially sealed, leaving a small space on the corner through which 100 ml. or 150 ml. of chicken broth was poured into the pouch. Then the remaining part was sealed.

3. Placement of thermocouples

Thermocouples were made from precision fine copper-constantan wire (Omega Engineering Company, Inc.) and were protected by a special polyester film tape (Minnesota Mining and Manufacturing Company). The thermocouples were connected through a standard connector to a junction allowing connection to recording devices.

Five and one-half ounces of ground beef were weighed into two equal weight portions. Each portion was made into a 5.25"x 2.75" patty by forming and pressing on the specially made 5.25" x 2.75" rectangular aluminum plates. The thermocouple was placed in a geometric center between these two patties and pressed to assure firm adherence of the two portions. These beef patties were inserted into a pouch with two sealed sides, using the two aluminum plates as guides. After placing the patties in position, the alu-

minum plates were removed. Care was taken not to touch the inside of the lamination on the two sides to be sealed later. The thermocouple in polyester tape between the meat patties was extended through the middle of the unsealed 3.75" side. First this side was sealed, next the last remaining edge was sealed, and then finally the thermocouple containing edge was sealed once more to reinforce it.

For the pouches containing fluids and to be processed in a vertical position the tip of the thermocouple was placed at 1/8, 1/4, 3/8 or 1/2 length from the bottom of the 6.25" length of the empty pouch, and the top side of the pouch was sealed. In the case of pouches containing chicken broth or carrot slices with chicken broth, both to be processed in a horizontal position, the polyester film used for protection of the thermocouple was extended past the thermocouple tip to traverse the length of the pouch. The total enclosed length of the thermocouple in the pouch was 6" which was the horizontal length of the pouch at the mid-plane of the pouch after being filled with chicken broth and carrot slices with chicken broth. The tip of the thermocouple was placed at 1/8, 1/4, 3/8 and 1/2 of the total length. The positions of the thermocouples in the pouches containing liquid food for the heat penetration study are illustrated in Figure 21 (Appendix E, page 177).

The polyester tape-imbedded thermocouples were capable of forming a part of the pouch heat seal under the sealing conditions used. In order to give additional support at the point through which the thermocouple was sealed into the package, a small piece of rubber was placed on each side of the seal and a heavy spring clip was clamped on top of them, to give them mechanical support.

Removal of air was accomplished prior to final sealing of the pouch by one of the following methods:

1. Mechanically compressing the pouches just prior to, and during, sealing to assure a tight fit between the food and pouch interior surface.

2. Connecting the pouch interior through a tygon tube (clamped securely to pouch) to a mechanical pump which maintained a vacuum prior to, and during, the sealing operation.

In some cases the air was not removed from the pouch to obtain high levels of residual air.

4. Processing methods

The pouches were placed in a specifically constructed aluminum wire rack to which the pouches were secured with adhesive tape, wooden clothes pins and paper clips. This arrangement allowed the pouches to be processed in the desired position (horizontal or vertical) without changing the free shape of the pouch and without introducing additional resistance to heat transfer. The spacing between pouches could also be controlled at the desired level. The spacing between the packages was 1.5". A preliminary experiment showed that 1.5" spacing gave the best heat transfer to the pouches under the conditions studied.

Ground beef, chicken broth, and carrot slices in chicken broth were processed under water at 15 psi and 250°F and cooled with steady flow of tap water at 15 psi of applied air pressure. The time required to reach the desired process temperature within the retort was determined and found to be 4.5 minutes. This was the time measured from the moment samples were placed in retort and retort closed to the time the retort reached the processing temperature. The temperature distribution in the different locations in the retort was also checked. The maximum temperature difference between any two points during heating under water of 3.5°F occurred during

the beginning of heating. During the beginning of the cooling, large temperature differences (up to 86°F) existed between different points because of the time required to fill the retort with water.

The temperature at the desired point was recorded by means of a 12 point Speedomax W recorder (Serial No. 65-33505-1-1, Leeds and Northrup Company). After processing, the measurement of air entrapped in each pouch was done by a modification of the method of Luh and Chaudry (1961). In essence, the method consists of puncturing the pouches under water and under an inverted funnel capped with a gas-tight top. The air escaping from the pouch was trapped in the stem of the funnel, under the gas-tight cap, and then withdrawn into a calibrated syringe and the volume of air measured.

The moisture and fat content of ground beef samples were determined whenever possible.

The moisture content was determined by a vacuum oven method (AOAC, 1960). The oven temperature was 80°C and the absolute pressure less than 1" Hg.

The fat content was determined by anhydrous ether extraction of the samples using a standard procedure (AOAC, 1960).

B. Procedure For Microbiological Study

1. Preparation of stock spore culture

a. Preparation of medium

Pork Infusion Medium A portion of 2 lb. fresh pork shoulder was trimmed, ground and mixed with 2 liter of water and boiled for 1 hour.

The solid meat pieces were removed by straining through a double layer of cheese cloth. The liquid was cooled and the solidified fat was removed by passing through a coarse filter paper under vacuum using a Buchner funnel.

The following ingredients were added and the volume was made up to 2 liters:

peptone	10.0 g
tryptone	3.0 g
dextrose	2.0 g
K_2HPO_4	2.5 g
Na thioglycollate	2.0 g

The pH was adjusted to 7.4 and the medium was tubed, 2 g. of cooked ground pork being added for every 10 ml. of solution.

b. Propagation of spores

A culture of Clostridium sporogenes (PA 3679) was inoculated into 10 ml. of pork infusion medium, prepared as described before and heat shocked at 85-90°C for 15 minutes. It was cooled and stratified with vaspar and incubated at 37°C overnight. This was then added to 90 ml. of preheated and cooled pork infusion medium, stratified and incubated for 5 hours. This was again transferred to 400 ml. of medium and incubated for 4 hours, then transferred once more to 500 ml. and incubated for 3 days in the same manner.

After incubation, the cell suspensions in pork infusion medium was asceptically filtered through a cheese cloth. The filtrate was then centrifuged in sterile cups. The supernatant was examined microscopically, placed in a sterile bottle containing glass beads and stored at refrigerated temperature.

2. Spore counts

a. Preparation of medium

Liver thioglycollate agar

Liver broth	250 g

The stock liver broth was made as follows:

liver (lb/liter)	500 g
peptone	10 g
K_2HPO_4	1 g

Grind the liver and boil 1 hour in 1000 ml distilled water. Press through cheese cloth to filter, bring liquid up to 1000 ml again. Add other ingredients and adjust pH 7.0 - 7.2 with 0.5N NaOH.

Distilled water	800 ml
Agar	16 g
Fluid thioglycollate	31 g

The above mixture was mixed and autoclaved at 15 lbs for 15 minutes.

2% agar (stratifying layer)

agar	10 g
water	500 ml

The above mixture was autoclaved at 15 psi for 15 minutes.

Dilution Blanks

Phosphate buffer	stock
Na_2HPO_4	5.68 g
KH_3PO_4	3.63 g
distilled water	1 liter

1 ml. of above mixture was made to 500 ml. with distilled water to make

the dilution blanks.

Peptone Dilution Blank	
peptone	5 g
distilled water	1000 ml

99 ml. of above solution was placed in each dilution bottle and autoclaved at 15 psi for 15 minutes.

b. Determination of number of spores

2.5 ml of 10% $NaHCO_3$, 5.0 ml of 4% Na_2CO_3, and 5.0 ml of 7% ferric citrate, all sterile, were added to 250 ml of liver-thioglycollate medium at 50°C just prior to pouring into Miller-Prickett tubes containing 1 ml of various dilutions of the samples. The tubes were shaken sufficiently to allow even mixing. About 0.75" layer of 2% agar was poured on the top of the medium to exclude air. The tubes were incubated at 30°C for 48 hours and colonies were counted. The tubes were then placed at room temperature for another day and the colonies were recounted. Each dilution of samples was counted in triplicate.

3. Determination of decimal reduction time of Clostridium sporogenes (PA 3679)

a. Preparation of samples

Beef puree Fresh lean eye of round beef after trimming off the fat was twice passed through an electrical meat grinder. 200 g of distilled water was added to every 100 g of ground meat in a sterile blender cup. This was mixed for 3 minutes (in the cold room), cooled for 10

minutes, again mixed for 3 minutes and cooled for 10 minutes, etc., for a total of 15 minutes mixing time. Mixing was carried out with a Servallomni mixer with the rheostat set at 45. The cup was placed in crushed ice during cooling. The mixture was filtered through cheese cloth in a Buchner funnel with applied pressure. The filtered puree was inoculated with stock spore culture, and injected into the prepared capillary tubes using modified Stern apparatus (Stern and Proctor, 1954).

Chicken Broth Chicken broth was prepared in the same manner as described in heat penetration study, inoculated with stock culture and filled into prepared capillary tubes in the manner described below.

b. Heating of thermal death time tubes

The equipment used for heating the spore suspension in capillary tubes was originally designed by Stern and Proctor (1954). Basically, this apparatus consists of a thermostatically controlled heating bath ($\pm$ 0.5°C) with Nujol as the heating medium, and a cooling bath of ice water. The spore suspension is sealed within capillary tubes which are held in place by a sample holder. An electronic device was used to transfer the tubes automatically and rapidly (0.4 sec) from the heating bath to the cooling bath at the end of the prescribed heating time. The oil bath was controlled to the desired temperature. The capillary tubes were immersed in the oil bath for the desired length of time plus 10 addition second to eliminate the effect of heating lag (See Appendix A, page 170).

c. Preparation of capillary tubes

The melting point capillary tubes (Kimax) used were 100 mm long

and 1.5 - 2.0 mm outside diameter. Since there was some variability in the diameters of the tubes, only those tubes with an internal diameter in the range 1.2 - 1.4 mm were used. The tubes were screened for size by rejecting those tubes that would accept a 1.4 mm diameter piano wire, and also rejecting those tubes that would not accept a 1.2 mm diameter piano wire (Licciardello, 1960).

Prior to use the acceptable tubes were cleaned in chromic acid cleaning solution, thoroughly rinsed with distilled water and dried.

A hook was made at one end of the tube by bending the glass in a flame. This hook held the capillary tube in the sample holder. A "glass bridge" (Farkas, 1955) was made at the mid-point of the tube by fusing the glass in a flame. This bridge prevented the liquid column from rising above the surface of the heating oil.

d. Device for filling capillary tubes

The conventional method for filling the capillary tubes involved the use of a 0.25 ml tuberculin syringe calibrated in 0.01 ml units.

For this investigation 0.025 ml quantities of suspension were to be filled into the capillaries. Since the conventional method was not likely to give the necessary accuracy, the method devised by Licciardello (1960) for filling the capillary tube was used. This device consisted of a modified Warburg-manometer calibrator (Micro-Metric Instrument Company, Cleveland) to deliver 0.025 ml with a greater degree of accuracy than the tuberculin syringe. The calibrator basically is a micrometer filled into a plastic adapter which connects the device to the Warburg manometer. A glass adapter was made with a tapered ground glass joint at one end to fit into the plastic adapter, and with a ground glass joint at the other

end to accept a hypodermic needle. In operation, the hollow plastic adapter was screwed into a threaded collar attached to the micrometer. About 4 ml of the spore suspension were pipetted into the chamber of the plastic adapter, and the glass adapter with its hypodermic needle was connected to the plastic adapter. One revolution of the micrometer barrel caused the displacement of 0.050 ml of liquid from the chamber. The micrometer barrel had 50 divisions and this device was capable of delivering 0.001 ml.

After being used, the filling device was dismantled and sterilized as follows: the metal piston of the micrometer was flamed; the plastic adapter was submerged for at least 1 hour in a solution of sodium hypochlorite and then rinsed with hot tap water; and the glass adapter and hypodermic needle were sterilized with dry heat.

The capillary tubes were sealed, after being filled, by wrapping a short piece (1 x 1.5") of wet paper towel around the tube (and covering the liquid column), inserting the open end of the capillary about 1/8" into the flame of a micro burner and drawing out the molten glass with forceps. The wet paper towel was drawn along the tube toward the sealed end to cool the glass.

e. Recovery and counting of spores from heated thermal death time tubes

After cooling the heated tubes, the outer surface was wiped with an absorbent "Wipette" tissue, and the tubes were then rinsed in petroleum ether and wiped dry again.

The capillaries were placed in cleaning solution (chromic acid) for at least 2 minutes and then rinsed with tap water and wiped dry.

The capillaries were broken off at the "glass bridge" and, in

each case, the section containing the spores was dropped into the dilution blanks. The tubes were then crushed with a sterile glass rod. The dilution blank was thoroughly mixed and appropriate dilutions were made. Spore counts were made in triplicate for each dilution.

C. Evaluation of Thermal Sterilization Process In Flexibly Packaged Foods

1. Preparation of samples for thermal processing

Ground beef

Ground beef was weighed into 5 1/2 ounce portions and refrigerated. After the meat had been thoroughly cooled, it was placed in a sterilized, chilled mortar. The stock spore culture inoculum was added drop-wise from a sterile pipette while mixing continuously with a sterile fork. This was made into patties and sealed in the pouches as described earlier.

Chicken broth

Chicken broth was prepared in the usual manner, cooled, inoculated with stock spore culture, and mixed thoroughly. A portion of 150 ml of inoculated chicken broth was put into each pouch in the usual manner.

2. Recovery and counting of spores from under processed samples

Ground beef

The heat processed pouch was cut open with a pair of scissors just inside of the seams. The beef patties were dropped onto sterile aluminum foil. The patties were sliced along the mid-plane and triplicate samples of approximately 2 g were removed from the mid-plane. The samples were placed in sterilized pre-weighed aluminum moisture dish and weighed. Ap-

propriate dilutions were made and the serial dilutions were cultured anaerobically as described previously.

Chicken broth

One corner of the heat processed pouch was flamed and cut with a pair of sterile scissors. Through this hole a sterile pipette was inserted and 2 ml of chicken broth sample was withdrawn, placed in dilution water, and counted as described above.

Control pouches

The pouches were prepared and spore counts were made in the same manner as described for the under-processed samples.

3. Microbial test for sterility

The samples were taken from the pouches and were processed to the point of expected sterility, using the same procedure as the one used for the under-processed samples. Duplicate samples of approximately 2 g in the case of ground beef, and 2 ml in the case of chicken broth, were placed in the tubes containing liver broth. The tubes were stratified with vaseline, incubated for 14 days at 30°C, and then were examined for growth and gas production. Samples were taken from the tubes which produced gas and were examined microscopically.

RESULTS AND DISCUSSION

V. RESULTS AND DISCUSSION

A. Heat Penetration Studies

1. Heat penetration into flexibly packaged ground beef

Experiments were undertaken in which ground beef was processed under the conditions described previously. Seventeen runs were made, in which the packages were positioned vertically in nine runs and horizontally in eight runs.

The geometric center was assumed to be the slowest heating point, and the rates of heat penetration at this point were studied. In these heat penetration studies, the effect of position of pouches during processing and the effect of residual air in the pouches were investigated.

The results of the experiments in which pouches were processed in vertical positions are presented in Table 1. The time required for the center to reach temperature of 240°F ranged from 18.5 to 28.5 minutes, with an average of 22.3 minutes. The run averages of the time required for the center to reach the temperature of 240°F are summarized in Table 3. They ranged from 19.7 to 27.2 minutes, having the average of the run averages of 22.9 minutes. The time required to reach 245°F ranged from 21.8 to 34.2 minutes, having an average of 27.2 minutes. The run averages for this temperature ranged between 23.3 to 32.8 minutes and the average of the run averages was 27.2 minutes. The time required to traverse one log cycle of temperature, f_h, ranged from 11.2 to 20.3 minutes with an average of 15.7 minutes. The run averages ranged from 12.8 to 18.5 minutes and the average of the run averages was 15.9 minutes.

A typical heat penetration curve for the pouches processed in ver-

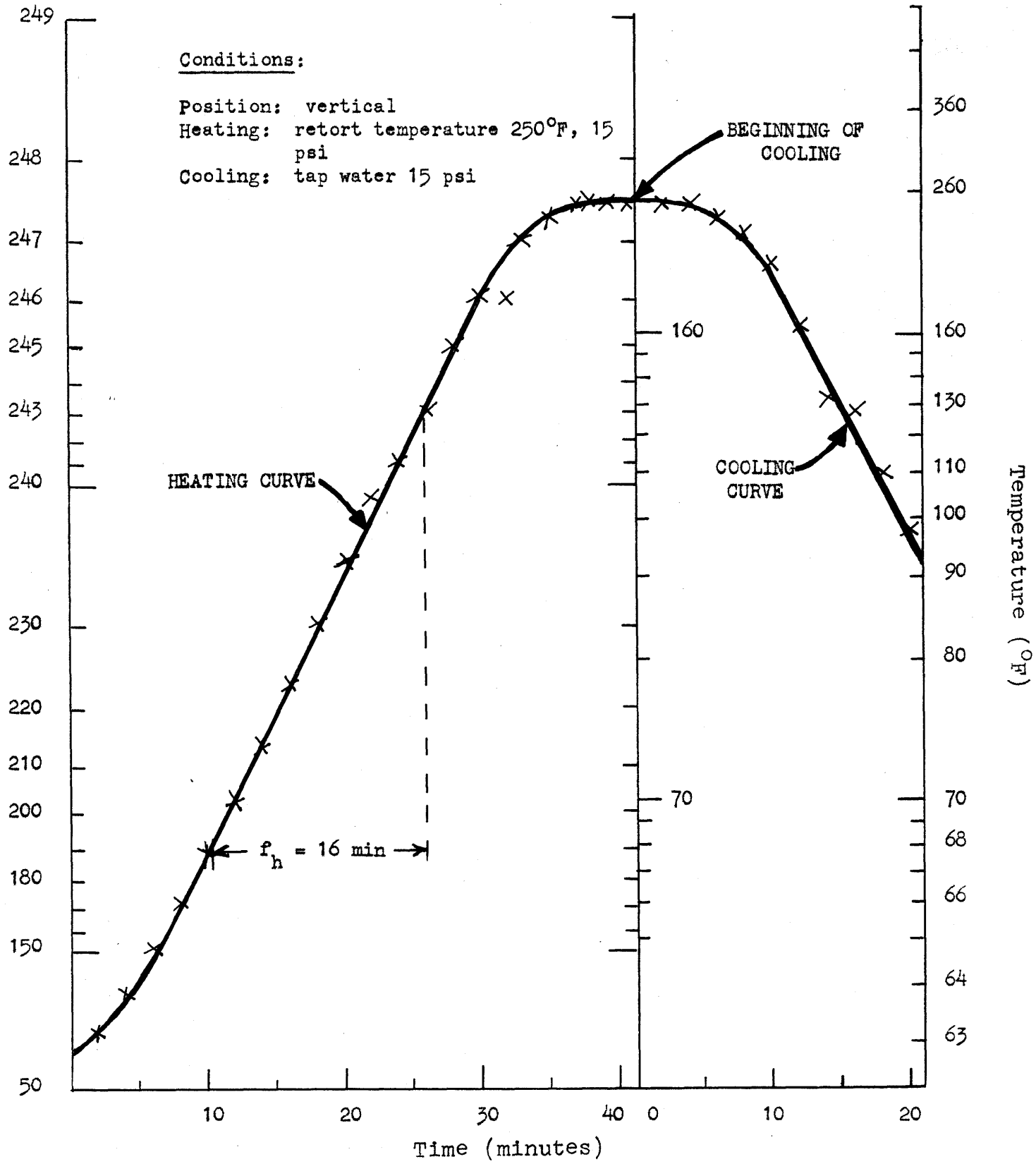
Table 1

RESULTS OF HEAT PENETRATION STUDIES
ON FLEXIBLY PACKAGED GROUND BEEF
(PROCESSED AT 250°F, 15 PSI UNDER WATER IN VERTICAL POSITION)

Run #	Package #	Time (min) Required for Center to Reach Temperature of 240°F	245°F	f_h	Residual Air (cc/pouch)
GB V-I	1	19.2	23.2	13.2	-
Fat	3	20.0	23.0	13.5	-
= 2.7%	4	21.0	24.7	12.5	-
Moisture	5	18.5	21.8	11.2	-
= 72.4%	6	20.5	24.2	12.3	-
	7	19.3	23.5	13.2	-
	11	18.8	22.7	13.2	-
GB V-II	1	20.2	24.3	14.3	2.4
	2	21.7	26.6	16.5	11.4
	3	20.7	25.2	14.8	-
	4	19.0	23.3	13.5	8.4
	5	20.3	24.8	14.5	-
	6	20.8	25.3	14.7	8.6
	7	24.5	29.5	16.5	8.0
	8	24.3	29.3	16.7	10.0
	9	23.0	27.8	16.0	7.2
	10	21.7	26.3	15.5	-
GB V-III	1	19.0	25.0	12.0 (not linear)	15.9
	3	23.8	28.2	14.5	6.4
	4	19.8	23.8	13.5	-
	5	22.7	27.3	15.8	-
	6	25.3	30.0	16.4	5.0
	7	20.8	25.2	14.4	-
	8	20.8	25.2	14.4	12.0
	9	20.0	24.0	14.2	-
	10	20.0	24.0	14.2	-
	11	20.0	24.0	14.2	-
	12	20.0	24.0	14.2	9.1
GB V-IV	1	25.8	31.3	19.0	-
	2	27.0	32.8	19.5	5.6
	3	21.2	25.5	15.0	1.2
	5	20.3	24.6	14.0	-
	6	25.9	31.2	18.2	-
	9	23.3	28.6	18.3	12.4
	10	25.0	30.7	18.5	-
	11	26.3	31.3	16.0	1.4
	12	26.3	31.2	16.0	5.6

Run #	Package #	Time (min) Required for Center to Reach Temperature of 240°F	245°F	f_h	Residual Air (cc/pouch)
GB V-V	2	21.0	26.3	13.6	6.8
	3	22.7	29.3	16.6	7.4
	4	23.3	29.7	15.8	8.2
	5	17.5	22.3	12.6	2.6
	6	19.0	23.3	14.5	17.4
	9	20.5	24.5	14.2	0.5
	10	21.0	27.5	16.5	25.8
	11	23.5	29.5	16.0	6.8
GB V-VI	1	23.5	28.0	15.5	5.4
	2	23.2	28.0	16.2	5.8
	3	21.4	25.8	15.0	6.2
	4	21.4	25.8	15.0	6.4
	5	23.3	28.2	16.3	5.4
	6	24.3	29.0	15.3	-
	9	20.3	25.3	16.4	-
	11	24.9	30.2	17.3	-
	12	26.6	32.2	18.2	-
GB V-VII	1	23.8	29.3	18.3	-
	2	23.0	28.5	17.5	-
	3	22.7	28.0	17.5	-
	4	24.7	30.5	19.0	-
	6	22.5	27.5	16.8	-
	7	23.2	29.3	18.5	-
	8	24.7	30.6	19.2	-
	10	24.1	29.6	18.3	-
	11	26.0	32.2	20.3	-
	12	22.2	27.3	16.5	-
GB V-VIII	1	20.8	25.2	14.5	8.2
	2	26.0	31.0	17.5	7.0
	3	19.8	23.8	13.2	9.0
	5	22.5	26.5	13.3	3.8
	7	27.8	33.3	18.8	5.4
	8	18.3	34.2	19.5	5.2
	10	19.3	23.2	14.0	7.4
GB V-IX	1	27.2	32.8	18.5	

Figure 1 Heat Penetration Curve For Ground Beef At the Geometric Center



tical positions (actual experimental data from package # 2, Run GB V-VI), having the average value for time required to reach 240°F and 245°F and to traverse one log cycle of temperature is presented in Figure 1.

These results show no correlation between rate of heat penetration and amounts of residual air which ranges from 0.5 - 26 cc per pouch.

The results of runs conducted with packages placed in horizontal positions during the processing are presented in Table 2 and summarized in Table 3. The time required for the center to reach a temperature of 240°F ranged from 21.3 to 29.4 minutes with an average of 26.5 minutes. The run averages ranged from 26.3 to 29.8 minutes having an average of run averages of 26.8 minutes. The time required to reach 245°F ranged from 26.3 to 33.9 minutes with the average of 31.5 minutes. The run averages ranged between 29.5 to 33.5 minutes having an average of run averages of 31.8 minutes. The time required to traverse one log cycle of temperature ranged from 14.2 to 20.0 minutes with an average of 16.9 minutes, and the run averages were between 15.9 to 17.7 minutes with the average of the run averages 17.0 minutes.

A typical heat penetration curve with the average values of time-temperature relationships for the pouches processed at horizontal positions, (actual experimental data from package # 5, Run GB H-III) is presented in Figure 2.

Again, as in the case of runs conducted in vertical position, there was no apparent correlation between the amount of residual air and the rate of heat penetration.

In Table 3, the summary of the heat penetration data from both vertical and horizontal runs are tabulated together for the ease of comparison between the two cases. The greatest difference between the two

Table 2.

RESULTS OF HEAT PENETRATION STUDIES ON
FLEXIBLY PACKAGED GROUND BEEF
(PROCESSED AT 250°F, 15 PSI UNDER WATER IN HORIZONTAL POSITION)

Run #	Package #	Time (min) Required for Center to Reach Temperature of 240°F	245°F	f_h	Residual Air (cc/pouch)
GB H-I	1	26.6	31.7	16.0	6.2
Fat	2	26.8	31.6	15.5	5.4
= 3.0%	3	27.0	31.8	15.4	5.6
Moisture	4	27.9	31.2	15.5	-
= 74.5%	5	26.9	31.7	15.7	3.8
	6	21.3	31.2	16.4	5.8
	7	26.3	31.0	14.7	4.4
	9	26.7	31.4	15.2	8.4
	10	27.4	32.7	17.3	5.8
	11	27.0	32.0	16.7	4.8
	12	24.8	30.0	16.9	5.6
GB H-II	1	28.4	33.6	17.0	-
	2	26.6	31.7	17.0	6.0
	3	26.7	31.8	17.0	4.2
	4	26.0	30.7	16.3	4.4
	5	26.5	31.7	17.2	4.8
	6	27.9	33.5	18.5	-
	7	26.2	31.3	17.3	-
	9	25.8	31.7	18.8	-
	10	27.8	33.8	19.5	-
	11	26.6	31.8	17.4	-
	12	27.7	33.7	20.0	6.6
GB H-III	1	24.6	30.0	17.7	-
Fat	3	28.1	33.7	18.2	6.4
= 3.5%	4	25.7	30.3	16.0	-
Moisture	5	26.7	31.8	17.0	-
= 71.7%	6	25.8	30.7	16.2	3.4
	7	25.8	30.6	15.5	5.2
	8	26.0	31.4	17.5	5.2
	9	26.2	30.2	16.7	1.0
	12	25.9	30.8	16.4	4.2

Run #	Package #	Time (min) Required for Center to reach Temperature of 240°F	245°F	f_h	Residual Air (cc/pouch)
GB H-IV	1	24.2	29.0	17.0	6.3
	2	21.8	26.3	16.0	-
	3	25.8	30.7	16.2	-
	4	25.7	30.7	16.7	-
	5	24.2	27.3	14.2	-
	6	25.1	29.7	15.0	4.0
	7	25.8	30.8	17.0	3.4
	9	25.0	29.7	15.2	5.8
	10	25.7	30.8	17.0	-
	12	25.0	30.0	16.5	4.2
GB H-V	2	25.2	30.2	16.5	-
	3	28.0	33.3	16.8	-
	4	27.8	32.8	17.0	-
	5	25.2	29.9	15.5	-
	6	28.6	33.2	16.7	-
	10	28.8	33.8	16.5	-
	12	27.8	33.2	17.0	-
GB H-VI	1	28.0	33.2	17.3	-
	3	28.1	33.4	17.7	-
	4	27.2	32.4	17.6	-
	7	28.2	33.7	18.2	-
	10	28.6	33.9	18.0	-
	11	27.5	32.8	17.5	-
	12	27.8	32.8	17.3	-
GB H-VII	1	24.8	30.0	17.5	21.2
	2	24.0	28.8	15.4	9.6
	3	29.4	30.2	18.8	7.0
	4	24.5	29.6	17.0	7.0
	5	29.2	34.8	18.7	-
	6	23.8	28.8	16.5	-
	7	25.8	30.8	16.6	-
	8	26.6	31.7	17.0	-
	10	28.7	34.4	19.8	-
	11	29.3	34.2	16.5	8.0
	12	23.0	27.7	15.7	8.6
GB H-VIII	1	28.5	33.5	17.7	-

Figure 2 Heat Penetration Curve For Ground Beef At the Geometric Center

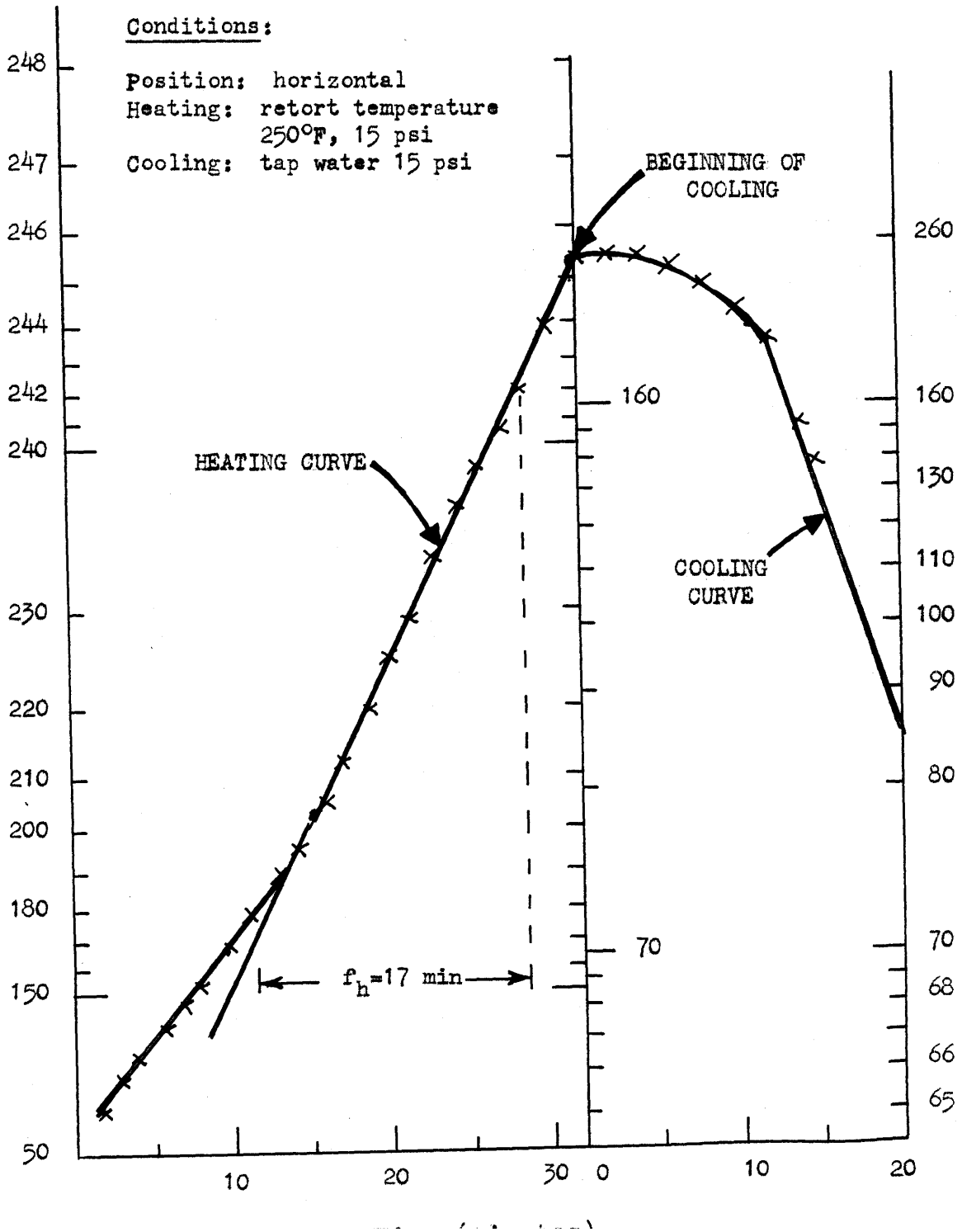


Table 3

SUMMARY OF THE RESULTS OF HEAT PENETRATION STUDIES
ON FLEXIBLY PACKAGED GROUND BEEF
(PROCESSED AT 250°F, 15 PSI UNDER WATER)

Run #	Number of Packages	Run Average Time (min) to Reach Temperature of 240°F	245°F	Run Average f_h	Minimum f_h for the run	Maximum f_h for the run
Samples Processed In Vertical Position						
GB V-I	7	19.7	23.3	12.8	11.2	13.5
GB V-II	10	21.6	26.2	15.3	14.3	16.7
GB V-III	11	21.1	25.5	14.4	12.0	16.4
GB V-IV	9	24.6	29.7	17.2	14.0	19.5
GB V-V	8	21.1	26.6	15.0	12.6	16.6
GB V-VI	9	23.2	28.1	16.1	15.0	18.2
GB V-VII	10	23.7	29.3	18.2	16.8	20.3
GB V-VIII	7	23.5	28.2	15.8	13.2	19.5
GB V-IX	1	27.2	32.8	18.5	18.5	18.5
Average of run averages		22.9	27.7	15.9		
Samples Processed In Horizontal Position						
GB H-I	1	26.3	31.5	15.9	14.7	17.3
GB H-II	11	26.9	32.3	17.8	16.3	20.0
GB H-III	9	26.1	31.1	16.8	15.5	18.2
GB H-IV	10	29.8	29.5	16.1	14.2	17.0
GB H-V	7	27.3	32.3	16.6	15.5	17.0
GB H-VI	7	28.1	33.2	17.7	17.3	18.2
GB H-VII	11	26.3	31.0	17.2	15.4	19.8
GB H-VIII	1	28.5	33.5	17.7	17.7	17.7
Average of run averages		26.8	31.8	17.0		

positions is in the time required to reach 240°F. There is a smaller difference between the times required to reach 245°F. The difference in f_h values is much smaller than the differences in times needed to reach the specified temperatures.

The Student "t" test was used to determine whether the heating characteristics varied significantly between the two positions (vertical versus horizontal). The values of t obtained in the test were as follows:

a) For the time to reach 240°F, t = 11.35

b) For the time to reach 245°F, t = 9.75

c) For the time to traverse one log cycle (f_h), t = 3.97

In these tests the degrees of freedom are 137. The critical values of t for 137 degrees of freedom or infinite degrees of freedom is 2.576 at 1% level (Youden, 1961; Mendenhall, 1964). The values obtained for t are greater than the critical value, therefore it can be concluded that the flexibly packaged ground beef heat significantly faster when it is processed in vertical position compared with that processed in horizontal position.

The heat penetration curves show that in vertical runs approximately 7 minutes is needed before the heating curve becomes a straight line, while in horizontal runs approximately 14 minutes are needed.

In considering the reasons forthis difference one notes that the natural convective heat transfer coefficients differ for the vertical versus horizontal cases (McAdams, 1954; Kreith, 1963). However the previously presented preliminary analysis of the various contributions to heat transfer resistance, would indicate that the outside film coefficient for convective heat transfer should be of relatively little importance com-

pared with the resistance of the beef inside the pouch. This analysis, was of course based on the assumption of a solid block of ground beef inside the package. The above results showing an effect of pouch position on rate of heat transfer, as well as the observations noted below, cast some doubt on the validity of this assumption.

During the course of this experiment, it was observed that some liquid came out from the ground beef upon thermal processing. The liquid produced was approximately 1.8 oz. or 50 ml. per pouch containing 5.5 oz of ground beef. Since this liquid produced comes from the ground beef, it inevitably causes shrinkage of ground beef. This shrinkage will produce small capillary channels within the ground beef, and the liquid produced will flow and drain through these channels.

If this model is valid, the faster heat penetration in vertically placed packages might be explained by the fact that the liquid has a longer path provided in this case for flow which aids in the heat transfer. But for this model to be considered, the relative importance of the resistances has to be re-evaluated. In this case, heat does not penetrate through half thickness of the ground beef patty but rather through half thickness of ground beef grains which are surrounded by channels through which liquid can form some convection currents.

Although the thermal conductivity of water was used for the conductivity of the solid food in earlier analysis, now the thermal conductivity of beef will be calculated to improve accuracy. Thermal conductivity of a mixed system may be estimated by considering the system composed of parallel layers of the different constituents (Wang and Knucken, 1958). When the parallel layers are perpendicular to heat flow, the equation for estimating the conductivity is

$$K = \frac{1}{\frac{\Omega 1}{K_1} + \frac{\Omega 2}{K_2} + \frac{\Omega 3}{K_3} \text{ -------}} = \frac{1}{\sum \frac{\Omega n}{K_n}}$$

when the parallel layers are parallel to heat flow

$$K = \Omega_1 K_1 + \Omega_2 K_2 + \Omega_3 K_3 \text{ - - -} = \sum \Omega_n K_n$$

where $K_1, K_2, K_3, \text{ --- } K_n$ = thermal conductivities of each constituent

$\Omega_1, \Omega_2, \Omega_3, \text{ ---} \Omega_n$ = volume fraction of each constituent or

$$(W_n \rho_T) / (W_T \rho_n)$$

where W and ρ are weight and density respectivey, and T signifies the total. The moisture and fat contents of the ground beef were determined to be approximately 73% and 3%, and the rest of 24% can be considered as protein. Densities of water, protein and fat are 1.0, 1.1, and 0.9 gm/cm^3, therefore the density of ground beef is about 1.02 gm/cm^3. The conductivities of water, protein and fat are 0.37, 0.3 and 0.12 Btu/hr.-ft-^oF (Charm, 1963; Hurwicz and Tischer, 1960).

When the parallel layers are perpendicular to heat flow the calculated conductivity of ground beef is 0.33 Btu/hr.-ft.-^oF while it is 0.37 Btu/hr.-ft.-^oF when they are parallel to heat flow. The average of these two values, 0.35 Btu/hr.-ft.-^oF is used as the conductivity of ground beef in the following calculations.

The diameter of a ground beef grain was found to be approximately 1/16". The resistance through the ground beef grains, x/KA, now becomes $(7 \times 10^{-3})/A$ BTU/hr.-°F. This is of the same order of magnitude as the resistance of the convective heat transfer, actually only two times larger. Therefore, the resistances other than those located in the grains themselves contribute approximately 30% of the total resistance and the heat transfer analysis based only on the resistance through solid layer becomes inadequate.

Now, since it is evident that convective resistance contributes significantly to the heat transfer in the groun beef system, it is necessary to evaluate the heat transfer coefficient proper to this system.

The average diameter of the grains of ground beef is approximately 1/16". Since 5.5 oz of ground beef produced approximately 1.8 oz of liquid, it is reasonable to assume that the ground beef grains are separated by a path having a diameter about a quarter of that of the diameter of grains or 1/64". So considered, the ground beef system has characteristics similar to that of a packed bed, and if the heating parameters are known the approximate calculations on heat transfer can be performed.

McAdams (1954) gives the relationship of the heating parameters in a packed bed as:

$$\frac{h}{C_p G}\left[\frac{C_p \mu}{k}\right]_f^{2/3} = 1.06\left[\frac{D_p G_o}{\mu}\right]^{-0.41}$$

or,

$$h = 1.06\,\frac{C_p G_o\left[\frac{D_p G_o}{\mu}\right]^{-0.41}}{\left[\frac{C_p \mu}{k}\right]_f^{2/3}}$$

However, he specified that the above equation is valid only for Reynolds number range from 60 to 4,000.

In the ground beef system, assuming that cooking or extrusion of liquid completes at about 10 minutes after the starting of the process, and the physical properties of liquid similar as those of water at 200°F, the Reynolds number of this system becomes:

$$Re = \frac{D_p G_o}{\mu} = \frac{(1/64 \times 1/12)(1.8/16 \times 600)}{0.205 \times 10^{-3}}$$

$$= 1.22 \times 10^{-3}$$

This is well below the lower limit of the above equation relating the heating parameters in packed bed. As a matter of fact, usually it is a general practice to perform heat transfer in a packed bed by turbulent convection currents or at least by transient currents because of the low heat transfer in a laminar flow, and any available relationship between heating parameters under these conditions have lower limiting conditions of Reynolds number at least 10^4 times higher than that calculated for ground beef. Therefore numerical analysis is not possible by this approach. On the other hand, Reynolds number of this magnitude indicates that flow of the liquid through channels between the ground beef grains is very slow. From the heat transfer consideration the liquid is almost like the stagnant layer and the resistance due to this liquid layer approaches that offered by a film with thickness equal to the radius of the channels. The resistance is then equal to the radius of the channel divided by the conductivity of the liquid.

The heat penetration calculations in such a system are shown

below.

First consider what is the order of magnitude of thermal diffusivities obtained from the experiments conducted in this study, if the beef is considered to be a solid block.

The half thickness of the ground beef patty is 1/4 inch. Consider the case when the temperature at the center of the ground beef is 240°F. First in the pouches processed in a vertical position the average time required to reach 240°F is 22 minutes or correcting for come up time the time becomes 19.4 minutes. Unaccomplished temperature change is

$$\frac{T - T_\infty}{T_o - T_\infty} = \frac{10}{190} = 0.0528$$

The convective heat transfer coefficient calculated in the same manner as shown elsewhere in this thesis at this temperature is 94 BTU/hr-ft^2-°F. The surface resistance ratio is therefore:

$$\frac{K}{Lh} = \frac{0.35}{2.08 \times 10^{-2} \times 94} = 0.179$$

The relative time, $\alpha\theta/L^2$, is found from Hottel chart (McAdams, 1954) at this condition to be about 1.78. Therefore

$$\alpha = (1.78)(4.32 \times 10^{-4})(60)/22$$

$$\alpha = 2.10 \times 10^{-3} \text{ ft}^2/\text{hr}$$

For the horizontally processed pouch, the time required is 27 minutes, correction for come up time makes it 24.4 minutes, where h = 84 BTU/hr-ft^2-°F

and K/Lh = 0.200. At this condition Hottel chart gives

$$\frac{\alpha\theta}{L^2} = 1.84$$

Therefore,

$$\alpha = (1.84)(4.32 \times 10^{-4})(60)/24.4$$

$$\alpha = 1.96 \times 10^{-3} \text{ ft}^2/\text{hr}$$

Thermal diffusivity for ground beef using the conductivity and density calculated above and assuming specific heat to be equal to 1.0 is 0.0053 ft^2/hr. This agrees well with the literature values (Hurwicz and Tischer, 1960; Charm, 1963) and the determinations from data obtained at M.I.T. (20.52 Laboratory Project Reports, 1965).

The above thermal diffusivities calculated from heat transfer data, 1.96×10^{-3} ft^2/hr and 2.10×10^{-3} ft^2/hr, roughly one third of that calculated from conductivity, density and heat capacity are obtained from the literature. If one assumes the literature values of thermal diffusivity (0.0053 ft^2/hr) apply, and calculates the time required to reach 240°F for the vertical and horizontal cases, using the previously calculated surface resistance ratios, the following results are obtained:

1. For the vertical case, θ = 8.7 minutes (from the end of come-up time). The actual experimental value is 19.4 minutes.

2. For the horizontal case, the calculated time is 9.0 minutes compared with the experimental value of 24.4 minutes.

It is apparent therefore that in this study the heat transfer is slower than one would expect for a system with the thermal diffusivity of beef, and the calculated values of heat transfer coefficient.

In order to determine what order of magnitude of surface resistance would be necessary to produce the slower heating rates, which were actually observed, the calculation proceeded as follows: α = 0.0053 then for the vertical case, at 240°F, $\alpha\theta/L^2$ = 4.34 and for the horizontal case it is equal to 5.3. In order to satisfy these relative times and the corresponding unaccomplished temperature ratios, the surface resistance ratio must be about 1.1 for the vertical and 1.45 for the horizontal case.

In the calculations the following cases are considered:

Case 1 Using experimental data, and calculation for h, obtain α

Case 2 Using literature value of α = 0.0053 and calculated h, obtain time needed to reach specified temperature

Case 3 Using experimental data, and α = 0.0053 ft^2/hr obtain K/hL

Temp. (°F)	Position	Experimental Time Required To Reach the Temperature (min.)	Case 1 K/hL	Case 1 ft^2/hr ($\times 10^3$)	Case 2 K/hL	Case 2 θ (min)	Case 3 K/hL
150	vertical	3.4	0.072	3.1	0.072	2.0	1.3
190	vertical	7.4	0.075	2.3	0.075	3.2	1.2
240	vertical	19.4	0.179	2.1	0.179	8.7	1.1
203	horizontal	12.4	0.111	1.7	0.111	4.0	1.7
240	horizontal	24.4	0.200	1.96	0.200	9.0	1.4

In evaluating the reasons for the slower observed heating rates the following factors may be considered.

a) Surface resistance

If a solid block of meat with $\alpha = 0.0053$ ft^2/hr is assumed, the surface resistance ratios corresponding to the experimental results range from 1.1 to 1.7. Therefore, the total surface resistance would be

$$R_s = 1.1 \times L/K = 1.1\ (2.08 \times 10^{-2}/0.35)$$
$$= 0.064 \text{ hr-ft}^2\text{-}^\circ\text{F/BTU}$$

Since the total surface resistance is assumed to be equal to the sum of the outside film resistance and the packaging material resistance:

$$R_s = 0.064 = 1/h + x_p/K_p = 1/h + 1.4 \times 10^{-3}$$

$$1/h = 0.063 \text{ hr-ft}^2\text{-}^\circ\text{F/BTU}$$

$$h = 15.2 \text{ BTU/hr-ft}^2\text{-}^\circ\text{F}$$

In the case when $K/hL = 1.7$, heat transfer coefficient h becomes 10. Therefore the heat transfer coefficient due to other than ground beef and packaging material is between 10-15 BTU/hr-ft^2-$^\circ$F. These seem improbably low coefficients. These are about one half to one third of that obtained in independent calculations based on experimental data with chicken broth, which was assumed to heat by convection which in turn was lower than the coefficient expected from theoretical calculations. Since a coefficient of this order of magnitude is unlikely for the free convection heat transfer, consideration should be given to the possibility that there is a resistant film on the package surface. Since this surface is hydrophobic, it is possible that gas bubbles are accumulated at this surface and result in a gas film with low conductivity. The resistance due to air film, of course, can be of this order of magnitude.

The lack of an effect of total residual gas increase from about

0.5 cc per pouch to 25 cc per pouch, may be due to the fact that additional air does not increase the entrapped air film thickness, but collects in pockets on the top of the pouch. Also the improved heat transfer in the vertical pouches may be due to the effect of draining hot liquid on heat resistance in this air film, as well as on heat resistance in a similar film surrounding individual beef granules.

Another possibility is that the gas film exists inside the three layer sandwich of the lamination, which shows a tendency toward delamination at high process temperatures. Even a very thin film of gases evolved from the polyethylene, or from adhesives used at the mylar-aluminum interface, or entrapped in these materials would increase the surface resistance to the observed value. This effect would be independent of the amount of residual air in the pouch. Whether vertical versus horizontal positions would have an effect on this hypothetical film depends on whether there are pockets inside the lamination in which the gas could collect when placed in vertical position.

The hypothesis of a gas film inside the lamination is further supported by the following considerations:

i) The components of the lamination are known to show a tendency to separate, as evidenced by observations of the pouches after heat processing.

ii) The methods used in fabricating laminations are not adequate to assure complete adherence between component films over the entire area.

iii) The differences in the coefficients of thermal expansion of the lamination components would also tend to cause the separation of layers.

On the other hand very limited data obtained by Wornick (1959) on single films indicate that the heat transfer resistance was of the same order

of magnitude as that obtained in the present study with chicken broth. However, the conditions under which Wornick obtained his results are not adequate to place significant confidence in the data to eliminate the lamination gas film hypothesis.

b) Assuming that the surface resistance is indeed low, the conclusion reached would be that the observed thermal diffusivity is indeed correct. The only phenomena which could account for this low diffusivity which is 32% to 60% of the literature values are those which would result in a high apparent specific heat, since density or conductivity changes of this magnitude are not likely. A high apparent specific heat will result from either heat being consumed in a phase transition, or in a chemical change. There is a possibility for both.

The thermal diffusivity of fat decreases with increasing temperature due to the increase in the apparent specific heat caused by the melting of fat, and according to Riedel (1955) this increase can be as high as three times. But even such high increase in apparent specific heat of fat cannot explain the low thermal diffusivity obtained for ground beef since it contains only 3% of fat.

The more likely reason is that the apparent specific heat of protein should be also very high at this temperature range since denaturation takes place during the processing. There is a lack of literature data on the contribution of heat of reaction on the total heat required for food processing. A rough estimate using as an assumption protein of molecular weight of 50,000 and a heat of reaction of 100 Kcal/mole, would indicate the specific heat could not account for all the observed change in diffusivity.

c) If the model of beef granules surrounded by liquid is assumed (packed bed) the heating should always be either faster or the same as in the case of a solid block, even if the liquid velocity in the capillaries is zero. This is because thermal conductivity of the liquid is about the same as that for the beef.

However if the capillaries are partially filled with gases evolved during cooking from the beef and then trapped at the surface of the granules then the heat transfer could indeed be greatly impeded. Unfortunately, no experimental parameters are avilable to measure or calculate the contribution of this mechanism to this case.

Of the three possibilities discussed above, the thin gas film hypothesis, either at the internal surface of the pouch or in the pouch lamination itself seem to contribute to the increase in the resistance, especially in view of the fact that both chicken broth and ground beef show greater than expected overall surface resistances. This is, as mentioned earlier, substantiated by the high incidence of delaminated pouches observed in processing.

The higher increase in resistance in ground beef may be due to the fact that unevenness of the surface can cause increase in the gas film thickness and the gas evolved from the ground beef and entrapped within the capillaries can contribute to the additional resistances.

2. Heat penetration into the flexibly packaged chicken broth

Studies in which thermocouples were placed in different locations within pouches containing chicken broth showed that the slowest heating point in flexibly packaged chicken broth during processing in vertical posi-

tions is at a point located at 1/8 of the pouch length (Appendix B, Table 24) measuring the length from the bottom of the pouch. This corresponds to a location of thermocouple at 25/32" from the bottom of the pouch, as measured prior to filling. This is not very different from the slowest heating point found in no. 2 cans by Jackson and Olson (1940).

The maximum lag to reach a given temperature between the different locations in the pouch was approximately 2 minutes or the maximum temperature difference after heating 8 minutes, was 2°F.

The results obtained with chicken broth processed in vertical position are presented in Table 4 and are summarized in Table 6. The time required for the slowest heating point to reach a temperature of 240°F ranged from 5.8 to 6.4 minutes. The run averages ranged from 6.0 to 6.1 minutes. The average for all samples was 6.1 minutes, and the same value was obtained also by averaging run averages. The time required to reach a temperature of 245°F ranged from 6.8 to 7.9 minutes, and run averages ranged from 7.2 to 7.4 minutes. The average for all samples and the average of the run averages was 7.3 minutes. There was a definite break in the heat penetration curve at 4.5 minutes after processing started, corresponding to a temperature of 225 to 230°F. The average time required to traverse one log cycle of temperature was 5.4 minutes before the break and 3.6 minutes after the break, and ranged from 4.7 to 5.7 minutes and 3.5 to 3.7 minutes respectively. The run averages were between 5.2 to 5.5 and the average of the run averages was 5.4. A typical heat penetration curve having the average time required to reach 240°F, to reach 245°F and to traverse one log cycle of temperature is shown in Figure 3.

The data indicate that there was no one point where the heat penetration is definitely slowest in the pouches processed in a horizon-

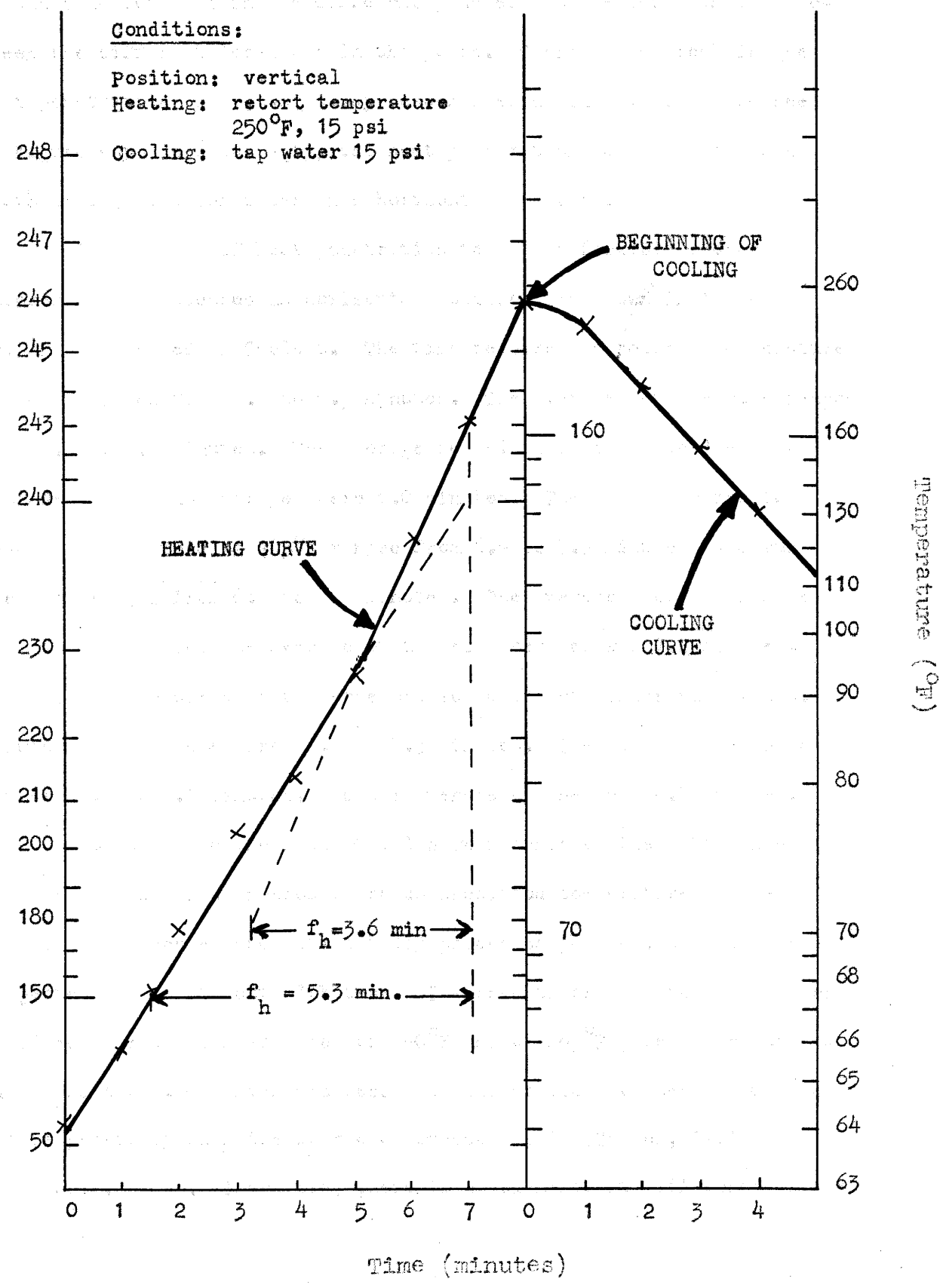
Table 4

RESULTS OF HEAT PENETRATION STUDIES ON
FLEXIBLY PACKAGED CHICKEN BROTH
(PROCESSED AT 250°F, 15 PSI UNDER WATER IN VERTICAL POSITION)

Run #	Package #	Time (min) Required to Reach Temperature of 240°F	245°F	f_h*	Residual Air (cc/pouch)
CB V-I	1	6.0	7.0	5.6,3.5	1.2
	5	6.1	7.3	5.1,3.7	1.2
	9	6.3	7.4	5.7,3.5	0.6
CB V-II	2	5.8	6.8	4.7,3.6	-
	3	5.8	7.3	4.9,3.5	-
	4	6.0	7.2	5.0,3.7	-
	5	6.3	7.9	5.4,3.6	-
	9	6.4	7.6	5.6,3.6	-
	11	6.1	7.8	5.1,3.7	-
	12	6.4	7.5	5.4,3.7	-
CB V-III	1	6.0	7.3	5.5,3.7	-
	2	6.0	7.3	5.5,3.7	-

*Heat penetration curve showed different slopes for first and second part of heating. The first number given is for the first part of the heat penetration.

Figure 3 Heat Penetration Curve For Chicken Broth At Slowest Heating Point



tal positions. The variations between the temperature at a given time at the same location in the different pouches was greater than that between the different locations in the pouch. There is no break in the heat penetration curve, which may be considered linear, as may be seen in Figure 4 which shows a typical heat penetration curve for chicken broth processed under water in a horizontal position.

The results of heat penetration tests for flexibly packaged chicken broth processed in horizontal position are shown in Table 5 and are summarized in Table 6. The time required to reach a temperature of 240°F ranged from 5.8 to 6.5 minutes. The averages of the runs ranged from 5.8 to 6.1 minutes. The average for all samples as well as the average of the run averages were 6.0 minutes. The time required to reach a temperature of 245°F ranged from 6.9 to 7.9 minutes, and run averages ranged from 6.9 to 7.5 minutes. The averages for all samples was 7.3 minutes and the average of the run averages was 7.2 minutes. The average time required to traverse one log cycle of temperature was 4.7 minutes and it ranged from 4.4 to 5.5 minutes. The run averages were between 4.3 to 5.1 minutes, and the average of them was 4.7 minutes.

To determine the statistical significance of the difference between heating times needed to reach specified temperature in the vertically processed and horizontally processed pouches, the data were subjected to the students "t" test. The results of this test for times required to reach temperatures of 240°F and of 245°F gave values of t = 0.687 and t = 0.705 which are less than the critical values at 50% and 40% respectively when the degree of freedom is 18 (Youden, 1961; Mendenhall, 1964). Therefore, there is no significant difference in the

Table 5

RESULTS OF HEAT PENETRATION STUDIES ON
FLEXIBLY PACKAGED CHICKEN BROTH
(PROCESSED AT 250°F, 15 PSI UNDER WATER IN HORIZONTAL POSITION)

Run #	Package #	Time (min) Required to Reach Temperature of 240°F	245°F	f_h	Residual Air (cc/pouch)
CB H-I	4	5.8	7.0	4.7	1.2
	7	6.2	7.7	5.0	1.2
	12	6.2	7.9	5.5	1.0
CB H-II	1	5.8	7.1	4.5	-
	2	5.8	7.1	4.5	-
	5	6.5	7.7	4.7	-
	6	5.7	7.0	4.4	-
	7	5.9	6.9	4.5	-
	8	6.3	7.5	4.8	-
CB H-III	1	5.8	6.9	4.3	-

Figure 4 Heat Penetration Curve For Chicken Broth

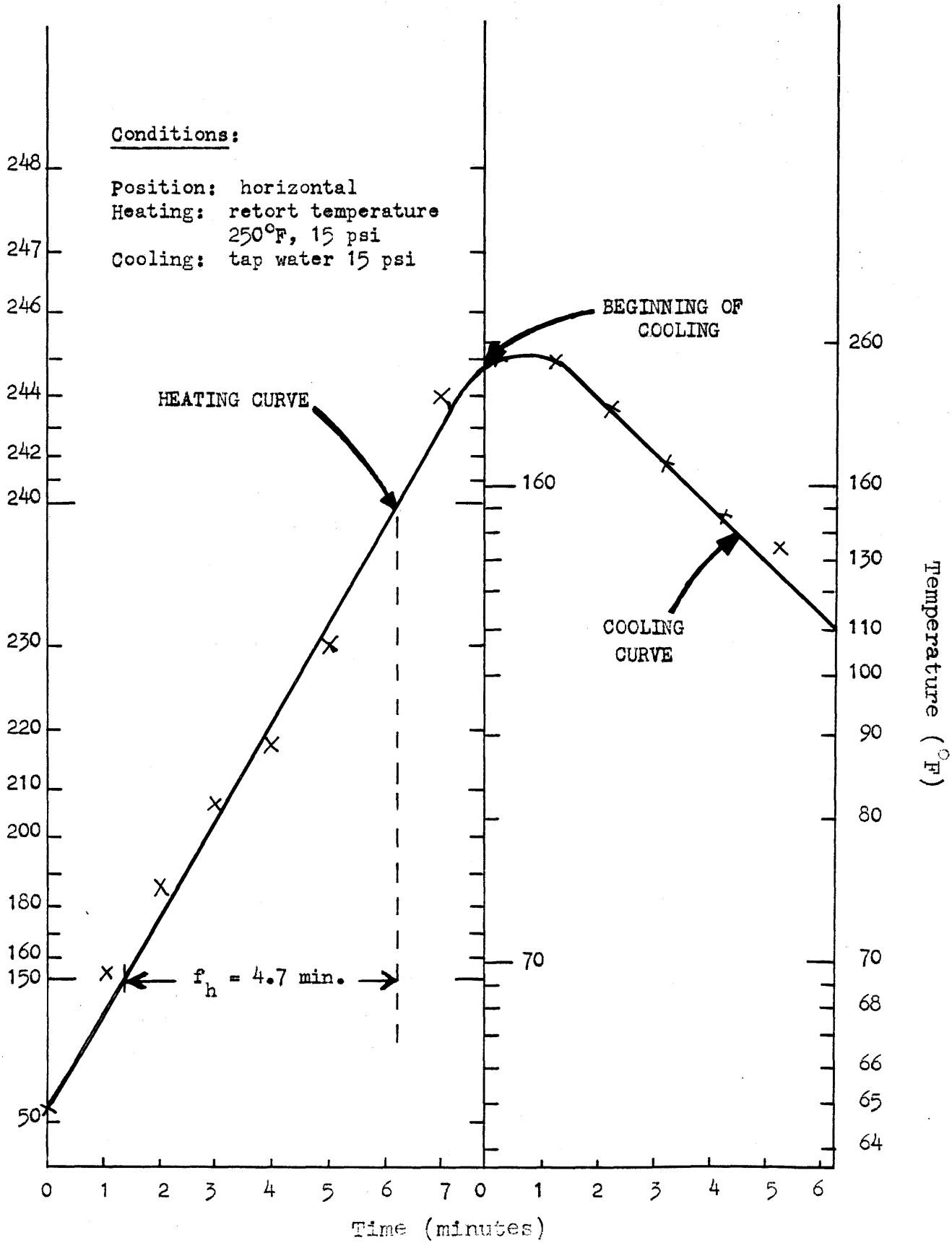


Table 6

SUMMARY OF THE RESULTS OF HEAT PENETRATION STUDIES
ON FLEXIBLY PACKAGED CHICKEN BROTH
(PROCESSED AT 250°F, 15 PSI UNDER WATER)

Run #	Number of Packages	Run Average Time (min) to Reach Temperature of 240°F	245°F	Run Average f_h	Minimum f_h for the run	Maximum f_h for the run
Samples Processed In Vertical Position						
CB V-I	3	6.1	7.2	5.5,3.6*	5.1,3.5*	5.1,3.7*
CB V-II	7	6.1	7.4	5.2,3.6	4.7,3.5	5.6,3.7
CB V-III	2	6.0	7.3	5.5,3.7	5.5,3.7	5.5,3.7
Average of run averages		6.1	7.3	5.4,3.6		
Samples Processed In Horizontal Position						
CB H-I	3	6.1	7.5	5.1	4.7	5.0
CB H-II	6	6.0	7.2	4.6	4.4	4.8
CB H-III	1	5.8	6.9	4.3	4.3	4.3
Average of run averages		6.0	7.2	4.7		

*Heat penetration curve showed different slopes for first and second part of the heating. The first number given is for the first part of the heat penetration.

time required to reach these temperatures whether packages are placed vertically or horizontally in the retort for processing. Although basically a difference exists in the manner of convection in two cases which is indicated by the different heat transfer coefficients and different shapes of the heat penetration curves, the heat penetration is too fast in these cases to show significantly different times.

In order to analyze the characteristics of the heating curves for the positions in which the pouches were processed, the known correlation of the heat transfer parameters in a system showing natural convection was studied.

In such a system, the plot of the log of Nusselt number, hL/K, versus the product of the following two dimensionless numbers: Grashof number, $(\rho^2 g \beta(T - T_\infty) L^3/\mu^2)$, and Prandtl number, $(C_p \mu/K)$, is a broken straight line for vertical plates and cylinders (Kreith, 1963). The break occurs because of the transition of the fluid flow from laminar to turbulent. The flow is laminar up to a Grashof number of about 10^8, a transition takes place between 10^8 and 10^{10}, and the flow becomes fully turbulent at the product of Grashof number and Prandtl number above 10^{10}. This type of behavior is considered typical of free convection on vertical surfaces.

In the chicken broth processed vertically at 250°F, the break of the curve occurs at the temperature around 228°F. At this instant, the mean temperature is 239°F, the temperature difference between the retort and chicken broth is 22°F, and assuming the physical properties of the chicken broth to be similar to those of water; it is found that

$$(Pr)_{239^\circ F} = (C_p \mu/K) = 1.55$$

$$(g \beta \rho^2/\mu^2) = 1.92 \times 10^9/^\circ F \qquad \text{(Kreith, 1963)}$$

Since the length of the pouch is 6.25 inches, the Grashof number is calculated as:

$$(Gr) = (g \beta \rho^2/\mu^2)(T - T_\infty) L^3$$

$$= (1.92 \times 10^9)(22)(0.143)$$

$$= 6.05 \times 10^9$$

$$(Gr)(Pr) = 9.3 \times 10^9$$

The product of Grashof number and Prandtl number calculated for the temperatures at which the heating curves for chicken broth processed in a vertical position show a break is 9.3×10^9 as shown above. Since this value falls in the range of transition from turbulent to laminar flow, it is reasonable to assume that the observed break is due to a change in the convective current flow pattern.

For the horizontal position, the log plot of Nusselt number versus Grashof number and Prandtl number is a smooth curve deviating

from linearity. The curve reported in the literature is shown with the upper limit only up to (Gr)(Pr) equal to 10^9, and the curve assumes linearity starting at (Gr)(Pr) equal to 10^6 (Kreith, 1963).

For the experiment with chicken broth processed in a horizontal position, the products of Grashof number and Prandtl number which were calculated as shown above, have the following values: when the product temperature is 100°F, 3.17×10^{10} and at the end of the process (249°F) 0.04×10^{10} (Appendix C, Table 25, page 175). Therefore the data obtained for horizontally processed pouches of chicken broth, which fall in the (Pr)(Gr) range of 4.0×10^8 to 3.17×10^{10} fall partly in the linear range and partly beyond the range reported in literature. Assuming that the curve continues to be linear above values of 10^9, the data seem to be in general agreement with a heating pattern reported for horizontal plates, in showing no breaks.

The above convective heat transfer parameters and convective heat transfer coefficients for vertical plate and horizontal plates are calculated for several temperatures and tabulated in Appendix C, Table 25, page 175.

A different analysis of heat transfer in a natural convection system is given by McAdams (1954). He presents semilog straight line equations

$$hL/K = 0.14 \left[(Gr)(Pr)\right]^{1/2}$$

for heated plates facing upward, or cooled plates facing downward. These equations hold for the turbulent range with (Gr)(Pr) ranging from 2×10^7 to 3×10^{10}. The equation:

$$hL/K = 0.27 \left[(Gr)(Pr)\right]^{0.25}$$

is expected to hold for heated plates facing downward, or cooled plated facing upward in the laminar range with (Gr)(Pr) of 3×10^5 to 3×10^{10}.

For the case of pouches with chicken broth placed in the retort horizontally, half the heated faces face upward and half of them face downward, therefore the heat transfer involved here is probably governed by some combination of both equations above.

In either case there is no abrupt discontinuity in the relationship between the heating parameters which is also indicated in the heat penetration curve of the horizontally processed chicken broth.

The experimental heating curve may be used to calculate the overall heat transfer coefficient U. The equation used is:

$$U = \left[C_p W/(A)(f_h)\right](2.303)$$

where,

U = overall heat transfer coefficient

A = area of the heat transfer, and for this case is 0.326 ft^2

C_p = specific heat = 1 BTU/lb.-°F

W = weight of the product, and for this case 0.33 lb

f_h = negative reciprocal slope of the heating curve

With this relationship, when the overall heat transfer coefficients were calculated for the vertically processed chicken broth. They were 26.8 BTU/ft^2-hr-°F before the break in the heating curve and 38.8 BTU/ft^2-hr-°F after the break. The overall heat transfer coefficient

for the horizontally processed chicken broth was 29.6 BTU/ft^2-hr-$^\circ$F. On the other hand, the overall heat transfer coefficients calculated from the given heating parameters given in the literature for plates heating by natural convection (Kreith, 1963) at the various product temperature are shown below. They are one and half times to ten times higher than those calculated from our experimental heat transfer data.

Temperature	Convective Heat Transfer Coefficient Vertical Position	Horizontal Position
60°F	49	49
100°F	295	186
150°F	279	184
200°F	150	144
228°F	119	126
240°F	94	84
245°F	84	84
249°F	57	55

When the instantaneous overall heat transfer coefficients were calculated using instantaneous retort temperature and the equation:

$$C_p W (T - T_i) = U A (T_R - T) d\theta$$

the instantaneous overall heat transfer coefficients ranged between 45 to 25 BTU/hr-ft^2-$^\circ$F (See Appendix D, page 176).

It is interesting to note that in the case of chicken broth processed in laminated pouches, the overall resistance to heat transfer (1/U) is of the same order of magnitude as that calculated for the surface resistance

(R_s) for the case of ground beef, when the thermal diffusivity of beef was based on its known thermal properties. Specifically, it is about 2-3 times smaller than that in the case of apparent surface resistance for ground beef, but still one and half to ten times larger than that expected from theory. It appears therefore, that when the need for conduction of heat in solids within the pouch is eliminated, as is the case in chicken, the overall resistance still comes to a limiting values of about 1/39 - 1/26 (hr-ft^2-$^\circ$F (BTU)$^{-1}$). The similarity of this limiting value between two different types of foods seems to indicate that at least a part of the increased resistance is due to a factor common to both. The first possibility, that it is due to a liquid film on the outside of the pouch ($1/h_o$) is unlikely because the theoretical values for the resistance of this type of a film are much smaller than the experimental values. Gas films on the inside of the pouch, on the outside of the pouch, or within the lamination sandwich itself, are likely to be the major causes of this limiting resistance. More detailed analysis on this point was presented in the discussion of the experiment with the ground beef.

3. Heat penetration into the flexibly packaged carrot slices in chicken broth

Pouches containing carrot slices in chicken broth were processed under water at 250°F, 15 psi in vertical and horizontal positions, and were cooled under continuously running tap water under 15 psi.

The results are shown in Tables 7 and 8, typical heat penetration curves are shown in Figures 5 and 6, and the results are summarized in Table 9.

The product showed typical convection heating behavior characterized by rapid attainment of process temperatures.

In the carrot slices in chicken broth processed in a vertical position, the average time required to reach temperature of 240°F at the location 1/8th from the bottom was 7.0 minutes. It ranged from 6.6 minutes to 7.7 minutes. The time required to reach 245°F at the same location ranged from 8.0 minutes to 9.5 minutes having the average value of 8.6 minutes. The time required to traverse one log cycle of temperature ranged from 4.7 minutes to 6.0 minutes, with an average of 5.2 minutes.

For the horizontally processed pouches, the time required to reach 240°F ranged from 5.8 minutes to 6.8 minutes with an average of 6.2 minutes. The time required to reach 245°F ranged from 6.3 minutes to 9.3 minutes with an average of 8.0 minutes. The time required to traverse one log cycle of temperature ranged from 4.0 minutes to 5.7 minutes with an average of 5.2 minutes.

There seemed to be no one point where heat penetration is slowest either in vertical or horizontal position. The result of "F" test performed on the time required to reach 240°F at the different locations in the pouch, 1/8th, 1/4th and 3/8th from the bottom of the pouch, processed at vertical position gave an F value of 1.235. The same test for same position for time required to reach 245°F gave F value of 0.753 and that for f_h was 0.098. The critical value for F at 5% level in these cases is 4.74 (Youden, 1961). Therefore, statistically there is no significant difference in heating time required to reach specified temperatures at the different positions in the pouch. This may be due to the effect of carrot slices

Table 7

RESULTS OF HEAT PENETRATION STUDIES ON FLEXIBLY PACKAGED CARROT SLICES IN CHICKEN BROTH (PROCESSED AT 250°F, 15 PSI UNDER WATER IN A VERTICAL POSITION)

Run #	Package #	Thermocouple Location (Fraction of Length from Bottom)	Time Required to Reach Specified Temperature (min)		f_h
			240°F	245°F	
CS V-I	1	1/8	6.6	8.0	4.7
	7	1/8	6.7	8.2	5.0
	10	1/8	7.3	10.0	5.5
	3	1/4	6.8	8.5	5.4
	6	1/4	6.8	8.5	5.4
	9	1/4	6.8	8.4	5.1
	12	1/4	6.5	8.0	5.2
	2	3/8	5.8	7.2	4.6
	5	3/8	6.4	8.0	4.5
	11	3/8	7.0	8.7	5.5

Table 8

RESULTS OF HEAT PENETRATION STUDIES ON FLEXIBLY PACKAGED CARROT SLICES IN CHICKEN BROTH (PROCESSED AT 250°F, 15 PSI UNDER WATER IN A HORIZONTAL POSITION)

Run #	Package #	Thermocouple Location (Fraction of Package Length)	Time Required to Reach Specified Temperature (min)		f_h
			240°F	245°F	
CS H-I	3	1/8	5.8	7.3	4.8
	6	1/8	6.7	9.3	5.5
	8	1/8	6.3	8.8	5.5
	2	1/4	5.6	8.3	5.6
	10	1/4	6.3	7.7	5.2
	11	1/4	5.9	6.3	4.0
	1	3/8	6.3	8.0	5.7
	9	3/8	6.1	7.7	5.2
	5	1/2	6.4	7.9	5.0
	12	1/2	6.8	8.4	5.5

Table 9

SUMMARY OF THE RESULTS OF HEAT PENETRATION STUDIES ON FLEXIBLY PACKAGED CARROT SLICES IN CHICKEN BROTH (PROCESSED AT 250°F, 15 PSI UNDER WATER)

Run #	Number of Pouches	Thermocouple Location (Fraction of Length from Bottom)	Average Time (min) Required to Reach Specified Temperature of 240°F	245°F	Average f_h
		Samples Processed In Vertical Position			
CS V-I	3	1/8	7.0	8.6	5.3
	4	1/4	6.7	8.3	5.3
	3	3/8	6.4	8.0	4.9
		Samples Processed In Horizontal Position			
CS H-I	3	1/8	6.2	8.5	5.3
	3	1/4	6.3	7.4	5.1
	2	3/8	6.3	7.9	5.4
	2	1/2	6.6	8.2	5.3

Figure 5 Heat Penetration Curve For Carrot Slices In Chicken Broth

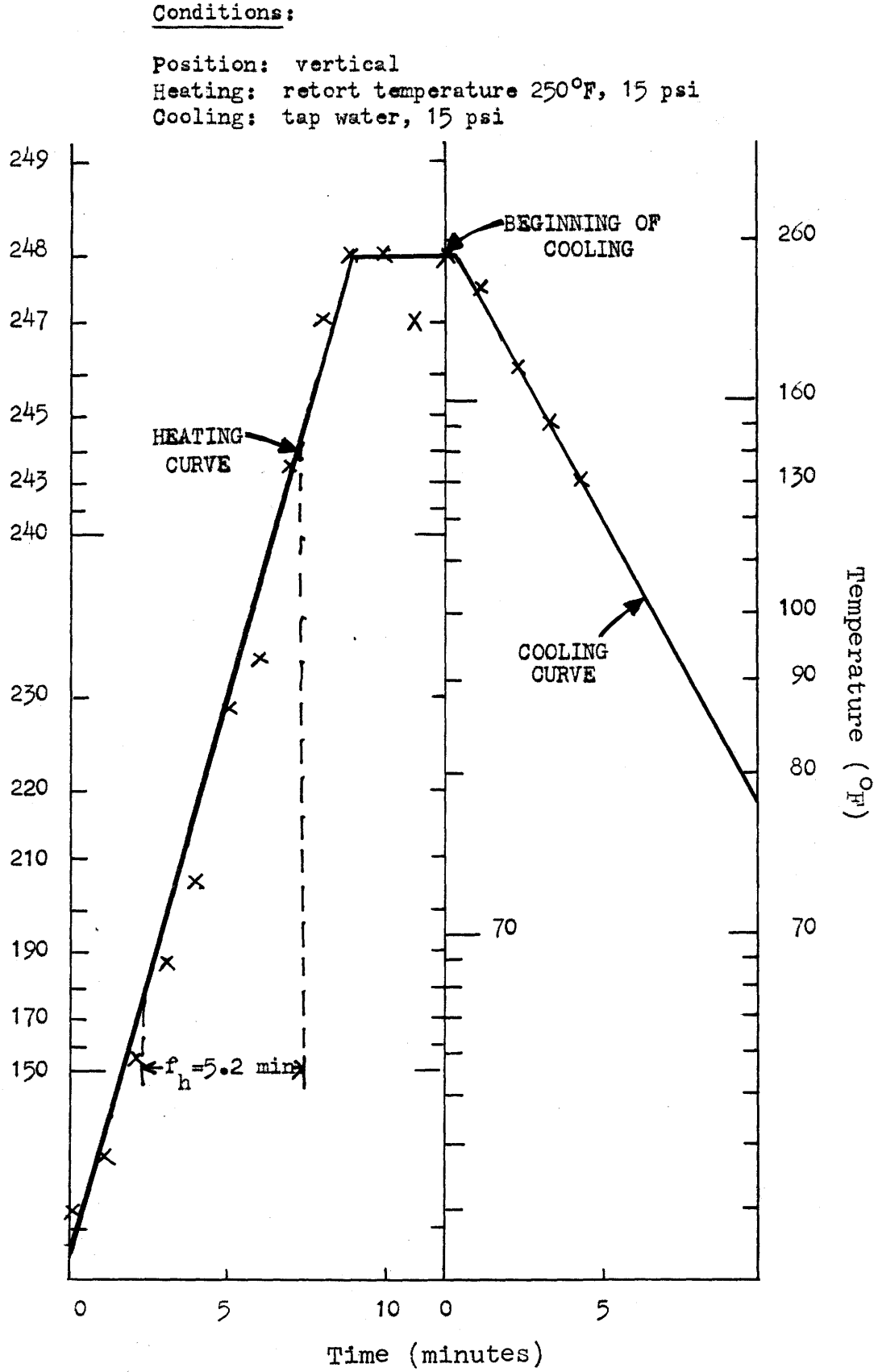
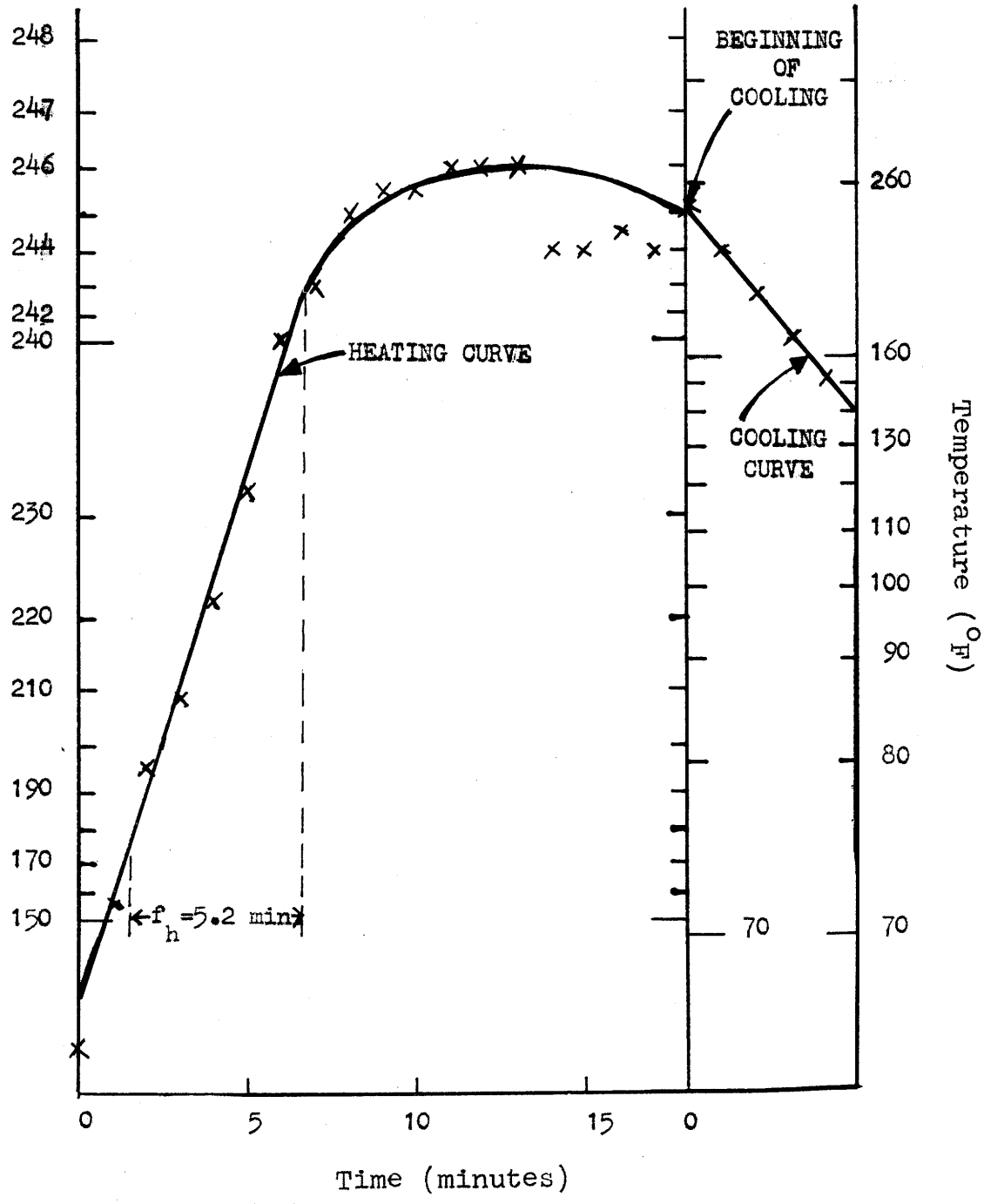


Figure 6 Heat Penetration Curve For Carrot Slices In Chicken Broth

Conditions:

Position: Horizontal
Heating: retort temperature 250°F, 15 psi
Cooling: tap water, 15 psi



acting as baffles and contributing to better mixing at least in the vertical case.

Student's "t" tests were applied to the time required to reach 240°F, 245°F and the time required to traverse one log cycle between the vertical and horizontal runs. The results obtained were t = 1.22, t = 1.39 and t = 0.187 respectively, and they were not significantly different at 25%, 20% and 50% levels respectively.

Both in the vertical and horizontal cases, the straight line heat penetration curve changed to a convex curve around 243°F or about 7 minutes after processing had started. This curve connected the first part of the heating curve to a nearly horizontal straight line in horizontal case. The same was not quite evident in vertical case due to the earlier starting of the cooling process. The second straight line started around 11 minutes after the processing. It may have some significance that the second straight line is aroumd the temperature region of 244°F to 245°F in the horizontal case while the region indicated in vertical case is aroumd 247°F although additional data would be required to confirm this difference in the temperature range in the position of the second portion straight line. This break in the heating curve may be caused by supplying of cooking energy to carrot slices.

While there were minor differences in heat penetration curves between chicken broth alone, and chicken broth containing carrot slices, the orders of magnitude of the overall heat transfer coefficients were the same as in both cases. Again the experimental heat penetration data show greater resistance as compared with the expected as was the case in the processing of chicken broth.

It appears therefore that the heating characteristics of this sys-

tems could be approximated well by chicken broth alone, and discussion given for the results obtained with chicken broth applies to the present system.

B. Thermal resistance of Clostridium sporogenes (PA 3679)

The heat resistance of a test organism, Clostridium sporogenes (PA 3679) was determined in two different media, beef puree and chicken broth at several different temperatures using the procedures described.

1. Thermal resistance of Clostridium sporogenes (PA 3679) in beef puree

The thermal resistance of Clostridium sporogenes (PA 3679) in beef puree was determined for the purpose of using it as a basis for the thermal process calculations for ground beef. The beef puree was used in place of ground beef since with ground beef it was not technically possible to fill the capillary tubes employed in thermal death time measurement apparatus used in this experiment.

The thermal inactivation data for Clostridium sporogenes in beef puree at 225°, 230°, 235°, 237°, 240° and 250°F are presented in Figures 7, 8, 9, 10, 11 and 12 respectively. The drawing of the lines and determination of the decimal reduction times are based on regression analysis of all the data points. The data are presented in Table 10.

The decimal reduction times obtained in the above manner for each temperature are employed to construct the D.R.T. curve for Clostridium sporogenes (PA 3679) in beef puree and presented in Figure 13. The drawing of the line and the determination of the negative reciprocal of the temperature to traverse one log cycle of time, Z, are both based on the regression analysis. The Z value thus determined is 18.9 minutes and the decimal reduction time at 250°F, D_{250}, is 1.16 minutes or approximately 1.2 minutes. These values lie within the range of data reported for semi-acid foods (Stumbo et al., 1950; Schmidt, 1957; Stumbo, 1965).

Table 10

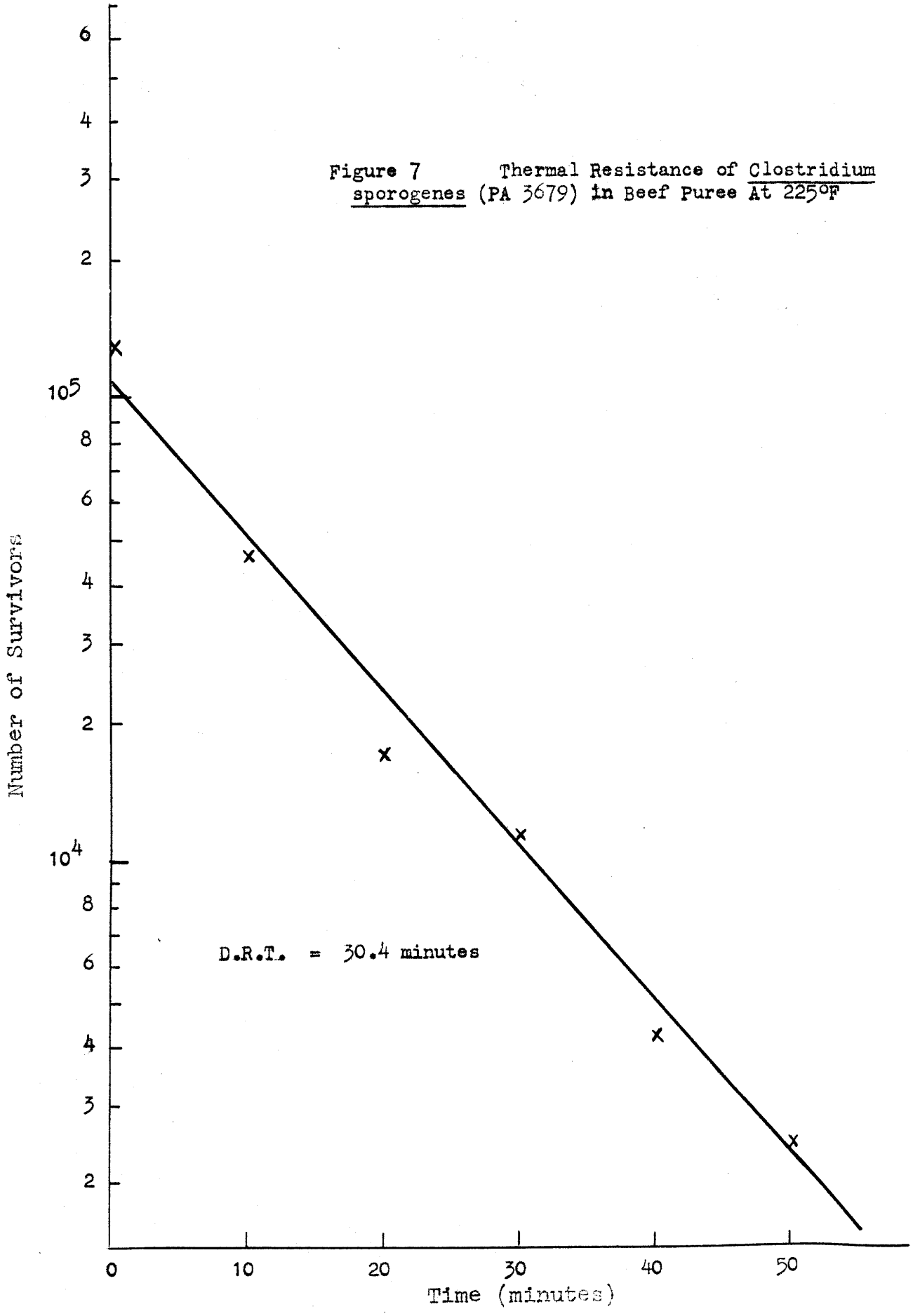
SURVIVAL OF *Clostridium sporogenes* IN BEEF PUREE AT VARIOUS TEMPERATURES

225°F		230°F		235°F	
Time of Heating (min.)	Average No. of Survivors	Time of Heating (min.)	Average No. of Survivors	Time of Heating (min.)	Average No. of Survivors
0.00	1.31×10^5	0.00	1.34×10^5	0.00	7.28×10^4
10.00	4.67×10^4	3.00	7.67×10^4	2.50	3.52×10^4
20.00	1.74×10^4	6.00	4.17×10^4	5.00	1.40×10^4
30.00	1.17×10^4	9.00	2.10×10^4	10.00	3.39×10^3
40.00	4.30×10^3	12.00	1.42×10^4	15.00	7.08×10^2
50.00	2.50×10^3	18.00	2.44×10^3		
D.R.T. = 30.4 min.		D.R.T. = 10.6 min.		D.R.T. = 7.5 min.	

237°F		240°F		250°F	
Time of Heating (min.)	Average No. of Survivors	Time of Heating (min.)	Average No. of Survivors	Time of Heating (min.)	Average No. of Survivors
0.00	1.30×10^5	0.00		0.00	5.20×10^4
3.00	2.93×10^4	1.00	1.48×10^4	0.50	4.08×10^4
6.00	1.00×10^4	2.00	5.97×10^3	1.10	1.04×10^4
9.00	2.53×10^3	3.00	3.50×10^3	1.67	5.35×10^3
12.00	8.10×10^2	4.00	1.38×10^3	2.20	1.82×10^3
15.00	2.50×10^2	5.00	7.80×10^2	2.77	4.35×10^2
D.R.T. = 5.7 min.		D.R.T. = 2.9 min.		D.R.T. = 1.3 min.	

D.R.T.'s presented above are determined by regression analysis. The negative reciprocal of the thermal death time curve, Z, determined with these D.R.T.'s by regression analysis is 18.9.

Figure 7 Thermal Resistance of Clostridium sporogenes (PA 3679) in Beef Puree At 225°F



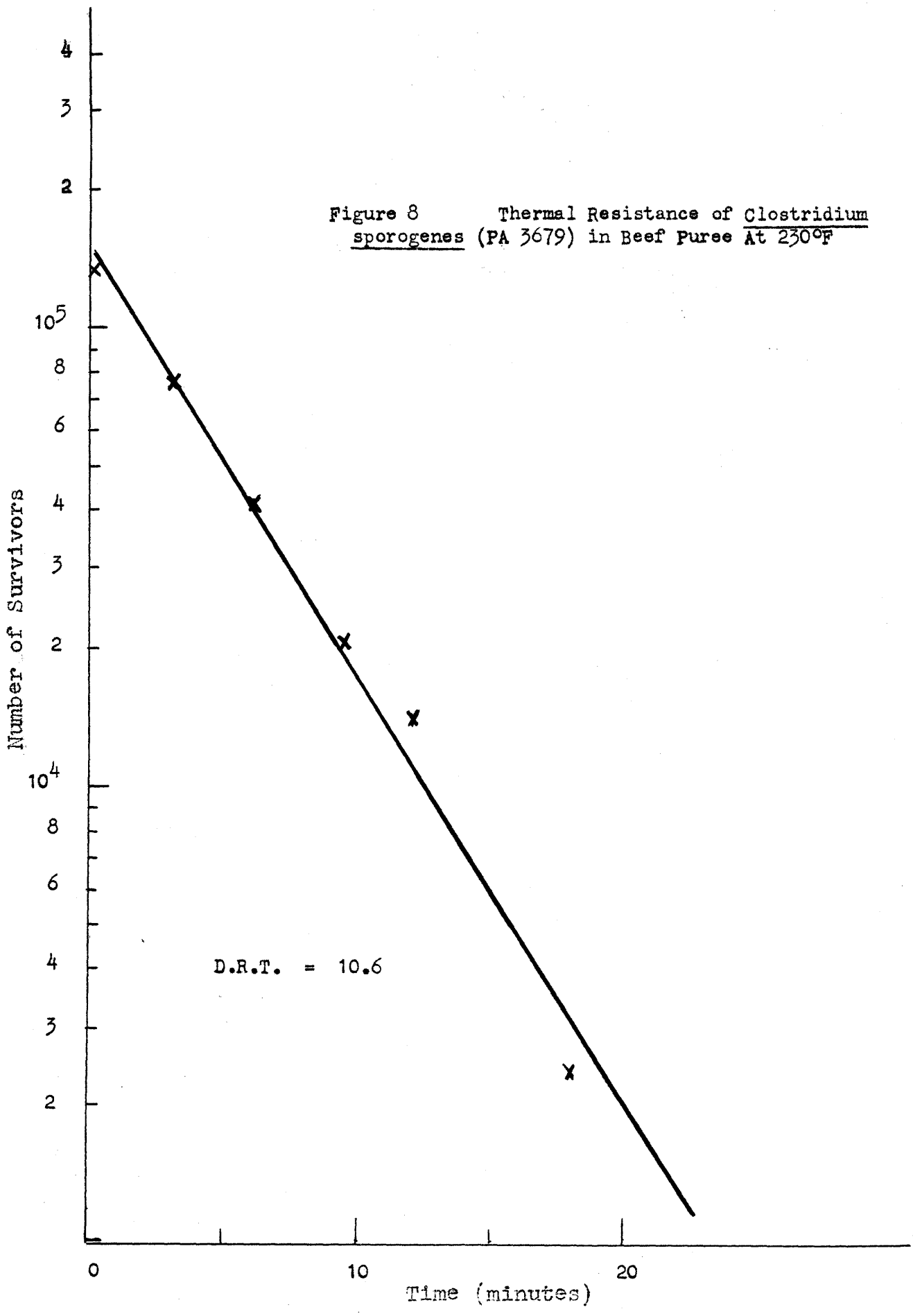


Figure 8 Thermal Resistance of Clostridium sporogenes (PA 3679) in Beef Puree At 230°F

Figure 9 Thermal Resistance of Clostridium sporogenes (PA 3679) in Beef Puree At 235°F

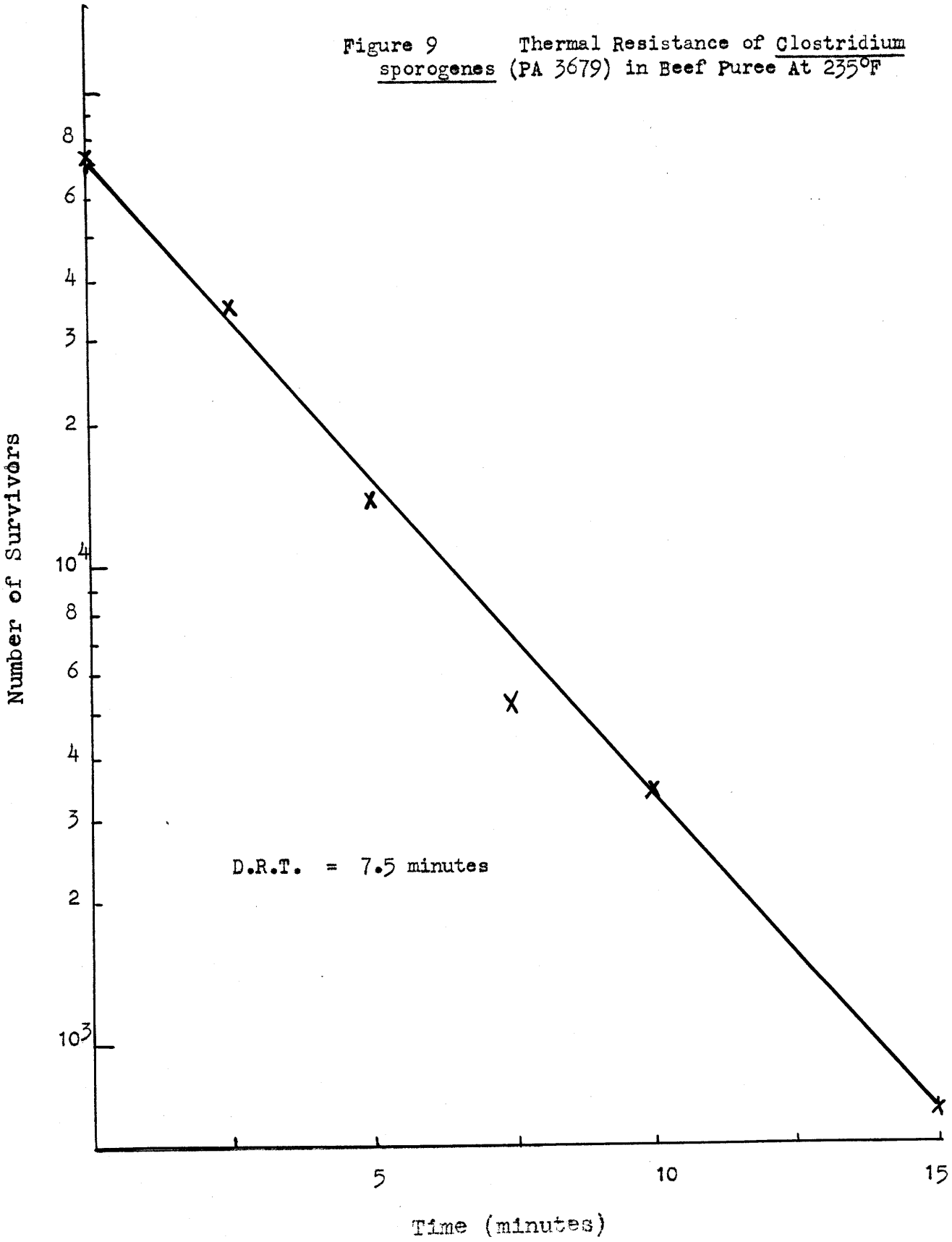


Figure 10 Thermal Resistance of Clostridium sporogenes (PA 3679) in Beef Puree At 237°F

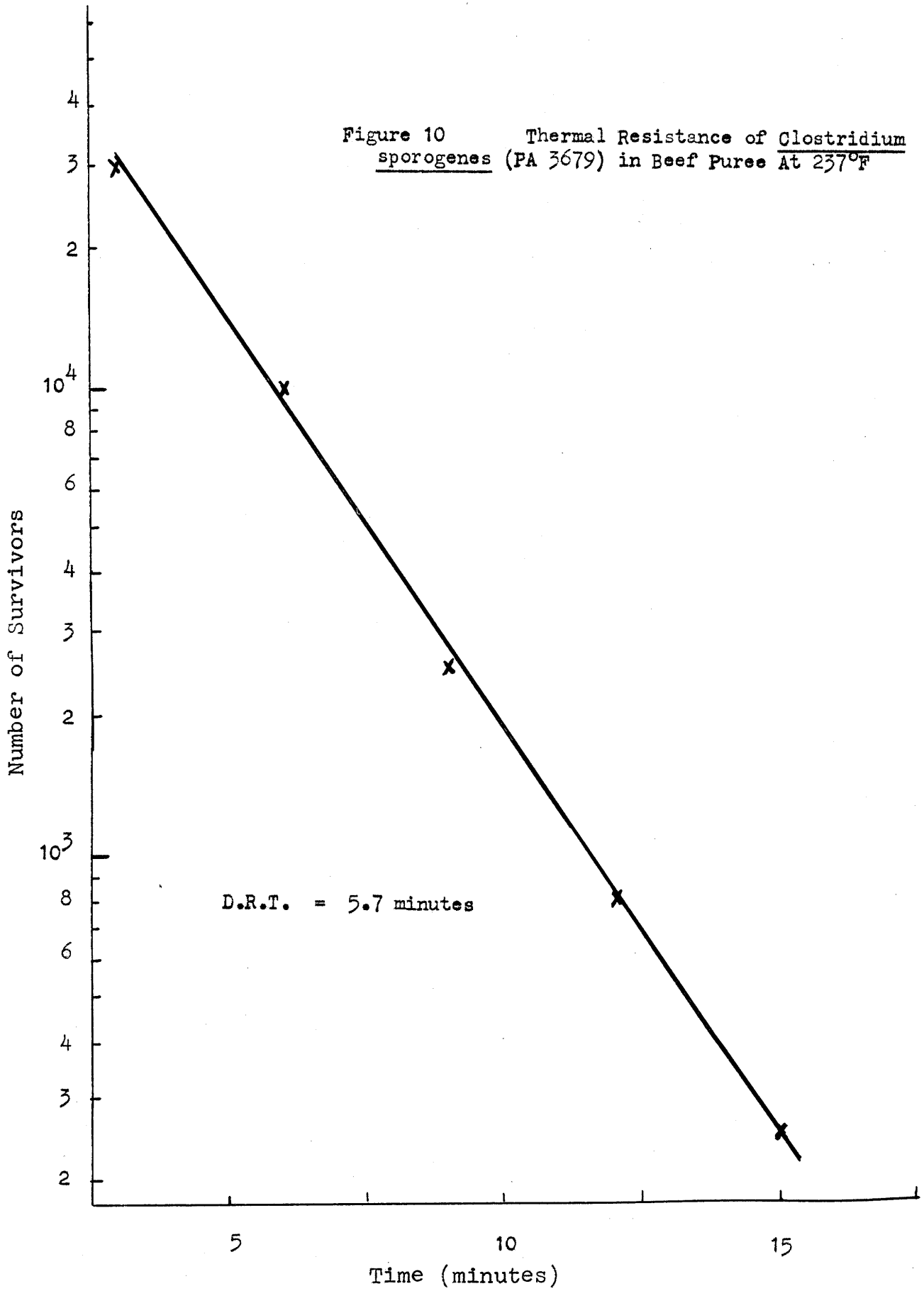
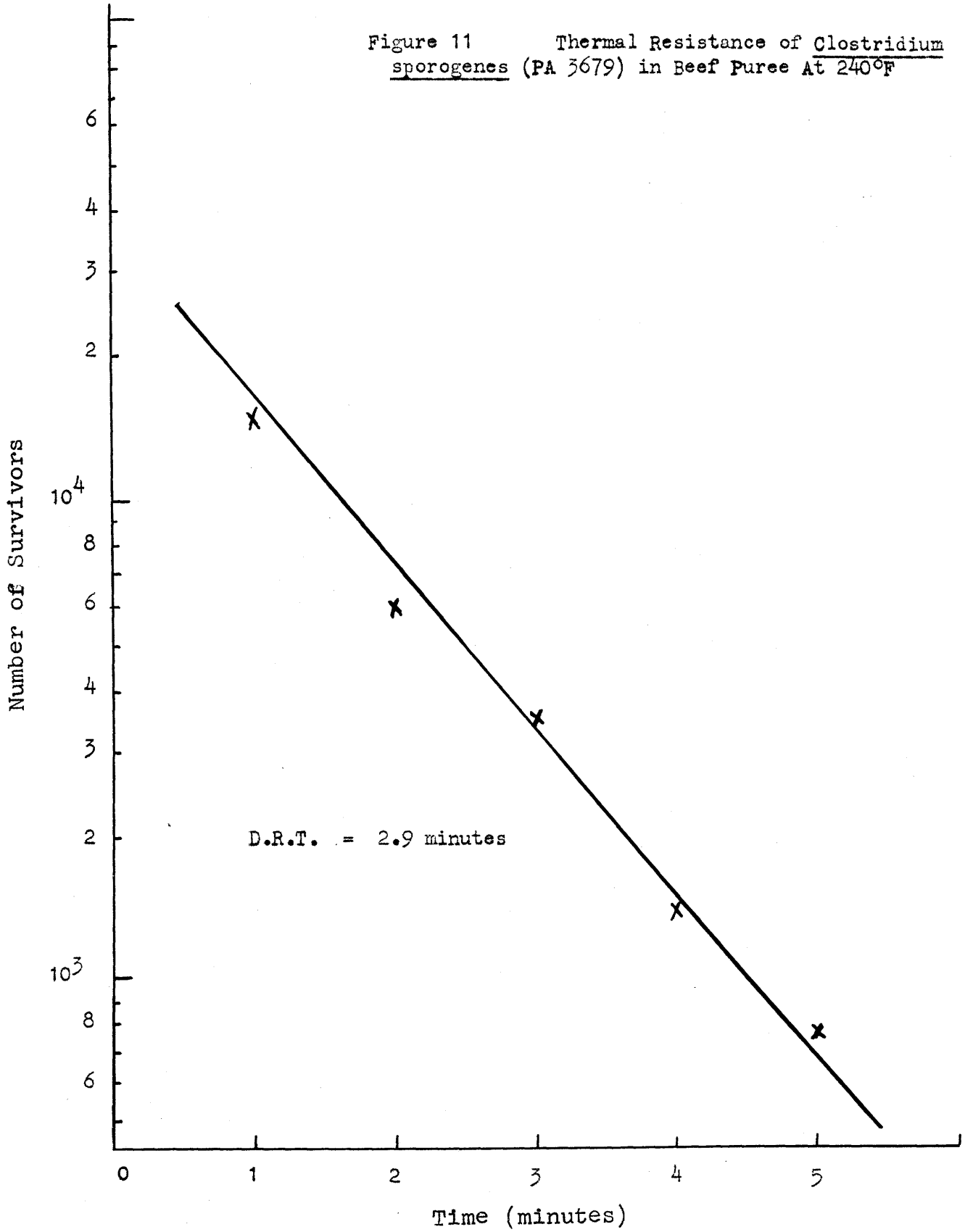


Figure 11 Thermal Resistance of Clostridium sporogenes (PA 3679) in Beef Puree At 240°F



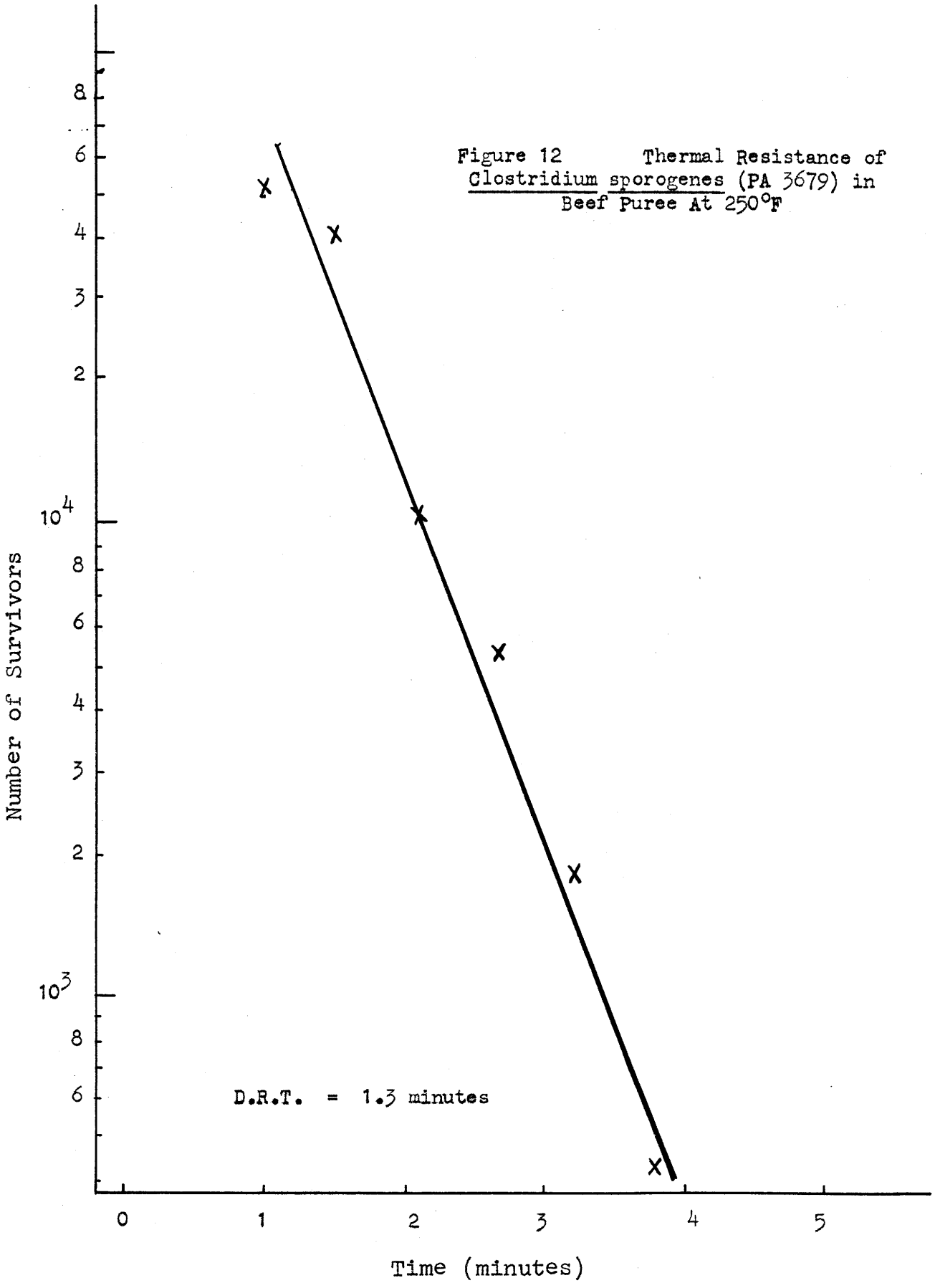
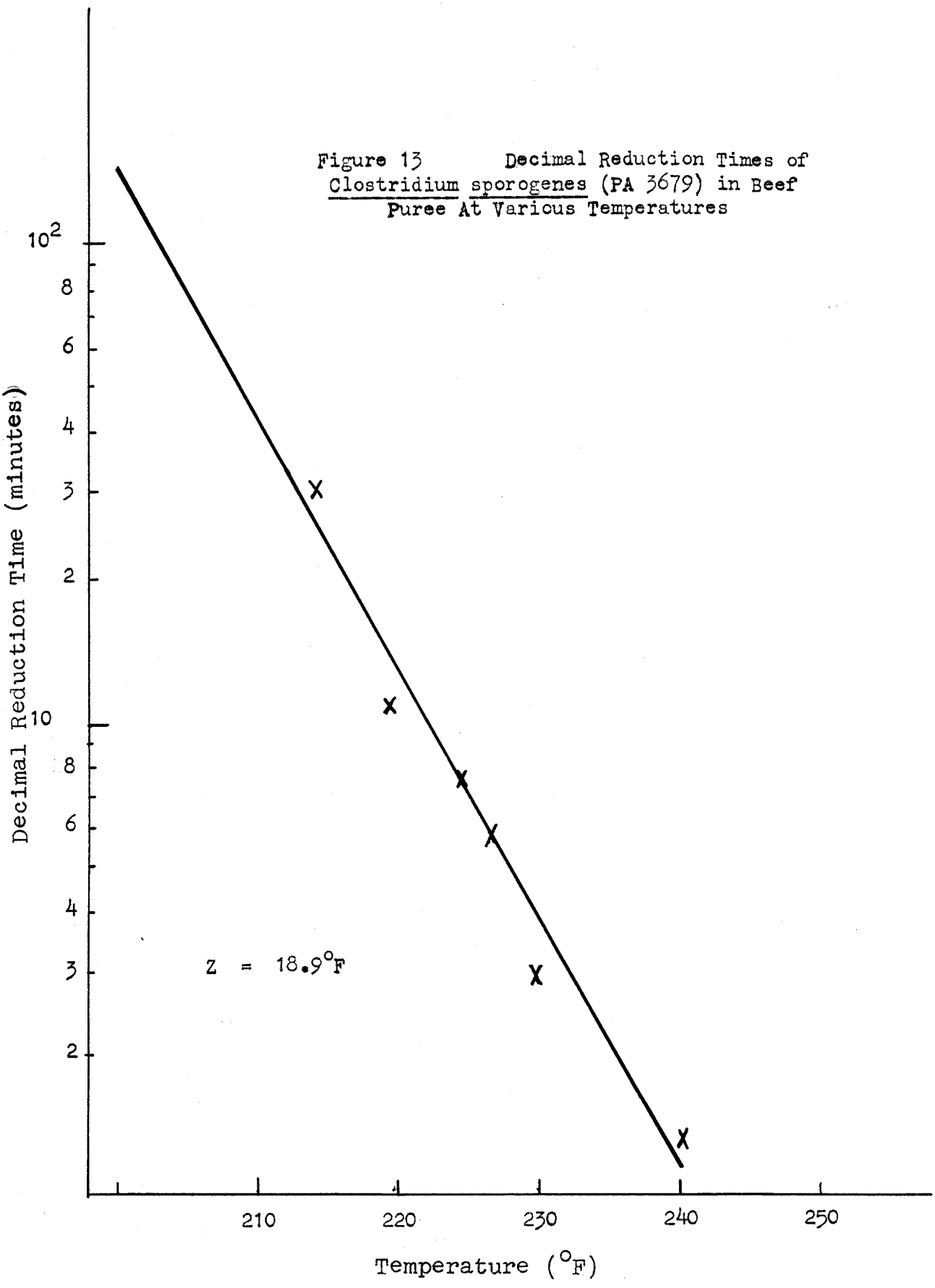


Figure 12 Thermal Resistance of Clostridium sporogenes (PA 3679) in Beef Puree At 250°F

Figure 13 Decimal Reduction Times of Clostridium sporogenes (PA 3679) in Beef Puree At Various Temperatures



2. Thermal resistance of Clostridium sporogenes (PA 3679) in chicken broth

The thermal inactivation data for Clostridium sporogenes (PA 3679) in chicken broth at 230.0°, 235.0°, 237.5°, 240.0°, 242.5° and 245°F are presented in Figures 14, 15, 16, 17, 18 and 19 respectively. All the lines and the decimal reduction times were determined by regression analysis of all the data points. The data are presented in Table 11.

The decimal reduction times obtained above for each temperature are used to construct the D.R.T. curve for Clostridium sporogenes (PA 3679) in chicken broth and the D.R.T. curve is presented in Figure 20. The determination of the slope of the line and the base point are also based on the regression analysis. The Z value determined in this case is 18.7 minutes with D_{250} of about 0.7 minutes. These values also lie well within the range of literature value (Stumbo, 1965).

3. Effect of media on thermal resistance of Clostridium sporogenes (PA 3679)

It is of interest to note that although D_{250} values differed, the slope of the thermal death time curves are quite similar either in chicken broth or beef puree. This is reasonable because the microorganisms used in both tests are from the same stock and since generally Z value depends more on the nature of the test organism while D value depends more on the nature of the suspending medium. The pH of both beef puree and chicken broth are the same and are 5.5, therefore the apparent difference in D values for the two media is not due to the effect of pH but some other factor.

Table 11

SURVIVAL OF *Clostridium sporogenes* IN CHICKEN BROTH AT VARIOUS TEMPERATURES

230.0°F		235.0°F		237.5°F	
Time of Heating (min.)	Average No. of Survivers	Time of Heating (min.)	Average No. of Survivers	Time of Heating (min.)	Average No. of Survivers
0.00	1.57×10^5	0.00	2.67×10^5	0.00	1.65×10^5
3.00	7.50×10^4	2.50	4.33×10^4	1.25	4.26×10^4
6.00	4.57×10^4	5.00	1.20×10^4	2.50	1.40×10^4
9.00	1.63×10^4	7.50	3.50×10^3	3.60	6.63×10^3
12.00	9.58×10^3	10.00	3.00×10^2	5.42	1.33×10^3
		12.50	3.75×10^2	7.20	2.55×10^2
D.R.T. = 9.7 min.		D.R.T. = 4.1 min.		D.R.T. = 2.7 min.	

240.0°F		242.5°F		245.0°F	
Time of Heating (min.)	Average No. of Survivers	Time of Heating (min.)	Average No. of Survivers	Time of Heating (min.)	Average No. of Survivers
1.00	2.95×10^4	0.00	7.80×10^4	0.00	5.97×10^4
2.00	1.70×10^4	0.92	4.60×10^3	0.66	2.73×10^4
3.00	8.70×10^3	2.75	3.63×10^3	1.33	7.08×10^3
4.00	2.70×10^3	3.67	7.40×10^2	2.00	2.40×10^3
5.00	1.07×10^3	4.58	2.50×10^2	2.67	6.00×10^2
				3.33	2.02×10^2
D.R.T. = 2.7 min.		D.R.T. = 2.1 min.		D.R.T. = 1.3 min.	

D.R.T.'s presented above are determined by regression analysis the negative reciprocal of the thermal death time curve, Z, determined with these D.R.T.'s by regression analysis is 18.7

Figure 14 Thermal Resistance of Clostridium sporogenes (PA 3679) in Chicken Broth At 230°F

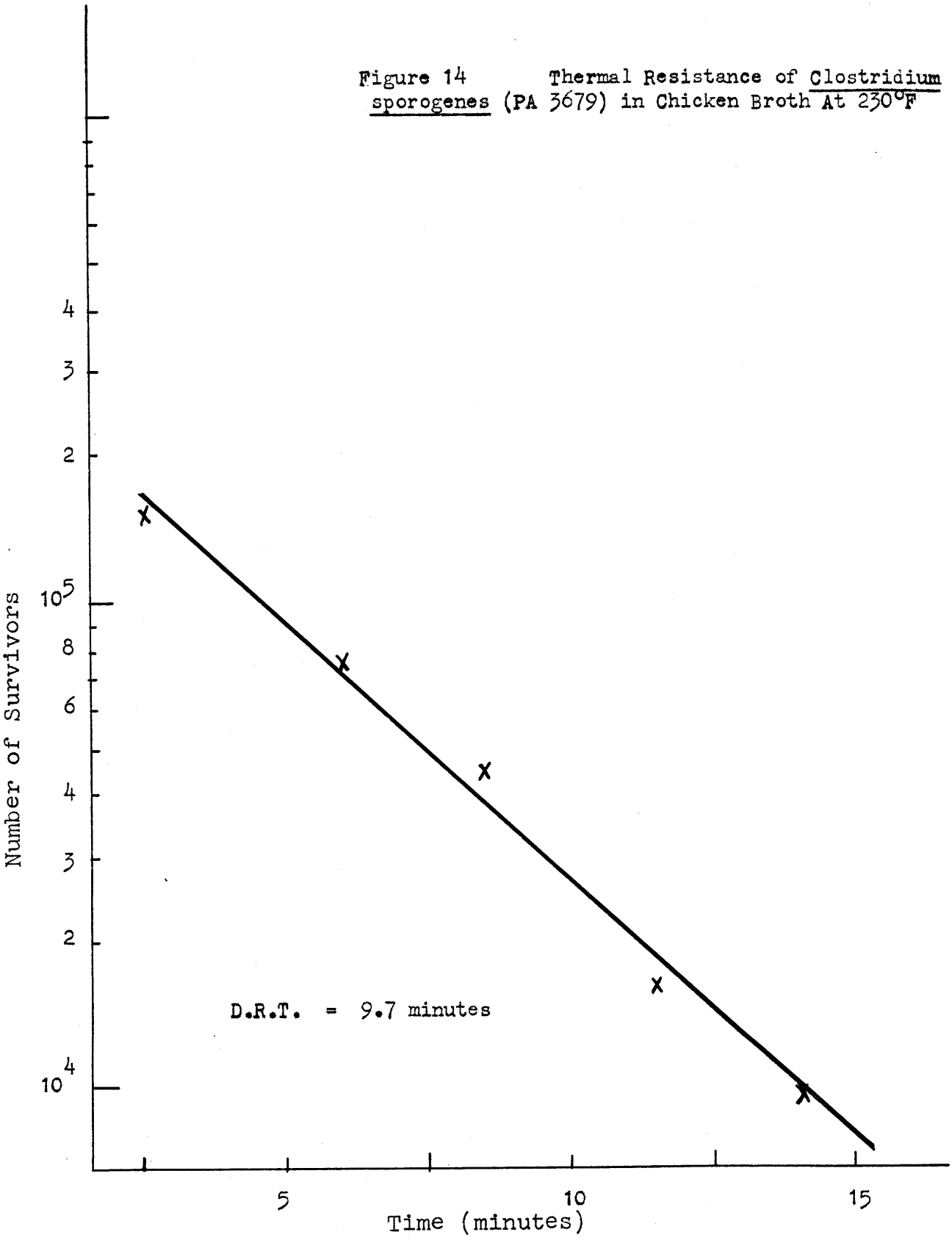


Figure 15 Thermal Resistance of Clostridium sporogenes (PA 3679) in Chicken Broth At 235°F

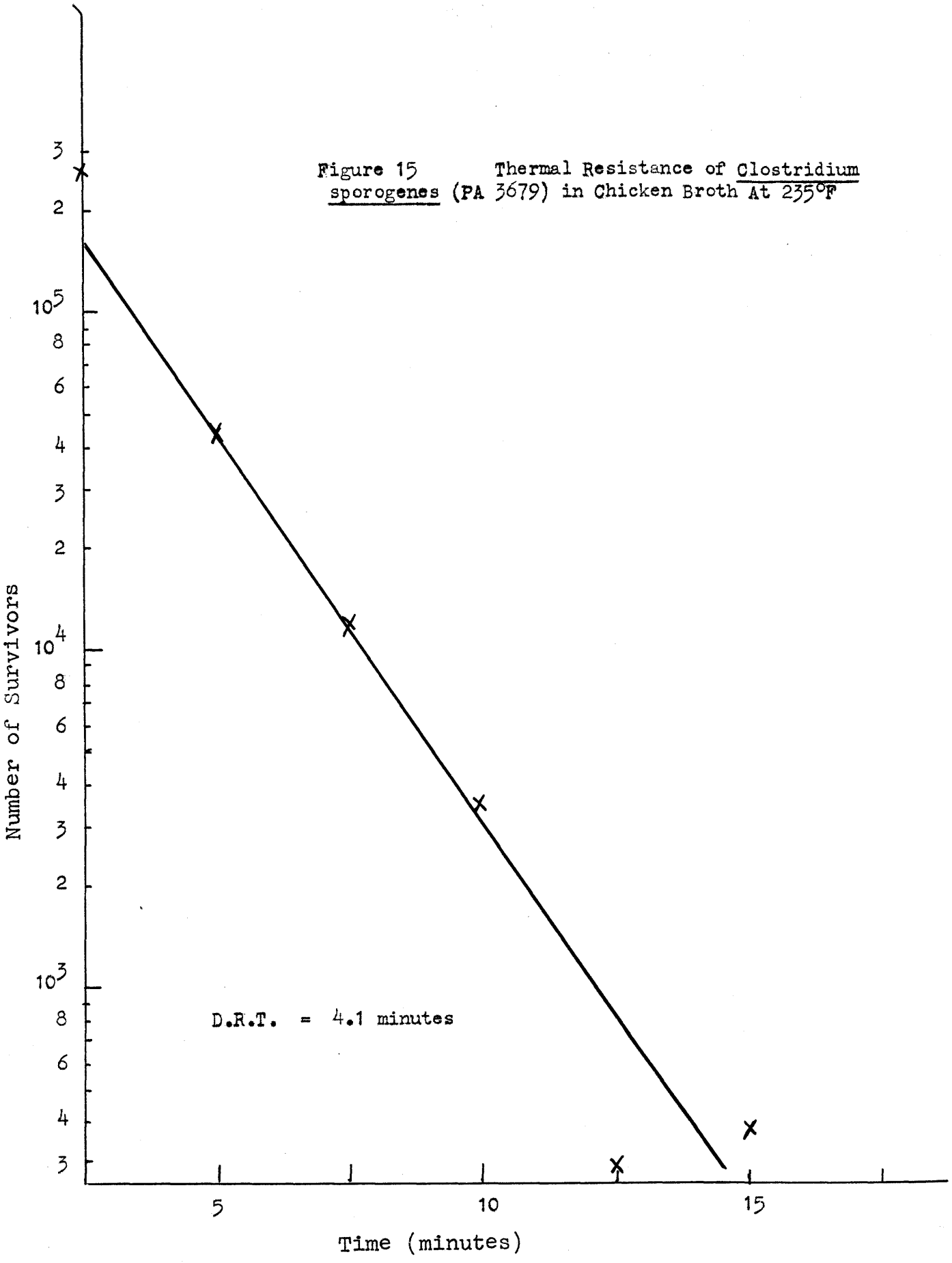


Figure 16 Thermal Resistance of Clostridium sporogenes (PA 3679) in Chicken Broth At 237.5°F

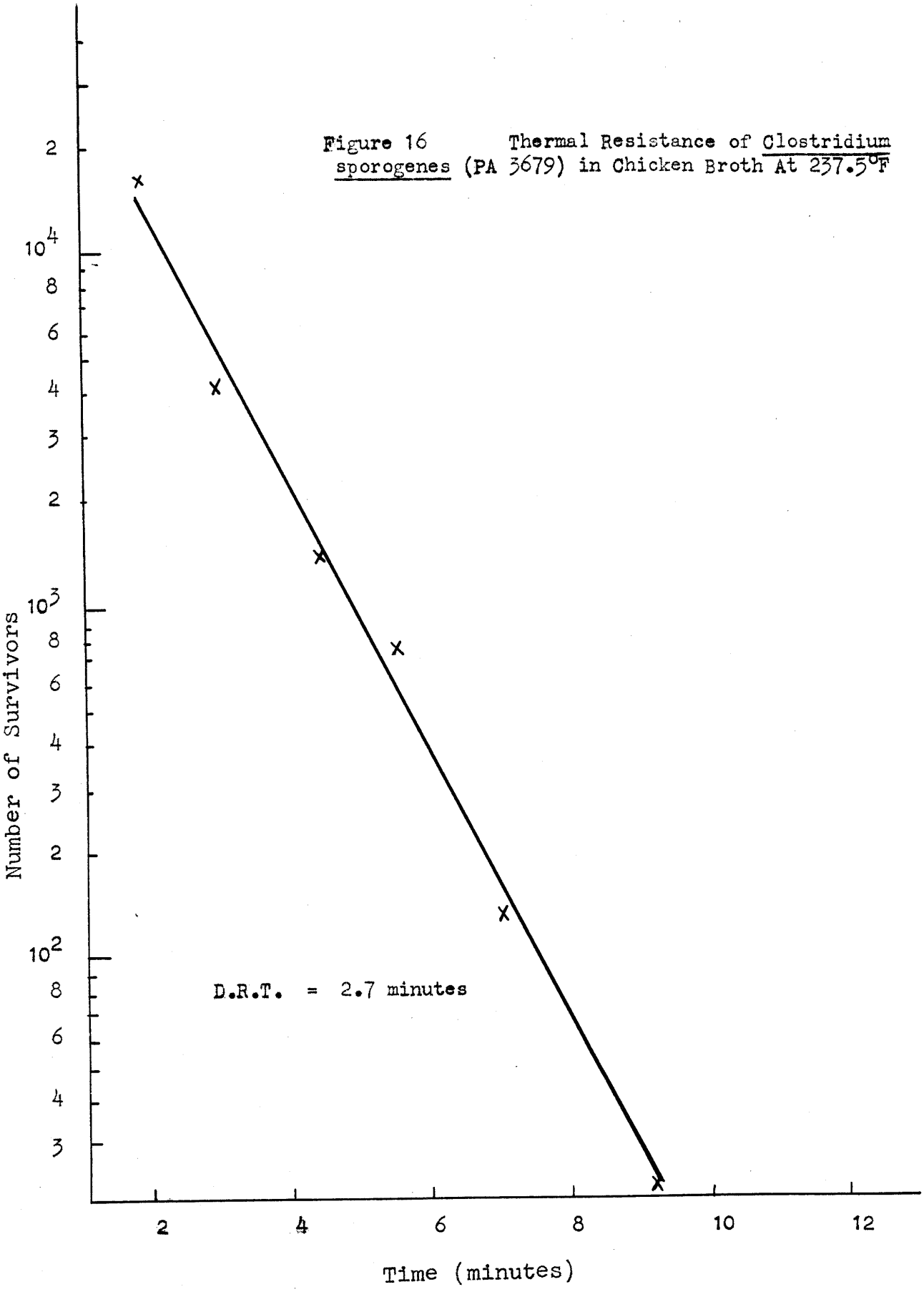
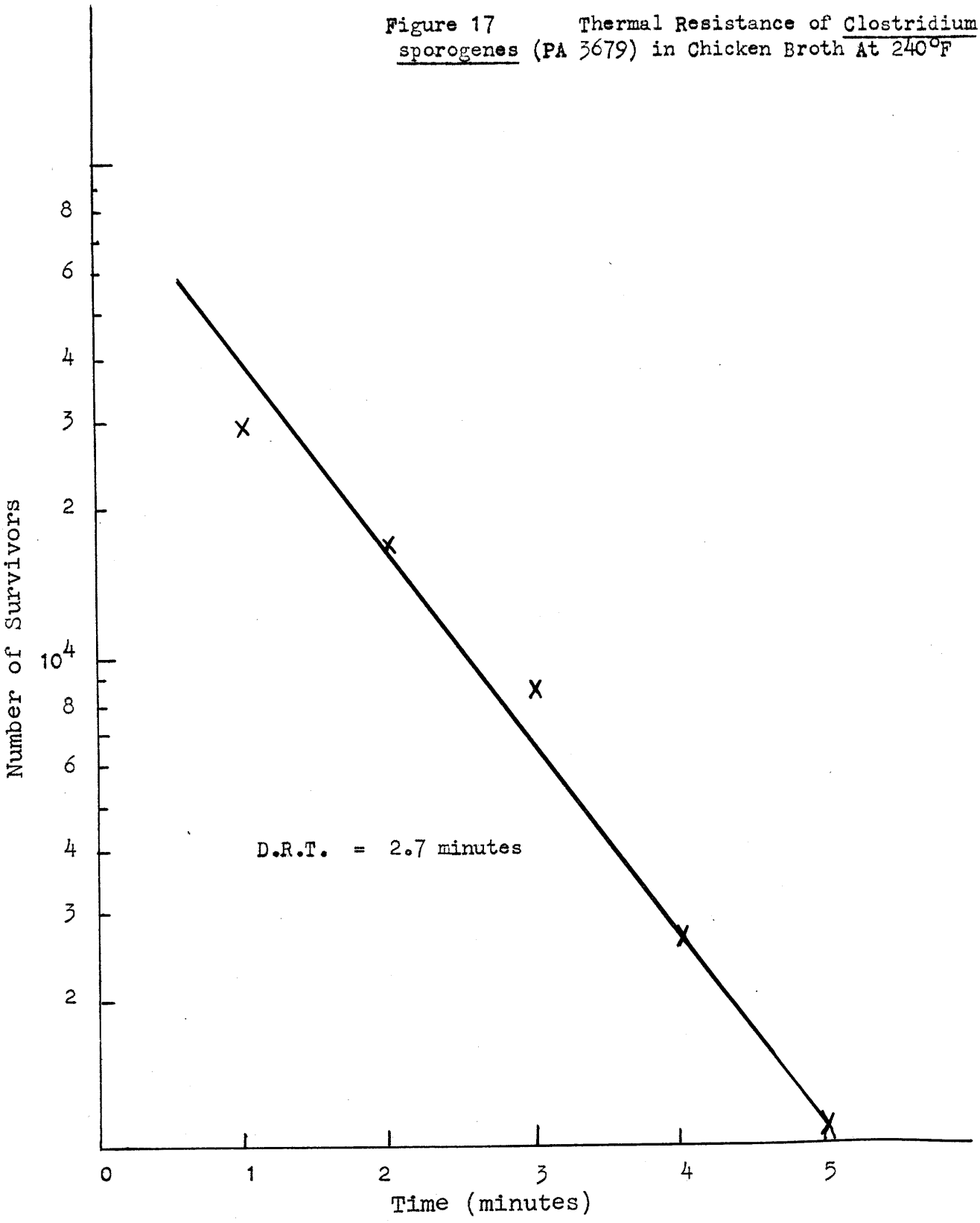


Figure 17 Thermal Resistance of Clostridium sporogenes (PA 3679) in Chicken Broth At 240°F



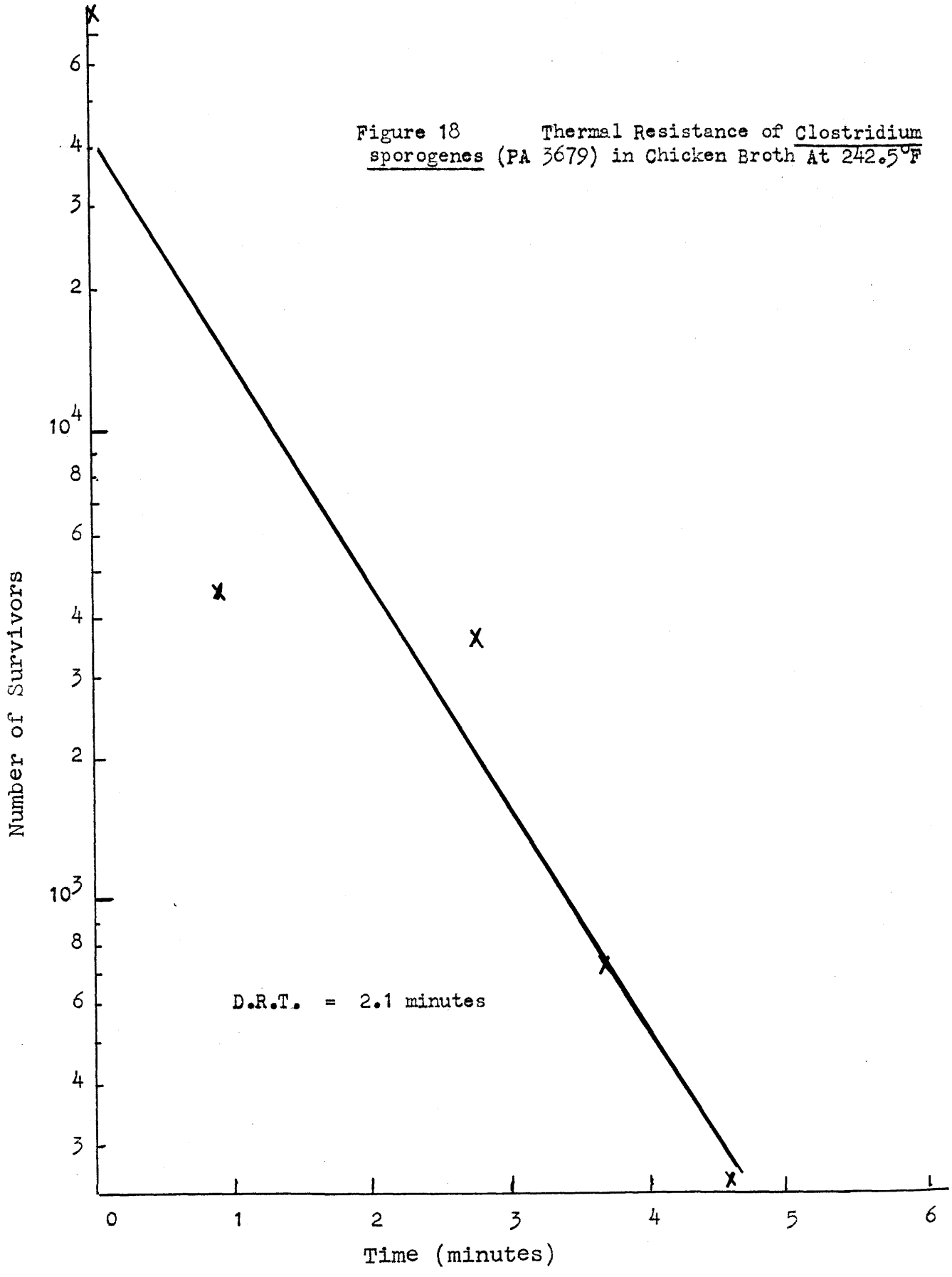
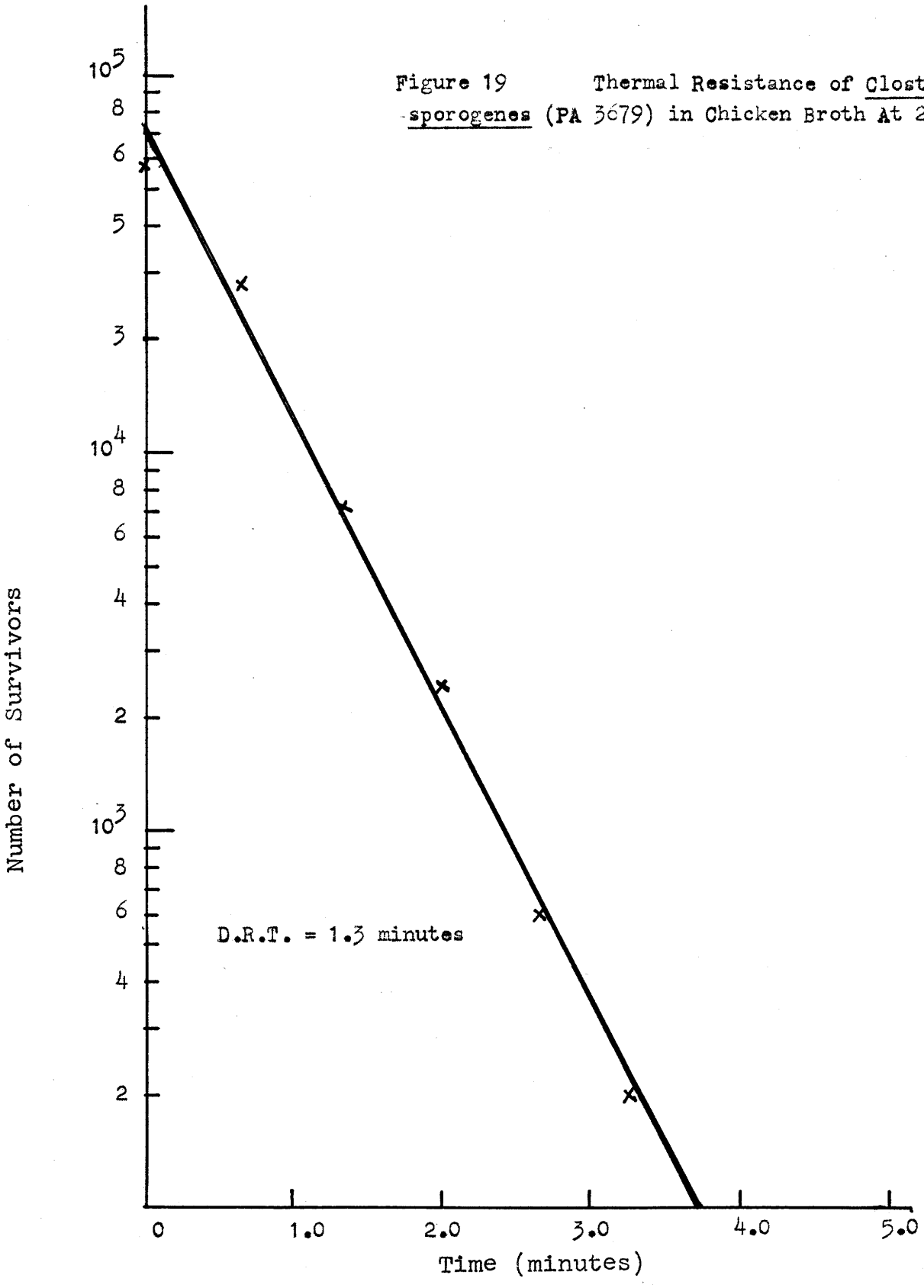


Figure 18 Thermal Resistance of Clostridium sporogenes (PA 3679) in Chicken Broth At 242.5°F

Figure 19 Thermal Resistance of Clostridium sporogenes (PA 3679) in Chicken Broth At 245°F



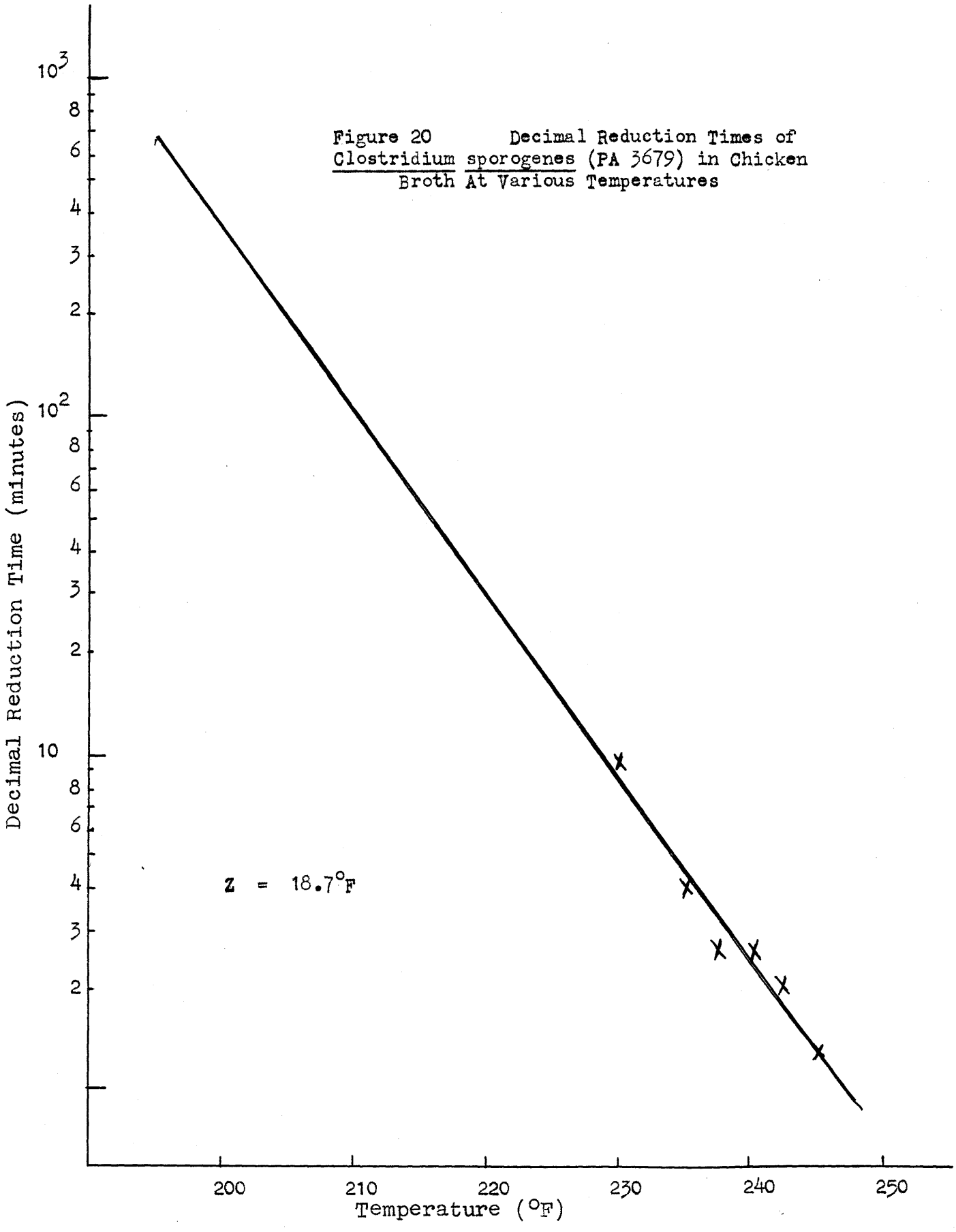


Figure 20 Decimal Reduction Times of Clostridium sporogenes (PA 3679) in Chicken Broth At Various Temperatures

Thermal death data were not obtained for the third system, carrots suspended in chicken broth, because of the time limitations. Considering the similarities in pH and the preponderance of chicken broth in the carrot-broth system, it was considered that the Z and D values obtained with chicken broth could also be used in the carrot-broth system.

C. Evaluation of thermal processing

1. Evaluation of calculated process time

Packages containing the two test products were processed to give a certain survival of organisms inoculated into the product. The calculation of the predicted number of organisms surviving is made as follows:

1. The temperature at the slowest heating point is predicted from the typical heat transfer curve (Figures 1 - 4) obtained for the same product under similar process conditions.

2. The decimal reduction time for the temperature at each 1 or 1/2 minute intervals (based on average temperature during that time interval) is obtained from the D.R.T. versus temperature curve (Figures 13 and 14).

3. The ratios of time interval to D.R.T. for the temperature corresponding to each time interval are summed to give the total lethal effect (number of D.R.T.'s) of the process.

4. The expected number of survivors is calculated by using the following equation:

$$N = (N_o)(10^{-\text{Total lethality of the process}})$$

or,

$$N = (N_o)\ (10^{-D.R.T.'s\ of\ the\ process})$$

where,

N = expected number of surviving organisms/gm

N_o = initial inoculum count/gm

a. Ground beef

The results of the microbiological determination on ground beef processed according to the process calculation in vertical position under water are presented in Table 12. The calculation of predicted survivors was based on the typical heat penetration curve shown in Figure 1. The D.R.T. values and the lethal effects at corresponding temperatures at each time interval are tabulated in Table 13.

The predicted number of survivors based on number inoculated is 4.15×10^4 organisms/g. When the prediction is based on the count from an unprocessed control it is 5.60×10^4 organisms/g. The actual survivors obtained after the processing were less by a factor of about 20 - 300. They are 0.19×10^3, 1.35×10^3 and 2.14×10^3 and the average is 1.23×10^3 organisms/g.

The experimental results and the prediction of survival from process calculations in a horizontal position are shown in Tables 14. The process calculation is based on the typical heat penetration shown in Figure 2 and presented in Table 15. The D.R.T. values and the lethal effects at corresponding temperatures at each time interval are tabulated in Table 15. The predicted number of survivors is 5.87×10^4 organisms/g based on the number of inoculum stock culture of 8.47×10^4

Table 12

RESULTS OF BACTERIOLOGICAL TEST FOR THE EFFECTIVENESS OF THERMAL PROCESSING OF FLEXIBLY PACKAGED GROUND BEEF*
(PROCESSED AT 250°F, 15 PSI UNDER WATER IN VERTICAL POSITION)

Package #	Sample Weight (g)	Average No. of Colonies	Survivors Found (org/g) Individual Samples	Average for the package
1 - a	2.00	55	1.38×10^3	1.35×10^3
b	2.00	54	1.38×10^3	
c	2.00	53	1.32×10^3	
2 - a	2.01	76	1.89×10^3	2.14×10^3
b	2.02	96	2.38×10^3	
3 - a	1.99	9	2.26×10^2	1.88×10^2
b	2.01	6	1.49×10^2	

*In all tests, the predicted survivors (org/g) were 4.15×10^4 when calculated with inoculum counts from the stock culture and 5.60×10^4 when calculated with the number of spores recovered from control package.

Table 13

CALCULATIONS FOR THE PREDICTION OF THE EFFECTIVENESS OF THERMAL PROCESSING OF FLEXIBLY PACKAGED GROUND BEEF (PROCESSED AT 250°F, 15 PSI UNDER WATER IN VERTICAL POSITION)

CALCULATIONS BASED ON THE TYPICAL HEAT TRANSFER DATA (PACKAGE # 2 RUN GB V-VI)

Time (min.)	Temperature (°F)	D.R.T.	Lethal Effect (1/D.R.T.)
11	197.0	690	0.001
12	204.0	295	0.004
13	210.0	143	0.007
14	215.0	68.5	0.015
15	219.0	47.0	0.021
16	223.0	28.5	0.035
17	227.0	17.5	0.057
18	230.0	12.0	0.083
19	232.6	8.70	0.115
20	234.7	6.98	0.143
21	236.8	5.50	0.181
22	237.6	5.10	0.196
23	236.0	5.80	0.172
24	226.0	19.8	0.051
25	212.0	111	0.009
		Total Lethal Effect:	1.090

Cooling was started 20 min. after processing started.

Table 14

RESULTS OF BACTERIOLOGICAL TEST FOR THE EFFECTIVENESS OF THERMAL PROCESSING OF FLEXIBLY PACKAGED GROUND BEEF*
(PROCESSED AT 250°F, 15 PSI UNDER WATER IN HORIZONTAL POSITION)

Package #	Sample Weight (g)	Average No. of Colonies	Survivors Found (org/g) Individual Samples	Average For the package
1 - a	3.08	38	6.17×10^4	
b	2.34	23	4.65×10^4	5.00×10^4
c	2.95	26	4.12×10^4	
2 - a	2.79	25	4.47×10^4	
b	3.59	15	2.08×10^4	3.40×10^4
c	4.78	35	3.65×10^4	
3 - a	2.93	29	4.93×10^4	
b	2.43	25	4.03×10^4	5.92×10^4
c	3.24	49	7.78×10^4	

*In all tests, the predicted survivors (org/g) were 5.87×10^4 when calculated with inoculum counts from the stock culture and 8.47×10^4 when calculated with the number of spores recovered from control package.

Table 15

CALCULATIONS FOR THE PREDICTION OF THE EFFECTIVENESS OF THERMAL PROCESSING OF FLEXIBLY PACKAGED GROUND BEEF (PROCESSED AT 250°F, 15 PSI UNDER WATER IN HORIZONTAL POSITION)

CALCULATIONS BASED ON THE TYPICAL HEAT TRANSFER DATA (PACKAGE # 5 RUN GB H-II)

Time (min.)	Temperature (°F)	D.R.T.	Lethal Effect (1/D.R.T.)
14	195.0	885	0.001
15	200.0	483	0.002
16	207.0	205	0.005
17	212.8	100	0.010
18	217.2	58.7	0.017
19	221.5	34.5	0.029
20	225.0	22.5	0.044
21	228.0	16.2	0.062
22	230.2	11.5	0.087
23	233.2	8.45	0.118
24	235.2	6.65	0.150
25	236.5	5.70	0.175
26	234.5	7.42	0.135
27	229.0	14.3	0.070
28	221.0	36.7	0.027
29	210.0	142.0	0.007
30	196.0	790	0.001
		Total Lethal Effect:	0.940

Cooling was started 24.5 min. after processing started.

organisms/g based on the recovery from the control pouches. The surviving microorganisms recovered from the pouch after processing are 3.40×10^4 organisms/g, 5.00×10^4 organisms/g and 5.92×10^4 organisms/g, with the average of 4.77×10^4 organisms/g. The number of the predicted survivors are of same order of magnitude as the actual recovery; therefore the predicted efficiency of thermal process agrees with the experimental one.

The generally lower recovery of the spores from the processed pouch compared with predicted calculations may be due to the fact that the calculations are based on the slowest heating point and most of the pouch contents receive more severe heat treatment than the geometric center. Although an attempt was made to take the sample as close to the geometric center as possible, impossibility of obtaining a finite sample from a geometrical point resulted in inclusion of some periphery and might have caused the lower recovery than predicted. However, the much lower recovery in the vertically processed packages suggests that the lower counts may be caused by other factors than this. This is most likely caused by the washing out of the spores adhered to ground beef by the liquid produced from ground beef during the processing. Of course, this effect is greater in the packages placed in the vertical position because of the increased vertical length which provide longer path for the liquid to drain and wash out the spores from ground beef. Once the liquid is drained, the liquid would be heated by convection and spores would be inactivated very rapidly.

b. Chicken broth

Similar tests were conducted on chicken broth processed under

water in vertical and in horizontal positions. Tables 16 and 17 show the results and predicted calculations for pouches containing chicken broth processed in vertical position. The predicted survival was 50.7 x 10^2 and 48.0 x 10^2 organisms/g; the actual survival was less by a factor of about 20, being 2.5 x 10^2, 2.7 x 10^2 and 3.4 x 10^2 organisms per gm with the average of 2.9 x 10^2 organisms/g.

In the case of pouches processed in a horizontal position (Tables 18 and 19) the variation between the experimental and predicted values are greater in this case than in vertical position. 30.3 x 10^3 survivors per gram and 25.5 x 10^3 survivors/g are predicted and 0.16 x 10^3, 0.34 x 10^3, 1.40 x 10^3 survivors/g are actually observed. The average of the survivors observed is 0.63 x 10^3 organisms/g. The difference is by a factor of between 20 to 200. The smallest and the largest number of survivors actually observed in this case differ by a factor of ten. This is because the cooling water is introduced from the bottom of the retort and therefore reaches faster to the packages placed at the lower level in the retort (packages # 3 and 4) compared to the packages at the higher position (packages # 9 and 10). In the processing of the convection-heating foods which heat fast and when the duration of the process is very short, such as in this case, some lag in the beginning of the cooling can contribute significant portion of the lethal effect of total process.

It may be concluded that the calculation of survivors results in predictions which are on the safe side as might be expected from the use of slowest heating points for calculation for both products.

2. Evaluation of sterility of the thermal processing

In addition to tests described above, which were calculated to give

Table 16

RESULTS OF BACTERIOLOGICAL TEST FOR THE EFFECTIVENESS OF THERMAL PROCESSING OF FLEXIBLY PACKAGED CHICKEN BROTH (PROCESSED AT 250°F, 15 PSI UNDER WATER IN VERTICAL POSITION)

Package #	Predicted Survivors (org/g)		Survivors Found (org/g)	
	From Stock Culture	From Control Pouch	Average No. of Colonies	Average For the Package
4	50.7×10^2	48.0×10^2	27	2.7×10^2
7	50.7×10^2	48.0×10^2	34	3.4×10^2
10	50.7×10^2	48.0×10^2	25	2.5×10^2

Table 17

CALCULATIONS FOR THE PREDICTION OF THE EFFECTIVENESS OF THERMAL PROCESSING OF FLEXIBLY PACKAGED CHICKEN BROTH (PROCESSED AT 250°F, 15 PSI UNDER WATER IN VERTICAL POSITION)

CALCULATIONS BASED ON THE TYPICAL HEAT TRANSFER DATA (PACKAGE # 12 RUN CB V-II)

Time (min.)	Temperature (°F)	D.R.T.	Lethal Effect (0.5/D.R.T.)
3.5	206.0	142	0.004
4.0	214.0	59.2	0.008
4.5	220.0	27.8	0.018
5.0	227.0	11.7	0.043
5.5	233.0	5.62	0.089
6.0	237.0	3.43	0.146
6.5	241.0	2.12	0.236
7.0	243.0	1.66	0.301
7.5	245.2	1.25	0.400
8.0	246.4	1.12	0.446
8.5	241.0	2.12	0.236
9.0	230.0	8.15	0.061
9.5	213.0	67.1	0.007
		Total Lethal Effect:	1.995

Cooling was started at 8 min. after processing started.

Table 18

RESULTS OF BACTERIOLOGICAL TEST FOR THE EFFECTIVENESS OF THERMAL PROCESSING OF FLEXIBLY PACKAGED CHICKEN BROTH (PROCESSED AT 250°F, 15 PSI UNDER WATER IN HORIZONTAL POSITION)

Package #	Predicted Survivors (org/g)		Survivors Found (org/g)	
	From Stock Culture	From Control Pouch	Average No. of Colonies	Average For the Package
3	30.3×10^3	25.5×10^3	16	0.16×10^3
4	30.3×10^3	25.5×10^3	34	0.34×10^3
9	30.3×10^3	25.5×10^3	14	1.40×10^3
10	30.3×10^3	25.5×10^3	12	1.20×10^3

Table 19

CALCULATIONS FOR THE PREDICTION OF THE EFFECTIVENESS OF THERMAL PROCESSING OF FLEXIBLY PACKAGED CHICKEN BROTH (PROCESSED AT 250°F, 15 PSI UNDER WATER IN HORIZONTAL POSITION)

CALCULATION BASED ON THE TYPICAL HEAT TRANSFER DATA (PACKAGE # 5 RUN CB H-II)

Time (Min.)	Temperature (°F)	D.R.T.	Lethal Effect (0.5/D.R.T.)
3.0	203.0	235	0.002
3.5	213.0	67.5	0.007
4.0	221.0	24.7	0.020
4.5	227.0	11.7	0.043
5.0	232.0	6.38	0.078
5.5	236.0	3.89	0.129
6.0	238.8	3.10	0.161
6.5	241.3	2.00	0.250
7.0	243.2	1.65	0.303
7.5	244.7	1.38	0.362
8.0	238.5	2.86	0.175
8.5	224.0	16.1	0.031
		Total Lethal Effect:	1.561

Cooling was started at 7.5 min. after processing started.

substantial survival, some tests were conducted in which the lethal effect of the process was adequate to give only minimum sterility in the samples processed.

a. Ground beef

In the case of ground beef the calculations of the D.R.T.'s of the processes are shown in Tables 20 and 21. These processes are 7.31 D.R.T.'s for the vertical and 7.04 for the horizontal and expected to result in a reduction of the count from the initial 10^4 organisms/g to approximately 10^{-3} and 2×10^{-3} organisms/g respectively. In actual experiments, 10 pouches each were processed in horizontal or vertical positions. From each pouch 2 tubes each containing 2 gm of sample were incubated as described before. In the case of pouches processed in a vertical position one tube out of twenty showed growth; in the case of the pouches processed in horizontal positions, three tubes showed growth. The growth was indicated by turbidity and the gas formation. The organisms from the positive tubes were examined microscopically. They were bacilli with subterminal spores indicative of Clostridium sporogenes, and upon incubation they produced a characteristic putrefactive odor.

The number of positive tubes was thus much greater than expected. The probability of getting such results are 2×10^{-3} and 1.1×10^{-9} respectively (Weintraub, 1963), and such low probabilities are not very likely to occur. Considering the fact that in all other tests the recoveries of microorganisms from the processed pouch were always lower than predicted, the reasons for the high recovery only in this case may be considered other than a failure in the prediction of the sterility of the process. It is possible that re-contamination took place after the

Table 20

CALCULATIONS FOR THE PREDICTION OF THE EFFECTIVENESS OF STERILITY OF FLEXIBLY PACKAGED GROUND BEEF (PROCESSED AT 250°F, 15 PSI UNDER WATER IN VERTICAL POSITION)

CALCULATION BASED ON THE TYPICAL HEAT TRANSFER DATA (PACKAGE # 2 RUN GB V-VI)

Time (min.)	Temperature (°F)	D.R.T.	Lethal Effect (1/D.R.T.)
11	197.0	690	0.001
12	204.0	295	0.004
13	210.0	143	0.007
14	215.0	68.5	0.015
15	219.0	47.0	0.021
16	223.0	28.5	0.035
17	227.0	17.5	0.057
18	230.0	12.0	0.083
19	232.6	8.70	0.115
20	234.7	6.98	0.143
21	236.7	5.30	0.189
22	238.5	4.15	0.241
23	240.0	3.53	0.283
24	241.3	3.03	0.330
25	242.5	2.62	0.382
26	243.5	2.32	0.431
27	244.3	2.11	0.474
28	245.0	2.00	0.500
29	245.7	1.85	0.541
30	246.3	1.63	0.613
31	246.6	1.55	0.645
32	246.4	1.57	0.637
33	245.4	1.82	0.549
34	243.0	2.47	0.405
35	236.8	5.28	0.189
36	236.6	5.31	0.188
37	236.0	5.80	0.172
38	226.0	19.8	0.051
39	212.0	111	0.009
		Total Lethal Effect:	7.310

Cooling was started 31.0 min. after processing started.

Table 21

CALCULATIONS FOR THE PREDICTION OF THE EFFECTIVENESS OF STERILITY OF FLEXIBLY PACKAGED GROUND BEEF (PROCESSED AT 250°F, 15 PSI UNDER WATER IN HORIZONTAL POSITION)

CALCULATIONS BASED ON THE TYPICAL HEAT TRANSFER DATA (PACKAGE # 5 RUN GB H-II)

Time (min.)	Temperature (°F)	D.R.T.	Lethal Effect (1/D.R.T.)
14	195.0	885	0.001
15	200.0	483	0.002
16	207.0	205	0.005
17	212.8	100	0.010
18	217.2	58.7	0.017
19	221.5	34.5	0.029
20	225.0	22.5	0.044
21	228.0	16.2	0.062
22	230.8	11.5	0.087
23	233.2	8.45	0.118
24	235.2	6.65	0.150
25	237.0	5.42	0.185
26	238.8	4.40	0.227
27	240.4	3.55	0.282
28	241.5	3.15	0.317
29	242.6	2.68	0.373
30	243.5	2.50	0.400
31	244.4	2.22	0.450
32	245.1	2.07	0.483
33	245.7	1.95	0.513
34	246.3	1.78	0.562
35	246.7	1.72	0.581
36	246.5	1.75	0.571
37	245.3	2.05	0.488
38	243.3	2.55	0.392
39	240.6	3.50	0.286
40	236.5	5.90	0.169
41	234.5	7.50	0.133
42	229.0	14.3	0.070
43	221.0	37.2	0.027
44	210.0	142	0.007
45	196.0	790	0.001
		Total Lethal Effect:	7.042

Cooling was started 35.0 min. after processing started.

processing during the microbial analysis. However, even these improbably high recoveries still fell well within the deviation covered by safe factors normally applied in commercial practice.

b. Chicken broth

Similar tests were carried out for chicken broth. The pouches processed in vertical position were given a process equivalent to 5.19 D.R.T.'s (Table 22), pouches in a horizontal position were given 3.56 D.R.T.'s (Table 23). The initial inoculum number was 10^3 organisms per ml. The recovery of the spores from the control pouch was 27×10^3 organisms per ml of chicken broth.

The predicted survival for pouches processed in vertical position was 6.45×10^{-2} organisms/ml on the basis of the inoculum, or 1.75×10^{-1} organisms/ml on the basis of the recovery from the control pouches. No growth was found in any of the twenty test tubes incubated as was expected.

In the case of pouches processed in a horizontal position 2.1×10^{-1} organisms/ml were predicted on the basis of the inoculum count, and 5.62 organisms/ml on the basis of the recovery from the control pouches. No growth was found in any of the twenty test tubes incubated.

This agrees reasonably well with the prediction which indicate a low probability of positive tubes when inoculum counts are used as a basis for prediction. The consistently higher microbial counts in the control pouches compared with inoculum is probably caused by the growth of the organisms during the time between the preparation of the sample and starting of the bacterial analysis.

Table 22

CALCULATIONS FORTHE PREDICTION OF THE EFFECTIVENESS OF STERILITY OF FLEXIBLY PACKAGED CHICKEN BROTH (PROCESSED AT 250°F, 15 PSI UNDER WATER IN VERTICAL POSITION)

CALCULATION BASED ON THE TYPICAL HEAT TRANSFER DATA (PACKAGE # 12 RUN CB V-VII)

Time (min.)	Temperature (°F)	D.R.T.	Lethal Effect (0.5/D.R.T.)
3.5	206.0	142	0.004
4.0	214.0	59.5	0.008
4.5	220.0	27.8	0.018
5.0	227.0	11.7	0.043
5.5	233.0	5.62	0.089
6.0	237.0	3.43	0.146
6.5	241.0	2.12	0.236
7.0	243.0	1.66	0.301
7.5	245.2	1.25	0.400
8.0	246.4	1.12	0.446
8.5	247.3	0.981	0.510
9.0	248.0	0.900	0.556
9.5	248.5	0.840	0.595
10.0	248.9	0.805	0.621
10.5	247.9	0.910	0.549
11.0	245.2	1.25	0.400
11.5	240.0	2.40	0.208
12.0	228.5	9.80	0.051
12.5	215.0	51.5	0.010
		Total Lethal Effect:	5.191

Cooling started 10.0 min. after processing started.

Table 23

CALCULATIONS FOR THE PREDICTION OF THE EFFECTIVENESS OF STERILITY OF FLEXIBLY PACKAGED CHICKEN BROTH (PROCESSED AT 250°F, 15 PSI UNDER WATER IN HORIZONTAL POSITION)

CALCULATION BASED ON THE TYPICAL HEAT TRANSFER DATA (PACKAGE # 5 RUN CB H-II)

Time (min.)	Temperature (°F)	D.R.T.	Lethal Effect (0.5/D.R.T.)
3.0	203.0	235	0.002
3.5	213.0	67.5	0.007
4.0	221.0	24.7	0.020
4.5	227.0	11.7	0.043
5.0	232.0	6.38	0.078
5.5	236.0	3.89	0.129
6.0	238.8	3.10	0.161
6.5	241.3	2.00	0.250
7.0	243.2	1.65	0.303
7.5	244.7	1.38	0.362
8.0	245.8	1.18	0.424
8.5	246.4	1.08	0.463
9.0	247.3	0.980	0.510
9.5	242.4	1.80	0.278
10.0	230.0	8.10	0.617
		Total Lethal Effect:	3.647

Cooling was started 9.0 min. after processing started.

CONCLUSIONS

VI. CONCLUSIONS

A. Heat Penetration Studies

The following conclusions were made from heat penetration studies:

1. Ground beef

a) Heat penetration data plotted in the usual manner, as plots of degrees below retort temperature on inverted logarithmic coordinates versus time on linear coordinates resulted in straight lines, preceded by a lag period.

b) The pouches processed in vertical position heated significantly faster than that processed at horizontal position as tabulated below:

Position	Time Required To Reach 240°F	Time Required To Reach 245°F	f_h
Vertical	22.3 minutes	27.2 minutes	15.9 minutes
Horizontal	26.5 minutes	31.5 minutes	17.0 minutes

c) Total amount of residual air in the pouches was varied from 0.5 to 26 cc/pouch. Within this range there was no affect of the amount of residual air on the rate of heat penetration.

d) The rate of heat penetration was significantly slower than expected on the basis of a simple model. The model considered the beef as a solid block with known thermal diffusivity in perfect contact with the internal pouch surface, and the surface resistance was computed from known thermal properties of packaging material and from published data on convective heat transfer.

Several reasons for the slower heating were considered, and the

most likely of these appears to be existence of air film outside or within the packaging film. In ground beef, additional air film formed at the uneven surface and the capillaries formed may have contributed to increased resistance.

2. Chicken broth

a) Heat penetration curves were broken straight lines, when plotted in the manner described above, for runs in which the pouches were processed in a vertical position. The break occurred at the temperature around 228°F. Pouches processed in a horizontal position showed no breaks in the straight lines.

b) The slowest heating point in the pouches processed in vertical position was at 1/8 th of the length or 25/32" from the bottom of the empty pouch, or at approximately the same location as that found in No. 2 cans.

In pouches processed in a horizontal position all points studied heated at approximately the same rate.

c) There was no significant difference in heat penetration between processing in vertical or horizontal positions shown below:

Position	Time Required To Reach 240°F	Time Required To Reach 245°F	f_h
Vertical	6.1 minutes	7.3 minutes	5.4 minutes
Horizontal	6.0 minutes	7.3 minutes	4.7 minutes

d) The resistance to heat flow was much higher than expected on the basis of a simple model, which considered convective transfer both outside and inside the pouch. The actual resistance found in this case was less than that in the case of ground beef after accounting for the

resistance through solid layer.

The possibility of existence of an air film outside or within the packaging film was considered to be a likely reason for slower heat transfer also in this case.

e) It is concluded that the actual resistance to heat flow of laminated packaging materials should be investigated in heat-process design, under use conditions, since their resistance may be greater than expected solely by summing the resistances of the individual lamination layers.

3. Carrot slices in chicken broth

a) The general heating characteristics, and in particular the magnitude of the overall heat transfer coefficient were the same as in the case of chicken broth without the carrots, with the following exceptions:

i) There was no clearly definable slowest heating point possibly because the slices acted as baffles.

ii) There seemed to be a tendency for the temperature to level off a few degrees below retort temperature. Whether this was a transient effect due to cooking of the carrots was not investigated further.

b) There was no significant difference in heat penetration between the pouches processed in vertical or horizontal position as shown below:

Position	Time Required To Reach 240°F	Time Required To Reach 245°F	f_h
Vertical	7.0 minutes	8.6 minutes	5.2 minutes
Horizontal	6.2 minutes	8.0 minutes	5.2 minutes

B. Thermal Resistivity of Clostridium sporogenes (PA 3679)

The following data on thermal resistivity of the test organisms under the test conditions were obtained:

1. The decimal reduction time of Clostridium sporogenes (PA 3679) in ground beef puree at 250°F was 1.2 minutes and the Z value was 18.2 minutes.

2. The decimal reduction time of Clostridium sporogenes (PA 3679) in chicken broth at 250°F was 0.7 minutes and the Z value was 18.7 minutes.

C. Evaluation of Thermal Processing

1. Evaluation of calculated process time

The survival of Clostridium sporogenes (PA 3679) inoculated into the sample product was predicted by summing up the lethalities of the processes and comparing them with the actual recovery from the processed sample. The following conclusions were reached:

a) Ground beef

In the experiment performed with the pouches processed in a vertical position, the predicted number of survivors were about twenty to forty times higher than actual recoveries.

In the pouches processed in a horizontal position, the actual survivors were less only by a factor of less than two, showing better agreement.

The generally lower recoveries were considered to be caused from

basing the process calculations on slowest heating point and washing effect of the liquid produced from the ground beef during the processing. The lower recoveries in vertically processed pouches indicate that the washing effect of the liquid may be the more likely effect.

b) Chicken broth

In the experiment performed with the pouches placed in a vertical position, the predicted survivors were about twenty times higher than actual recovery.

In the pouches processed in a horizontal position the predicted survivors were greater than the recovery by the factor of twenty to two hundred times.

Again, the number of survivor predicted based on the slowest heating point may contribute to some of the lower recoveries. The much lower recoveries in some of the horizontally processed pouch are due to longer times required for the cooling water to reach the pouches.

The actual survivors were less than predicted in all cases. Considering that and all the variables involved, the agreement between the predicted and experimental survivor may be considered satisfactory, and therefore, one may conclude that the method used for the prediction of survivors in this study, summation of the lethalities at the slowest heating point of the process, is applicable for the prediction of the lethality of the process for flexibly packaged foods.

2. Evaluation of sterility of the thermal processing

The following conclusions were made from the results of the tests

conducted in which the lethal effect of the process was adequate to give only minimum sterility.

a) Ground beef

Ground beef processed in a vertical position and in a horizontal position both gave improbably high survivors. Since higher than predicted survivors occurred only in this case, this may not be considered a failure in the prediction of the lethality of the process, but rather is due to contamination. Additional experiments are necessary to demonstrate better agreement between the predicted and recovered survivors.

b) Chicken broth

Chicken broth processed in a vertical position and in a horizontal position resulted in more efficient sterilization than predicted.

Although additional experiments are needed to show better agreement in predicted and experimentally obtained sterility in the ground beef, the deviation still fell within the deviation covered by safe factors normally applied in commercial practice. Therefore, it may be concluded that the method used for the prediction of survival in this study, summation of the lethalities at the slowest heating point of the process, is applicable for predicting the sterility of the process for flexibly packaged foods.

SUGGESTIONS FOR FUTURE STUDY

VII. SUGGESTIONS FOR FUTURE STUDY

During the course of this study it was felt that the present study conducted on model systems would contribute more to the understanding of the mechanism of the heat transfer processes. Many factors and variables that can affect to the process can be studied independently under more controlled conditions in model systems. The variables which are recommended for study are:

1. Liquid systems with different thermal conductivities, heat capacities, viscosities and densities.

2. Solids with different thermal conductivities, heat capacities and densities.

3. Suspended systems with different sizes and weight ratios of the suspension in the liquids with different physical characteristics.

The most important reason for higher than expected resistance to heat flow was postulated to be caused by a gas film on either side or within the package lamination.

In order to validate and clarify this consideration, the heat penetration studies can be carried out at different pressures to see if the resistance to heat flow can be decreased with increased pressure.

In order to test the existence of gas film outside of the packaging material, the following experiments can be performed.

1. After determining the surface characteristics (wettability) of a single packaging film, make heat penetration studies in the food material contained in the pouches made from those materials and determine relationship

between the wettability of the film and overall heat transfer coefficient in these systems.

2. Alter the surface active forces by adding surface active agent to investigate if lowering the surface tension can increase the rate of heat penetration.

The following experiments can be carried out in order to validate the existence of gas film within the packaging material.

1. Heat penetration studies should be carried out with single films similar to the inside and outside components of the lamination used. Faster heat penetration in this case compared with the lamination would indicate the presence of gas films within the lamination.

2. Heat penetration studies can be repeated with the systems already under went thermal processing. Since these systems have been degassed by the processing, if the resistance to heat transfer is still high, this will indicate the existence of gas films within the lamination.

3. It is also recommended that steady-state thermal conductivity measurements be made on various laminations, and that these studies include conditions under which the laminations show a tendency to layer separation, as was the case in heat processing especially under water.

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APPENDIX

APPENDIX A

Determination of heating lag in capillary tubes

Stern (1953) determined that at a bath temperature of about 115°C the time required for a point along the central axis of a capillary tube to reach 0.1°C below bath temperature was 6 seconds.

Since the heating temperatures for this investigation were to be from about 90-110°C, it was desirable to determine what the lag time would be.

Olson and Schultz (1942) present a numerical solution for calculating this lag time. They state that the temperature at a point on the axis of an infinite cylinder at any time t is given by the equation:

$$U = C\left(\frac{kt}{r^2}\right)$$

and,

$$U = \frac{T_1 - T}{T_1 - T_0}$$

where,

k = thermal diffusivity of the object

t = time (sec)

r = radius of the infinite cylinder (mm)

T = temperature (°C) at time t

T_1 = temperature (°C) of heating medium

T_0 = initial temperature (°C)

U = temperature on "theoretical" scale, related to T by $U = (T_1 - T)/(T_1 - T_0)$

The value of k for the infinite cylinder was calculated by the equation of Olson and Jackson (1942) whereby

$$k = \frac{0.398\ r^2}{f}$$

Farkas (1955) has determined experimentally the value of f (reciprocal of the slope of the heating curve) and found it to be 3.25 seconds. The average radius of the capillary tubes to be used was 0.85 mm. From this data k was calculated to be 0.0885. (This k is actually an overall value of k for glass and water).

Licciardello (1960) gives an example of how this method is applied in practice. Suppose it is the object to determine what the temperature would be at the center of the capillary column after 10 seconds heating in a bath at 100°C when initial temperature of capillary column = 20°C.

$$U = C\left(\frac{kt}{r^2}\right)$$

$$U = C(1.23)$$

let $U = C\ominus$ and in this problem $\ominus$ becomes equal to 1.23.

Solve for $C\ominus$ according to the relationship:

$$C\ominus = 1.60197 \text{ anti-log } (-2.51161\ominus)$$

and

$$C\ominus = 0.00130 = U$$

but

$$U = (T_1 - T)/(T_1 - T_0)$$

therefore,

$$0.0013 = (100 - T)/(100 - 20)$$

$$T = 99.89^{\circ}C$$

This means that after 10 seconds heating at 100°C the temperature at the center of the capillary is 99.89°C or 0.1°C below bath temperature.

In the same manner, Licciardello (1960) found that with a bath temperature of 90°C, after 10 seconds of heating, the temperature at the center of the capillary would be 89.91°C, and for a bath temperature of 110°C the temperature at the center of the capillary after 10 seconds would be 109.88°C.

Later on in the course of Licciardello's investigation, a Leeds and Northup "Speedomax" became available and he determined the lag time experimentally. A copper-constantan thermocouple was connected to the Speedomax and the thermocouple junction was inserted in a capillary tube which contained water. The capillary was inserted into a beaker of water, the temperature of which was measured with a calibrated thermometer. This served to establish the base line on the graph traced by the recorder. The capillary was plunged into a thermostatically controlled oil bath maintained at 100°C. When the contents of the capillary tube reached bath temperature, as indicated by a plateau on the graph, the capillary was plunged into chilled water (12-14°C) and the cooling rate was recorded.

Licciardello estimated graphically that about 12 seconds were

required for the temperature at the center of the capillary to go from 20°C to within 0.1°C of bath temperature, and about 4.5 seconds were necessary to cool the capillary from 100°C to 20°C.

In a similar manner, Licciardello determined the lag time for a capillary tube containing ham puree and it was found to be 14.5 seconds. 5 seconds were required to cool from 100°C to 20°C.

The lag times calculated above are for the conditions not equal to that used in this experiment. However, in the view of the errors involved in the lag time determination and the relatively long heating time used in this experiment, the lag time was not determined experimentally but assumed to be 10 seconds for this experiment. To eliminate this effect of the heating lag in these tubes, all capillary tubes were heated for an additional 10 seconds. The control tubes, which represented zero heating time, were given a 10 second heat treatment.

APPENDIX B

Table 24

RESULTS OF HEAT PENETRATION STUDIES ON FLEXIBLY PACKAGED IN CHICKEN BROTH
(PROCESSED AT 250°F, 15 psi UNDER WATER IN A VERTICAL POSITION)

Package #	Thermocouple Location (Fraction of Length from Bottom)	Time Required to Reach Specified Temperature (min)	
		240°F	245°F
1	1/8	7.8	8.9
9	1/8	7.8	8.9
10	1/8	7.8	8.9
2	1/4	6.8	7.8
6	1/4	6.8	7.8
12	1/4	6.8	7.8
3	3/8	5.5	7.0
7	3/8	5.5	7.0
4	1/2	5.2	6.2
8	1/2	5.2	6.2
12	1/2	6.8	8.0

APPENDIX C

Table 25

The Relationship Between Heat Transfer Parameters In Convection Heating

Temperature of the Product (°F)	Retort Temp. (°F)	Pr	$g\beta\rho^2/\mu^2$ ($\times 10^9$)	$L^3\Delta T$	Gr ($\times 10^{-10}$)	GrPr ($\times 10^{-10}$)	Nu
			Vertical				
60	200.0	3.45	0.00316	29.82	0.00942	0.00335	70
100	205.0	2.70	0.52375	22.36	1.17	3.17	380
150	217.0	2.16	0.88890	14.30	1.27	2.75	280
200	236.2	1.72	1.48	7.7	1.14	1.96	200
228	250.0	1.54	1.92	3.13	0.60	0.93	150
240	250.0	1.49	2.04	1.42	0.29	0.43	123
245	250.0	1.47	2.09	0.71	0.15	0.22	110
249	250.0	1.45	2.14	0.14	0.03	0.04	75
			Horizontal				
60	200.0	3.45	0.00316	29.82	0.00942	0.00335	69.2
100	205.0	2.70	0.52375	22.36	1.17	3.17	251
150	215.5	2.18	0.87296	13.95	1.27	2.65	245
200	232.5	1.74	1.42	6.92	0.982	1.72	190
228	250.0	1.54	1.92	3.13	0.60	0.93	166
240	250.0	1.49	2.04	1.42	0.29	0.43	129
245	250.0	1.47	2.09	0.71	0.15	0.22	110
249	250.0	1.45	2.14	0.14	0.03	0.04	72

APPENDIX D

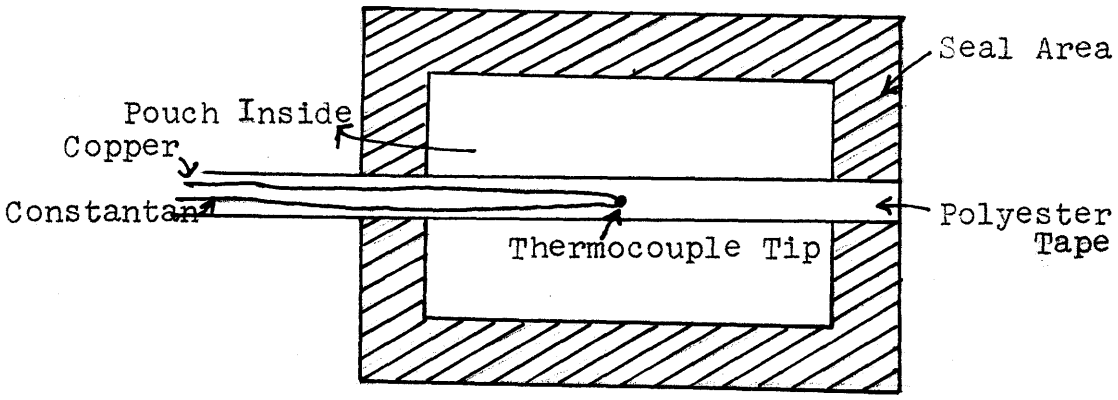
Table 26

INSTANTANEOUS OVERALL HEAT TRANSFER COEFFICIENTS FOR CHICKEN BROTH

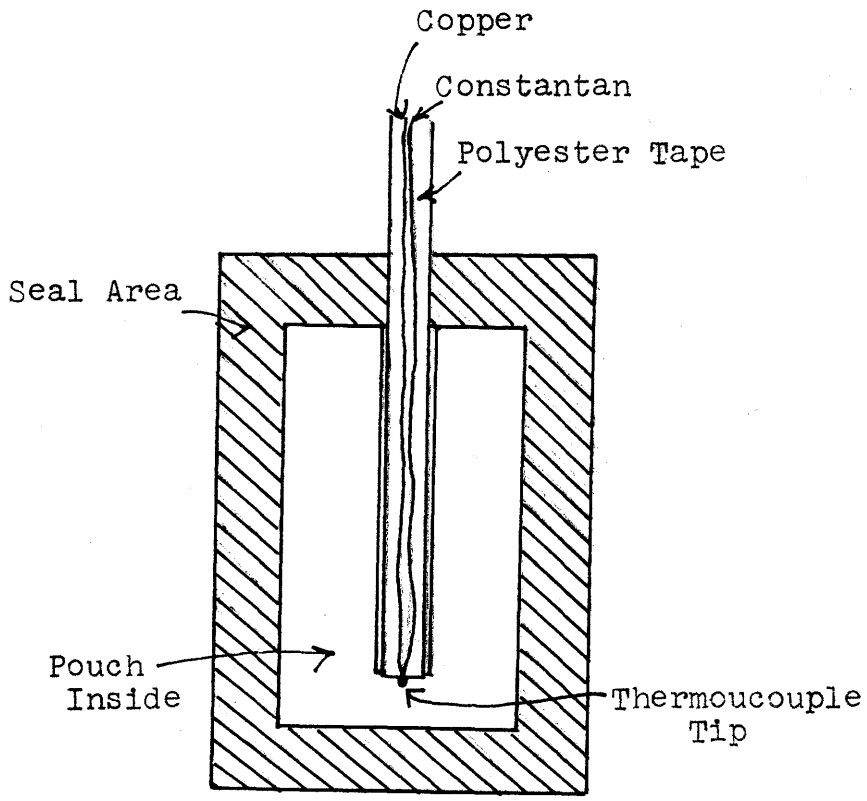
Heating Time (min)	Retort Temp. °F	Vertical Product Temp. °F	Vertical U $\frac{BTU}{hr\text{-}ft^2\text{-}^oF}$	Horizontal Product Temp. °F	Horizontal U $\frac{BTU}{hr\text{-}ft^2\text{-}^oF}$
0	200	60		60	
0.5	205.3	100	40	100	40
1.0	210.3	125	32	130	39
1.5	217.0	150	40	156	42
2.0	222.8	172	45	176	45
3.0	235.0	198	36	203	42
4.0	247.0	216.5	33	221	33
5.0	250.0	227.5	25	233	34
6.0	250.0	238	37	240	32

APPENDIX E

Figure 21 Schematic Diagrams of Thermocouples Placed in the Pouches Containing Fluid System



A Pouch Processed in a Horizontal Position



A Pouch Processed in a Vertical Position

BIOGRAPHICAL SKETCH

BIOGRAPHICAL SKETCH

Chokyun Rha was born as the first child of eight children of Dr. and Mrs. Sea Zin Rha in Seoul, Korea on October 5, 1933. She has a son, TaeMinn Rha Song. She graduated from Kyung-gi Girls High School in Seoul, Korea. In 1962, she has received the Bachelor of Sciences in Life Sciences from the Massachusetts Institute of Technology. She has received the Master of Science in Food Technology in 1964 and the Master of Science in Chemical Engineering in 1966 from the same institution. In 1966, she organized the Association For Graduate Women Students and was elected to the first president.

Society Memberships

Sigma Xi, Phi Mu Epsilon, Institute of Food Technologists.

Publications

Song, C., 1962. Effect of Storage Conditions On Dried Scallions. S.B. Thesis, Massachusetts Institute of Technology.

Song, C., Charm, S. and Kurland, G., 1963. Energy Losses For Blood Flowing Through Tapered Tubes and Curved Tubes. Fourth International Congress On Rheology, Brown University, Providence, Rhode Island.

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Rha, C., 1966. Rheological Properties of Food Materials. Phi Tau Sigma Symposium, Cornell University, Ithaca, N. Y.

Awards

1958 - 1959	Massachusetts Institute of Technology Undergraduate Scholarship.
1959 - 1960	Massachusetts Institute of Technology Undergraduate Scholarship.
1960 - 1961	Massachusetts Institute of Technology Undergraduate Scholarship.
1966	Best paper award, Phi Tau Sigma Symposium, Cornell University, Ithaca, N.Y.